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Advances in Nuclear Cardiac Instrumentation with a View Towards Reduced Radiation Exposure

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Abstract

Recent advances in nuclear cardiology instrumentation have enabled myocardial perfusion imaging (MPI) with improved image quality and fast scan times. These developments also can be exploited to reduce the effective radiation dose to the patient. In this review, we discuss these technologies including new single photon emission computed tomography (SPECT) and positron emission tomography (PET) scanners, as well as novel reconstruction software with regard to their potential for the reduction of the patient radiation dose. New advances in nuclear cardiology instrumentation will allow routine rest/stress MPI imaging with low radiation doses (< 5 mSv) and fast imaging times, even by the software-only solutions. It is possible to further reduce the MPI radiation dose to less than 2 to 3 mSv range with standard acquisition times. PET perfusion imaging also can be performed with very low doses especially by the three-dimensional scanners allowing hybrid PET/computed tomographic angiography (CTA) imaging with low overall dose. In addition, stress-only protocols can be utilized to further reduce the radiation dose and the overall test time.

Keywords

Myocardial perfusion PET; Solid-state detectors; Fast SPECT; Nuclear cardiology; Cardiac imaging; Radiation dose; Myocardial perfusion SPECT; Nuclear cardiac instrumentation; Reduced radiation exposure

Introduction

The last few years have brought several rapid developments in nuclear cardiology instrumentation, both in scanner hardware and in reconstruction software. The impact of these developments is potentially very significant, since single photon emission computed tomography (SPECT) myocardial perfusion imaging (MPI) is the most commonly used stress imaging approach, with approximately 9 million studies being performed annually in the United States. Traditionally, stress and rest SPECT acquisitions required about 15 minutes to register a sufficient number of photon events. New instrumentation and accompanying software have now enabled acquisition times as short as 2 minutes [1•]. These new systems also can be utilized to reduce radiation exposure to the patients during the MPI scan. Although the true relationship of cancer risk to doses in a lower range of radiation exposure (< 100 mSv) is unknown since the risk estimates are extrapolated linearly from higher doses [2, 3], recent media coverage of radiation exposure and discussion of cardiac imaging procedures contributing to hypothetical cancer risk has put cardiac imaging in a spotlight. From the patient's perspective, a radiation exposure, which is "as low as can be reasonably achieved" is certainly desirable. In this article, we briefly summarize recent technical MPI advances including advances in PET and discuss the potential role of these developments in radiation dose reduction.

Advances in SPECT

Hardware Advances

The key characteristic of the new dedicated cardiac imaging systems now available from several instrumentation vendors is significantly increased photon sensitivity. Figure 1 illustrates at least a sevenfold increase in sensitivity for one solid-state system when compared with a standard SPECT system. Similar results are reported for other scanners. The higher sensitivity is primarily achieved by a radical redesign of the collimation methods. Traditional systems utilizing low-energy high-resolution collimators are only able to detect less than 0.1% of the photon events [4]. The new designs of collimation include the multiple pinhole principle and ultra-high-sensitivity detectors focusing on the heart. The overall system sensitivity can be further improved by dedicated scanner geometry surrounding the patient, which allows the capture of a higher fraction of the photons than is possible with a general purpose dual or triple-head gamma camera. Optimized scanner geometry may allow simultaneous collections of counts from all directions without camera rotation. Additionally, the traditional, bulky combination of scintillation crystals with photomultiplier tubes has been replaced with solid-state photon detectors (cadmium zinc telluride [CZT] or cesium iodide [CsI]). The use of solid-state detectors can result in improved energy resolution and consequently less undesirable scatter events [5]. These new cameras often have a reduced footprint, allow easier patient positioning, and in many cases upright imaging, increasing patient comfort and throughput. Digirad Inc. (Poway, CA) has developed a cardiac Cardius XPO solid-state camera combined with new three-dimensional (3D) iterative reconstruction technology (n-speed). Clinical studies on this system have been reported with less than 5-minute imaging time [6]. Spectrum Dynamics (Haifa, Israel) has developed a dedicated cardiac system (D-SPECT) with semi-stationary CZT pixilated detectors, high-sensitivity collimation, and reconstruction optimized specifically for cardiac

imaging. To date, several clinical studies have been reported with scan times as short as 2 minutes [5, 7]. General Electric Healthcare (Fairfield, CT) has developed a stationary imaging camera based on multi-pinhole collimation, an alternative technique for photon collimation [8-10], and CZT detectors [11] including optional CT attenuation correction (AC) [12]. Patients are imaged in a supine position with their arms placed over their heads and prone imaging can be used to aid in the assessment of soft tissue artifact. Several clinical studies have been published on this system with scan times also as short as 2 minutes [13].

