Approaches to Reduce Radiation Dose from Radionuclide Myocardial Perfusion Imaging

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Abstract

Radionuclide myocardial perfusion imaging (MPI) plays a vital role in the evaluation and management of patients with coronary artery disease. However, due to a steep growth in MPI in the mid 2000’s, concerns about inappropriate use of MPI and imaging related radiation exposure increased. In response, the professional societies developed appropriate-use criteria to reduce inappropriate utilization of MPI. Simultaneously, novel technology, image-reconstruction software for traditional scanners and dedicated cardiac scanners, emerged and facilitated the performance of MPI with low-dose and ultra-low dose radiotracers. This paper provides a practical approach to performing low radiation dose MPI using traditional and novel technologies.
Introduction

Over the past 40 years, radionuclide myocardial perfusion imaging (MPI) has become a major tool in the non-invasive evaluation of coronary artery disease (CAD). Since that time, advances in MPI technology and radiotracers have increased opportunities for improved diagnosis and treatment of patients with CAD. However, there are concerns about its overutilization, especially in lower risk patients, which has coincided with a six-fold increase in background radiation from medical imaging. In response, multiple professional Societies have jointly developed Appropriate Use Criteria to encourage the appropriate use of MPI, and to lower costs and radiation dose from MPI. Manufacturers of nuclear medicine equipment have also responded to radiation concerns by introducing technological advances that allow individualized low-dose protocols while maintaining or enhancing image quality, thereby paving the way for important changes in the practice of MPI. This paper will focus on the vital importance of appropriate patient selection, patient-centered techniques to reduce radiation dose, and practical ways to reduce the life-time radiation dose for the individual patient as well as for the population of patients being considered for MPI.

The vital importance of radionuclide MPI to manage CAD

Radionuclide MPI is the most mature cardiovascular imaging technique with advanced quantitative tools and a vast evidence base in over 100,000 patients. Stress MPI with SPECT and PET is widely used to identify the hemodynamic significance of CAD. The greatest strength of MPI, however, is its established value for risk assessment. The extent and severity of ischemia and scar on SPECT and PET MPI are powerful predictors of future cardiovascular events. In addition, left ventricular ejection fraction measured on SPECT and PET MPI has well-established incremental value for patient management and risk stratification. MPI is cost-effective for the management of CAD. In patients with stable angina pectoris, a noninvasive SPECT MPI guided management strategy was economically superior to an