Software Advances

The new SPECT scanner devices are coupled with improved image reconstruction techniques implemented in software. New reconstruction algorithms include physical modeling of the collimators and detectors, as well as resolution recovery [14]. Most systems now offer compensation for image resolution loss (especially needed for the high-sensitivity collimation) via accelerated iterative reconstruction [15]. Sophisticated software reconstruction methods also can improve image quality obtained by standard SPECT cameras, which can be exploited to reduce imaging time or radiation dose. The principal advantage of retro-fitting the traditional systems with the new software is significantly lower cost compared with the replacement of the system with a new scanner. Several imaging vendors have taken this approach. UltraSpect Inc. (Haifa, Israel) has developed the Wide Beam Reconstruction (WBR™) algorithm [16, 17], which models the collimator characteristic. When applied to SPECT projection data from a standard camera, this method has allowed effective time reduction of up to four times [18•]. Siemens (Hoffman Estates, IL) has combined an astigmatic collimator, an optimized organ-of-interest centered acquisition, and a new iterative reconstruction with CT-based AC (on Symbia platform) and energy window-based scatter correction in their IQ•SPECT system [19]. Philips (San Jose, CA) has developed a fast SPECT reconstruction algorithm (Astonish) that includes corrections for photon scatter, photon attenuation, variations in spatial resolution, and allows reduced imaging time. Half-time imaging has been demonstrated to be equivalent to filtered back-projection full time [20]. This system has been approved by the US Food and Drug Administration for equivalent half-dose imaging. Similarly, GE (Milwaukee, WI) has developed the Evolution reconstruction algorithm, which has been applied to half-time imaging in several studies [21-23].

Dose Reduction

To date, the new scanners and software technologies have been put into clinical practice primarily to reduce the acquisition times, since fast imaging provides immediate benefits in terms of patient throughput and patient comfort. However, equivalent radiation dose reduction is also possible by performing standard time acquisitions with lower injected doses. Table 1 lists some of the clinical SPECT ^{99m}Tc studies performed with the new instrumentation and software for the purposes of shortening the acquisition time and specifies hypothetical dose reduction (rightmost column), which could be obtained if standard 15-minute acquisitions were used instead. Nevertheless, in view of the recent sensitivity toward patient radiation dose, a few clinical studies have been conducted to evaluate the new equipment specifically with the reduced-dose protocols [24]. These studies are summarized in Table 2. Low-dose stress-only protocols allowed the radiation dose as low as 4.2 mSv for a 12.5-mCi 5-minute stress-only ^{99m}Tc scan [25]. A low-dose rest-stress ^{99m}Tc protocol has been studied resulting in 5.1- to 6.1-mSv exposure to patients [26, 27•]. Low-dose imaging was also demonstrated on a standard SPECT camera, utilizing an iterative reconstruction technique with standard acquisition times [28]. In another study, the patient dose was reduced to 4.3 mSv for stress/rest protocols when background activity subtraction was applied [29]. In one study, fast 6-minute ²⁰¹Tl acquisition has been

performed with a 2-mCi injected dose [30], but the potential of the new instrumentation for ^{201}Tl protocols needs to be fully exploited.

One problem with conducting such prospective low-dose studies is that one needs to be conservative in dose reduction since the quality of the images could potentially suffer significantly if the injected dose is too low. From the diagnostic standpoint, this would be especially critical for stress studies. Therefore, at Cedars-Sinai, our group has been gathering preliminary experience in ultra-low-dose technique applied to rest imaging. We have found that it is possible to obtain good quality images with injected doses below 3.5 mCi (resulting in patient doses below 1 mSv) and standard imaging times (10–15 minutes). In Figure 2, we show an example of upright and supine rest images of a patient who underwent such ultra-low-dose protocol using a D-SPECT camera. Presumably, stress images acquired at similar dose level should be of similar quality. In Figure 3, we show typical patient doses and their biodistribution for the standard and reduced-dose $^{99\text{m}}\text{Tc}$ protocols.

Low-Dose Attenuation Correction

Although still not routinely used at this point [31], AC has the potential to improve the diagnostic accuracy of cardiac SPECT imaging. It has been shown that AC can be used with stress-only imaging to reduce the imaging time and radiation dose [20]. However, AC can be associated with a small but additional radiation dose, especially if CT is used for this purpose in SPECT/CT scanners. The typical stress and rest dose from such CT AC scans is in the order of 0.3 to 1.3 mSv [32] and therefore it is not negligible when compared with the dose from radioisotopes especially for new low-dose protocols. To reduce the AC radiation dose, various new designs have been developed for SPECT scanners by equipment vendors. Digirad has developed an integrated system with a 5- μSv effective dose in which photons from the x-ray source are detected by solid-state detectors with a fan beam collimator operating in high counting rate mode [33]. The scan time for the acquisition of the AC maps is 60 seconds. Another example of new AC technology is BrightView XCT from Philips. The unique flat panel x-ray detector system provides low-dose (0.12-mSv) CT images that can be used for AC of the SPECT data. Although it is not geared exclusively toward nuclear cardiology, it can be used for low-dose AC for MPI studies. Moreover, the attenuation scan of the entire heart volume (14-cm axial field of view) is acquired in a single 60-second rotation with the patient breathing normally. As a result, the attenuation data is averaged over multiple respiratory cycles to match the position of the heart during the SPECT acquisition.

Stress-Only Imaging

MPI radiation dose to the patient can be significantly reduced if the rest scan is not performed. Furthermore, stress-only protocols could improve the overall efficiency of the imaging laboratory, lower the radiation exposure to the laboratory personnel, and enhance patient convenience due to less time needed for the overall test [34]. The improved imaging characteristics of the new scanners can be utilized to obtain the most optimal stress images, possibly reducing the need for rest imaging. The expected frequency of normal stress studies using current appropriateness criteria for the performance of MPI exceeds 50%. There is ample evidence in the literature that when stress images are normal there is no additional prognostic information added by performing the rest study [35–37]. Furthermore, in the population of patients with suspected coronary artery disease, the rest scan does not add value diagnostically especially when automated tools are used for the analysis [38••]. Similarly, when the stress scan is performed with AC, it has been shown that the visual diagnostic performance is similar to that of a stress-rest scan [39]. Additionally, the accuracy of stress-only imaging can be improved with combined quantitative analysis of stress supine-prone or supine-upright data [38••, 40]. The supine/prone studies are performed with

one injected stress dose. The requirement of extra time for the supine prone/upright approach may be mitigated by the new fast cameras and reconstruction algorithms [38••]. Stress-only protocols have been also proposed in conjunction with computed tomographic angiography (CTA) imaging for sites that are equipped with CTA scanners. Husmann et al. [41] proposed a low-dose stress-only scan in combination with CTA. The total radiation dose for the MPI and CTA scan was 5.4 ± 0.8 mSv (the dose for the CTA scan was 2.2 ± 0.7 mSv), which is lower than for most current stress/rest MPI protocols.

Advances in PET

Technical Advances

Modern PET/CT scanners from all vendors operate in 3D coincidence detection mode. Specifically for cardiac applications, PET scanners have been recently optimized to cope with high count levels in first-pass ^{82}Rb imaging for myocardial blood flow measurements [42] and with additional ^{82}Rb gamma-prompt decays affecting 3D imaging [43]. The system sensitivity of 3D PET scanners is four to six times higher than scanners operating in two-dimensional (2D) mode, at the expense of a higher scatter fraction [44]. Further technical advances include developments of photon time-of-flight methods [45] and new high-definition iterative reconstruction techniques based on scanner-specific 3D modeling of system resolution with effective tomographic resolution as low as 2 mm [46]. Preliminary reports have been published demonstrating the application of these improved PET reconstruction methods to cardiac imaging [47]. Further image quality improvements have been proposed [48] by combining new reconstruction with cardiac motion-frozen techniques to reduce blurring due to cardiac motion [49]. Although the initial application of the new PET technology was in the field of oncology, 3D acquisition and new software methods offer a potential for dose reduction in cardiac imaging, beyond already very low radiation levels. It should be noted that there is a small additional radiation dose associated with CT AC scans for PET imaging. Unlike in SPECT, AC in PET is mandatory due to the principle of photon coincidence detection. Considering the dose-reducing efforts undertaken by vendors for SPECT-AC (see section above), the PET-CT AC remains relatively dose inefficient. Therefore, further efforts to reduce the radiation dose associated with PET AC are warranted especially in the view of the very low dose incurred from the injection of the PET radiotracers.

Clinical Applications

Although PET MPI imaging is currently not widely utilized compared with SPECT, it offers significant potential advantages because in addition to relative perfusion, it allows measurements of myocardial blood flow and perfusion flow reserve [50]. New PET systems registering the photon events in list mode allow reconstruction of both perfusion and blood flow data from one scan. Due to increased sensitivity of 3D PET, it is possible to obtain high-quality ^{82}Rb perfusion images at doses as low as 20 mCi [51]. The estimated patient radiation doses have recently been revised down to 3.7 mSv for ^{82}Rb PET scans obtained on a standard 2D scanner with 80 mCi of total injected dose (stress + rest) by more precise patient-specific calculations [52]. Therefore, the effective radiation dose of stress-rest ^{82}Rb scans obtained in 3D mode could be further reduced to approximately 1.85 mSv (< 1 mSv for stress scan). Similarly, the doses for the other tracers are very low. For example, the radiation dose from a single 3D PET perfusion study is 0.8 mSv for ^{15}O water and 1 mSv for ^{13}N ammonia [53]. Furthermore, PET imaging offers true stress (rather than post-stress) functional measurements and allows time-efficient (< 30 -minute) stress-rest protocols [50]. Analogous to stress-only SPECT MPI imaging, it is also possible to perform stress-only low-dose PET imaging. Kajander et al. [54] demonstrated that the analysis of stress blood flow (rather than myocardial perfusion reserve) from ^{15}O blood PET scans (at approximate

patient dose of 0.85 mSv for stress PET injection) resulted in per-vessel sensitivity of 92% and specificity of 92%. Further incremental improvement of accuracy was demonstrated when a CTA scan obtained on a hybrid PET/CT scanner was added; however, the CTA scan was associated with a higher effective dose (7.6 mSv). Although ^{15}O imaging is possible for sites equipped with cyclotron, similar low-dose protocols could be explored for ^{82}Rb or ^{13}N imaging.

Time Versus Dose Reduction

The initial applications of the new cardiac imaging instrumentation were directed toward drastic reduction of scan times with only a few recent studies focusing on dose reduction (Table 2). Nevertheless, it should be noted that from a physics point of view, the reduction of time or dose is equivalent. The key parameter determining myocardial perfusion image quality is the number of counts in the myocardium. It is therefore possible to obtain an almost identical ratio of dose reduction instead of time reduction with the new equipment. The improvement in sensitivity of the new systems is in the order of seven to eight times (Fig. 1). Thus, the dose can theoretically be reduced by the same amount with standard imaging times. Consequently, the results obtained in the studies with reduced imaging times can be extrapolated to the future studies with lower-dose protocols, if a similar count level in the left ventricular myocardium is maintained. In Figure 4 we show the potential dose- or time-reducing protocols, which could be implemented with new instrumentation. However, there are some possible limitations in the assumption that the same counts in the left ventricle will result in equivalent images. Studies acquired in a shorter time may potentially have less motion artifacts since they are associated with greater patient comfort. Additionally, there could be some dynamic physiologic changes during the longer scan reducing the image quality of the longer scan. Nevertheless, MPI imaging scans with longer acquisition times (15 minutes or longer) have been performed for the last few decades clinically. Patient motion artifacts as well as the biodistribution of the standard tracers are well understood for these scan durations. Therefore, count-equivalent lower-dose or fast-imaging protocols should be suitable for clinical implementation.

It should be noted that prospective low-dose trials may not be able to determine the most optimal imaging time or imaging dose for a particular scanner since dose reduction in such studies must be conservative. One approach to finding a minimum imaging time or dose more aggressively is by retrospective analysis of full-dose full-time data and reconstruction of only a fraction of the counts. Such an approach is facilitated by the list-mode capabilities of the new scanners (for both SPECT and PET). Therefore, especially for the new stationary scanners, it is possible to simulate retrospectively a scan with an arbitrary activity or alternatively duration, from the original full-dose/full-time acquisition data. Using this approach, Herzog et al. [55] have shown by the retrospective list-mode reconstruction that 2-minute acquisition time is the most optimal for the GE Healthcare UFC scanner (Fig. 5). A similar method could be applied to determine the minimal injected dose for a particular scanner or protocol.

The current health care environment will favor technological advances that will be at the same time cost-saving, diagnostically accurate, and mindful of radiation burden from diagnostic imaging. Introduction of the above-described technologies and development of new imaging protocols for MPI have the potential to address all those demands.

Conclusions

Advances in new instrumentation allow routine stress/rest MPI imaging with low radiation doses (< 5 mSv) and fast imaging times. It is possible to significantly reduce radiation dose

of stress/rest scans with the new systems to a less than 2-to-3 mSv range with standard acquisition times. Stress-only protocols can be utilized to further reduce the radiation dose and the overall test time. Hybrid stress-only imaging SPECT-CTA or PET-CTA can be potentially performed with low overall dose. PET perfusion imaging can be performed with very low doses especially on the new 3D scanners. Further studies including retrospective simulations are needed to establish the optimal thresholds for minimal dosing and optimal imaging time.

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References

Papers of particular interest, published recently, have been highlighted as:

- Of importance
 - Of major importance
- 1•. Slomka PJ, Patton JA, Berman DS, Germano G. Advances in technical aspects of myocardial perfusion SPECT imaging. *Journal of Nuclear Cardiology*. 2009; 16(2):255–276. This is an in depth-review of the new technologies for MPI. [PubMed: 19242769]
 2. Tubiana M, Feinendegen LE, Yang C, Kaminski JM. The linear no-threshold relationship is inconsistent with radiation biologic and experimental data. *Radiology*. Apr; 2009 251(1):13–22. [PubMed: 19332842]
 3. Laskey WK, Feinendegen LE, Neumann RD, Dilsizian V. Low-level ionizing radiation from noninvasive cardiac imaging: can we extrapolate estimated risks from epidemiologic data to the clinical setting? *JACC Cardiovasc Imaging*. May; 2010 3(5):517–524. [PubMed: 20466348]
 4. Gunter, DL. Gamma Camera Collimator Characteristics and Design. In: Henkin, RE., editor. *Nuclear Medicine*. Vol. 1. Philadelphia, PA: Elsevier; 2006. p. 107-126.
 5. Sharir T, Slomka P, Hayes S, et al. Multicenter trial of high-speed vs. Conventional SPECT Imaging: Quantitative Results of Myocardial Perfusion and Left Ventricular function. *JACC*. 2010 in press.
 6. Maddahi J, Mendez R, Mahmarian JJ, et al. Prospective multicenter evaluation of rapid, gated SPECT myocardial perfusion upright imaging. *Journal of Nuclear Cardiology*. 2009; 16(3):351–357. [PubMed: 19247734]
 7. Sharir T, Ben-Haim S, Merzon K, et al. High-Speed Myocardial Perfusion Imaging: Initial Clinical Comparison With Conventional Dual Detector Anger Camera Imaging. *JACC Cardiovascular Imaging*. 2008; 1(2):156–163. [PubMed: 19356422]
 8. Jaszcak RJ, Li J, Wang H, Zalutsky MR, Coleman RE. Pinhole collimation for ultra-high-resolution, small-field-of-view SPECT. *Physics in Medicine and Biology*. 1994; 39:425–437. [PubMed: 15551591]
 9. Schramm NU, Ebel G, Engeland U, Schurrat T, Behe M, Behr TM. High-resolution SPECT using multipinhole collimation. *Nuclear Science, IEEE Transactions on*. 2003; 50(3):315–320.

10. Beekman FJ, Vastenhouw B. Design and simulation of a high-resolution stationary SPECT system for small animals. *Physics in Medicine and Biology*. 2004; 49(19):4579–4592. [PubMed: 15552418]
11. Volokh, L.; Hugg, J.; Bleviss, I.; Asma, E.; Jansen, F.; Manjeshwar, R. Effect of detector energy response on image quality of myocardial perfusion SPECT. Paper presented at: IEEE Nuclear Science Symposium and Medical Imaging conference; 19–26, 2008; Dresden.
12. Herzog BA, Buechel RR, Katz R, et al. Nuclear Myocardial Perfusion Imaging with a Cadmium-Zinc-Telluride Detector Technique: Optimized Protocol for Scan Time Reduction. *Journal of Nuclear Medicine*. 2010; 51(1):46–51. [PubMed: 20008999]
13. Slomka P, Berman D, Germano G. New Imaging Protocols for New Single Photon Emission CT Technologies. *Current Cardiovascular Imaging Reports*. 2010; 3(3):162–170. [PubMed: 20461125]
14. Hudson HM, Larkin RS. Accelerated image reconstruction using ordered subsets of projection data. *Medical Imaging, IEEE Transactions on*. 1994; 13(4):601–609.
15. Lau YH, Hutton BF, Beekman FJ. Choice of collimator for cardiac SPET when resolution compensation is included in iterative reconstruction. *Eur J Nucl Med*. 2001; 28(1):39–47. [PubMed: 11202450]
16. Ultraspect. [09/06, 2008] www.UltraSPECT.com
17. Borges-Neto SPR, Shaw LK, et al. Clinical results of a novel wide beam reconstruction method for shortening scan time of Tc-99m cardiac SPECT perfusion studies. *J Nucl Cardiol*. 2007; 14:555–565. [PubMed: 17679065]
18. DePuey EG, Bommireddipalli S, Clark J, Thompson L, Srour Y. Wide beam reconstruction “quarter-time” gated myocardial perfusion SPECT functional imaging: a comparison to “full-time” ordered subset expectation maximum. *Journal of Nuclear Cardiology*. 2009; 16(5):736–752. Software-only reconstruction improvement allows quarter-time acquisition of the data obtained on the standard SPECT camera. [PubMed: 19533264]
19. Vija H, Chapman J, Ray M. IQ•SPECT technology White Paper. Siemens Medical Solutions USA Molecular Imaging. 2008:1–7.
20. Bateman TM, Heller GV, McGhie AI, et al. Multicenter investigation comparing a highly efficient half-time stress-only attenuation correction approach against standard rest-stress Tc-99m SPECT imaging. *Journal of Nuclear Cardiology*. 2009; 16(5):726–735. [PubMed: 19548048]
21. Valenta I, Treyer V, Husmann L, et al. New reconstruction algorithm allows shortened acquisition time for myocardial perfusion SPECT. *European Journal of Nuclear Medicine and Molecular Imaging*. 2010; 37(4):750–757. [PubMed: 19921186]
22. Gutstein A, Solodky A, Mats I, et al. Feasibility of myocardial perfusion SPECT with prone and half-time imaging. *Nuclear Medicine Communications*. 2011; 32(5):386–391. 310.1097/MNM.1090b1013e328343d328368e. [PubMed: 21386736]
23. Ali I, Ruddy TD, Almgrahi A, Anstett FG, Wells RG. Half-Time SPECT Myocardial Perfusion Imaging with Attenuation Correction. *Journal of Nuclear Medicine*. Apr; 2009 50(4):554–562. [PubMed: 19289436]
24. Henzlova M, Duvall W. The future of SPECT MPI: Time and dose reduction. *Journal of Nuclear Cardiology*. 2011; 18(4):580–587. [PubMed: 21638153]
25. Duvall W, Croft L, Godiwala T, Ginsberg E, George T, Henzlova M. Reduced isotope dose with rapid SPECT MPI imaging: Initial experience with a CZT SPECT camera. *Journal of Nuclear Cardiology*. 2010; 17(6):1009–1014. [PubMed: 21069489]
26. Duvall W, Croft L, Ginsberg E, et al. Reduced isotope dose and imaging time with a high-efficiency CZT SPECT camera. *Journal of Nuclear Cardiology*. 2011; 18(5):847–857. This is a clinical demonstration of the low-dose imaging with the new multi-pinhole camera. [PubMed: 21528422]
27. Gimelli A, Bottai M, Genovesi D, Giorgetti A, Di Martino F, Marzullo P. High diagnostic accuracy of low-dose gated-SPECT with solid-state ultrafast detectors: preliminary clinical results. *Eur J Nucl Med Mol Imaging*. Sep 2.2011
28. DePuey E, Bommireddipalli S, Clark J, Leykekhman A, Thompson L, Friedman M. A comparison of the image quality of full-time myocardial perfusion SPECT vs wide beam reconstruction half-

- time and half-dose SPECT. *Journal of Nuclear Cardiology*. 2011; 18(2):273–280. [PubMed: 21287370]
29. Nkoulou R, Pazhenkottil AP, Kuest SM, et al. Semiconductor Detectors Allow Low-Dose–Low-Dose 1-Day SPECT Myocardial Perfusion Imaging. *Journal of Nuclear Medicine*. Aug 1; 2011 52(8):1204–1209. [PubMed: 21810589]
 30. Berman DS, Kang X, Tamarappoo B, et al. Stress thallium-201/rest technetium-99m sequential dual isotope high-speed myocardial perfusion imaging. *JACC: Cardiovascular Imaging*. 2009; 2(3):273–282. [PubMed: 19356571]
 31. Germano G, Slomka PJ, Berman DS. Attenuation correction in cardiac SPECT: the boy who cried wolf? *J Nucl Cardiol*. 2007; 14(1):25–35. [PubMed: 17276303]
 32. Einstein AJ, Johnson LL, Bokhari S, et al. Agreement of Visual Estimation of Coronary Artery Calcium From Low-Dose CT Attenuation Correction Scans in Hybrid PET/CT and SPECT/CT With Standard Agatston Score. *Journal of the American College of Cardiology*. 2010; 56(23):1914–1921. [PubMed: 21109114]
 33. Maddahi J. Viability assessment with MRI is superior to FDG-PET for viability: Pro. *J Nucl Cardiol*. Apr; 2010 17(2):292–297. [PubMed: 20225004]
 34. Mahmarijan JJ. Stress only myocardial perfusion imaging: Is it time for a change? *J Nucl Cardiol*. Aug; 2010 17(4):529–535. [PubMed: 20512440]
 35. Duvall WL, Wijetunga MN, Klein TM, et al. The prognosis of a normal stress-only Tc-99m myocardial perfusion imaging study. *J Nucl Cardiol*. Jun; 2010 17(3):370–377. [PubMed: 20390394]
 36. Duvall WL, Wijetunga MN, Klein TM, et al. Stress-Only Tc-99m Myocardial Perfusion Imaging in an Emergency Department Chest Pain Unit. *Journal of Emergency Medicine*. Aug 27.2011
 37. Chang SM, Nabi F, Xu J, Raza U, Mahmarijan JJ. Normal Stress-Only Versus Standard Stress/Rest Myocardial Perfusion Imaging: Similar Patient Mortality With Reduced Radiation Exposure. *Journal of the American College of Cardiology*. 2010; 55(3):221–230. [PubMed: 19913381]
 - 38•. Nakazato R, Tamarappoo BK, Kang X, et al. Quantitative upright-supine high-speed SPECT myocardial perfusion imaging for detection of coronary artery disease: correlation with invasive coronary angiography. *J Nucl Med*. Nov; 2010 51(11):1724–1731. This is a fully quantitative analysis of supine and upright MPI data from the new fast SPECT system with angiographic validation. [PubMed: 20956478]
 39. Bateman TM, Heller GV, McGhie AI, et al. Multicenter investigation comparing a highly efficient half-time stress-only attenuation correction approach against standard rest-stress Tc-99m SPECT imaging. *J Nucl Cardiol*. Sep-Oct;2009 16(5):726–735. [PubMed: 19548048]
 40. Nishina H, Slomka PJ, Abidov A, et al. Combined supine and prone quantitative myocardial perfusion SPECT: method development and clinical validation in patients with no known coronary artery disease. *J Nucl Med*. Jan; 2006 47(1):51–58. [PubMed: 16391187]
 41. Husmann L, Herzog BA, Gaemperli O, et al. Diagnostic accuracy of computed tomography coronary angiography and evaluation of stress-only single-photon emission computed tomography/computed tomography hybrid imaging: comparison of prospective electrocardiogram-triggering vs. retrospective gating. *European Heart Journal*. 2009; 30(5):600. [PubMed: 19106197]
 42. Klein R, Beanlands R, deKemp R. Quantification of myocardial blood flow and flow reserve: Technical aspects. *Journal of Nuclear Cardiology*. 2010; 17(4):555–570. [PubMed: 20596841]
 43. Esteves F, Nye J, Khan A, et al. Prompt-gamma compensation in Rb-82 myocardial perfusion 3D PET/CT. *Journal of Nuclear Cardiology*. 2010; 17(2):247–253. [PubMed: 19937169]
 44. Knešarek K, Machac J, Krynyckyi BR, Almeida OD. Comparison of 2-Dimensional and 3-Dimensional 82Rb Myocardial Perfusion PET Imaging. *Journal of Nuclear Medicine*. Aug 1; 2003 44(8):1350–1356. [PubMed: 12902427]
 45. Jakoby BW, Bercier Y, Conti M, Casey ME, Bendriem B, Townsend DW. Physical and clinical performance of the mCT time-of-flight PET/CT scanner. *Phys Med Biol*. 2011; 56(8):2375–2389. Epub 2011 Mar 2322. [PubMed: 21427485]
 46. Panin VY, Kehren F, Michel C, Casey M. Fully 3-D PET reconstruction with system matrix derived from point source measurements. *IEEE Trans Med Imaging*. 2006; 25(7):907–921. [PubMed: 16827491]

47. Le Meunier L, Slomka P, Dey D, et al. Enhanced definition PET for cardiac imaging. *Journal of Nuclear Cardiology*. 2010; 17(3):414–426. [PubMed: 20151238]
48. Le Meunier L, Slomka PJ, Dey D, et al. Motion frozen (18)F-FDG cardiac PET. *J Nucl Cardiol*. 2011; 18(2):259–266. Epub 2010 Dec 2016. [PubMed: 21161704]
49. Slomka PJ, Nishina H, Berman DS, et al. “Motion-frozen” display and quantification of myocardial perfusion. *J Nucl Med*. Jul; 2004 45(7):1128–1134. [PubMed: 15235058]
50. Di Carli MF, Dorbala S, Meserve J, El Fakhri G, Sitek A, Moore SC. Clinical myocardial perfusion PET/CT. *J Nucl Med*. May; 2007 48(5):783–793. [PubMed: 17475968]
51. Schwaiger M, Ziegler SI, Nekolla SG. PET/CT challenge for the non-invasive diagnosis of coronary artery disease. *European Journal of Radiology*. 2010; 73(3):494–503. [PubMed: 20206454]
52. Senthamizhchelvan S, Bravo PE, Esaias C, et al. Human Biodistribution and Radiation Dosimetry of ⁸²Rb. *Journal of Nuclear Medicine*. Oct 1; 2010 51(10):1592–1599. [PubMed: 20847168]
53. Knuuti J. Integrated positron emission tomography/computed tomography (PET/CT) in coronary disease. *Heart*. Sep 1; 2009 95(17):1457–1463. [PubMed: 19684196]
54. Kajander S, Joutsiniemi E, Saraste M, et al. Cardiac Positron Emission Tomography/Computed Tomography Imaging Accurately Detects Anatomically and Functionally Significant Coronary Artery Disease / CLINICAL PERSPECTIVE. *Circulation*. Aug 10; 2010 122(6):603–613. [PubMed: 20660808]
55. Herzog BA, Buechel RR, Husmann L, et al. Validation of CT attenuation correction for high-speed myocardial perfusion imaging using a novel cadmium-zinc-telluride detector technique. *J Nucl Med*. Oct; 2010 51(10):1539–1544. [PubMed: 20847159]
56. Buechel RR, Herzog BA, Husmann L, et al. Ultrafast nuclear myocardial perfusion imaging on a new gamma camera with semiconductor detector technique: first clinical validation. *European Journal of Nuclear Medicine and Molecular Imaging*. 2009 in press.
57. Esteves FP, Raggi P, Folks RD, et al. Novel solid-state-detector dedicated cardiac camera for fast myocardial perfusion imaging: multicenter comparison with standard dual detector cameras. *Journal of Nuclear Cardiology*. 2009; 16:927–934. [PubMed: 19688410]
58. Fiechter M, Ghadri J, Kuest S, et al. Nuclear myocardial perfusion imaging with a novel cadmium-zinc-telluride detector SPECT/CT device: first validation versus invasive coronary angiography. *European Journal of Nuclear Medicine and Molecular Imaging*. 2011; 38(11):2025–2030. [PubMed: 21761267]
59. Venero CV, Heller GV, Bateman TM, et al. A multicenter evaluation of a new post-processing method with depth-dependent collimator resolution applied to full-time and half-time acquisitions without and with simultaneously acquired attenuation correction. *Journal of Nuclear Cardiology*. 2009; 16(5):714–725. [PubMed: 19582531]
60. Gimelli A, Bottai M, Giorgetti A, et al. Comparison between ultrafast and standard single-photon emission CT in patients with coronary artery disease: a pilot study. *Circ Cardiovasc Imaging*. Jan; 2011 4(1):51–58. [PubMed: 21068188]

Figure 1.

System sensitivity. The higher system sensitivity of high-speed system is demonstrated by significantly higher myocardial count rate (7 to 8 times) compared with conventional single-photon emission tomography (SPECT) at stress and rest images. CPM = counts/min. (Reproduced with permission from: Sharir T, Ben-Haim S, Merzon K, et al. High-Speed Myocardial Perfusion Imaging: Initial Clinical Comparison With Conventional Dual Detector Anger Camera Imaging. *JACC Cardiovascular Imaging*. 2008;1(2):156-163) [7].

Figure 2.
Example of ultra-low-dose 10-minute 3.3 mCi ^{99m}Tc rest sestamibi scan of an 83-year-old male patient obtained at Cedars-Sinai Medical Center on D-SPECT scanner. The effective radiation dose for this scan is less than 1 mSv. Both upright and supine images are shown.

Figure 3. Effective radiation doses from typical ^{99m}Tc myocardial perfusion imaging protocols.

Figure 4.

Relationship between doses and imaging times and possible new investigational protocols with new instrumentation. SPECT—single photon emission computed tomography.

Figure 5.

A, Intraclass correlation is used to compare segmental uptake between standard γ -camera (Ventri; GE Healthcare) and ultrafast CZT camera (Discovery NM 530c; GE Healthcare). Correlation coefficient increases with prolonged scan time, but no further improvement appears after scan duration of 3 minutes is reached for low ^{99m}Tc -tetrofosmin dose (stress scan) and 2 minutes for high dose (rest scan). Thus, minimally required scan times are 2 minutes for high dose and 3 minutes for low dose. **B**, Diagnostic accuracy of CZT, compared with that of standard camera, increases (and significant differences according to McNemar test disappear) after scan intervals are prolonged to 3 minutes for low dose (stress) and 2 minutes for high dose (rest). This indicates solid clinical agreement for the above scan durations, further supported by excellent Cohen κ -value (low dose, 3 minutes: 0.90; high dose, 2 minutes: 0.92). (Reprinted by permission of the Society of Nuclear Medicine from: Herzog BA, Buechel RR, Katz R, et al. Nuclear Myocardial Perfusion Imaging with a Cadmium-Zinc-Telluride Detector Technique: Optimized Protocol for Scan Time Reduction. *J Nucl Med.*2010; 51(1): 46-51. Figure 1) [12].

Table 1

Recent clinical studies demonstrating the possibility of shortened imaging times at standard doses with ^{99m}Tc protocols and estimated hypothetical dose reduction for standard 15-minute stress and rest acquisitions

Study/system	Protocol	Injected dose	Acquisition time	Patient dose	Estimated patient dose for count-equivalent 15-min acquisitions
Herzog et al. [12] GE UFC	1-day ^{99m}Tc -tetrofosmin adenosine stress/rest	Stress/rest 8.8/25.1 mCi	3 min/2 min	9.0 mSv	1.5 mSv
Buechel et al. [56] GE UFC	1-day ^{99m}Tc -tetrofosmin adenosine stress/rest	Stress/rest 9.1/25.6 mCi	3 min/2 min	9.3 mSv	1.5 mSv
Maddahi et al. [6] Digirad	Rest/stress ^{99m}Tc	Rest/stress 7-10/20-30mCi	4.2 min/4.8 min	7.9/11.7 mSv	2.4-3.5 mSv
Esteves et al. [57] GE UFC	1-day ^{99m}Tc -tetrofosmin rest/stress	Rest/stress 10-15/30-45 mCi	2 min/4 min	10.7-16.0 mSv	2.1-3.2 mSv
Sharir et al. [7] D-SPECT	1-day ^{99m}Tc stress/rest sestamibi	Stress/rest 11/28 mCi	4 min/2 min	11.4 mSv	2.3 mSv
Sharir et al. [5] D-SPECT	Rest/stress tetrofosmin/sestamibi ^{99m}Tc	Rest/stress 10/30 mCi	4 min/2 min	10.7 mSv	2.1 mSv
DePuey et al. [18] UltraSpect	Rest/stress ^{99m}Tc -sestamibi	Rest/stress 9/32mCi	4 min/4.5 min	12.0 mSv	3.8 mSv
Bateman et al. [20] Astonish	Stress-only ^{99m}Tc -sestamibi	Stress 25-35 mCi	6 min/N/A	7.3-10.3 mSv	1.5-2.1 mSv
Duvall et al. [25] GE 530c	Stress-only ^{99m}Tc	Stress (25-36 mCi) or 12.5 mCi	3 or 5 min	7.3-10.6 mSv or 3.7 mSv;	1.2-1.8 mSv or 0.6 mSv
Herzog et al. [55] GE 530c	1-day ^{99m}Tc tetrofosmin adenosine stress/rest	Stress/rest 9/22-27 mCi	3 min/2 min	8.3-9.6 mSv	1.4-1.6 mSv
Nakazato et al. [38] D-SPECT	Rest/stress Tc/Tc	8-10/25-40 mCi	2 min/4 min	10.0-14.0 mSv	2.0-2.9 mSv
Fiechter et al. [58] GE 530c	Stress/rest 1 day	9/22-27 mCi	3 min/2 min	8.3-9.6 mSv	1.4-1.6 mSv
Venero et al. [59] Astonish	Rest/stress ^{99m}Tc	10 mCi/35 mCi,	8 min/6 min	13.2 mSv	6.2 mSv
Gimelli et al. [60] GE 530c	Single-day ^{99m}Tc -tetrofosmin stress/rest	10mCi/20mCi	5 min/4 min	8.0 mSv	2.4 mSv

Table 2

Recent clinical studies with reduced dosing and new instrumentation

Study	N	Protocol	Injected dose	Total radiation dose
Husmann et al. [41]	100	Stress-only/prospective gated CTA	Stress: 8.1 mCi	(5.4 ± 0.8) mSv
Duvall et al. [25]	209	Stress-only ^{99m} Tc sestamibi	Stress: 12.5 mCi	4.2 mSv
DePuey et al. [28]	160	^{99m} Tc sestamibi	Rest: 5.8 ± 0.6 Stress: 17.5 ± 2.5 mCi	6.8 mSv
Nkoulou et al. [29]	50	1-day ^{99m} Tc tetrofosmin adenosine stress/rest	Stress/Rest 8.6/17.3 mCi 5 min/5 min	4.3 mSv
Duvall et al. [26•]	131	^{99m} Tc sestamibi Rest: 5-8 min Stress: 3-5 min	Rest: 5 mCi Stress: 15 mCi	5.8 mSv
Gimelli et al. [27]	137	^{99m} Tc tetrofosmin	Stress: 5-6 mCi Rest: 10-12 mCi	5.10 mSv men 6.12 mSv (women) ^a

^aEstablished by gender-specific phantom scans.

CTA—computed tomographic angiography.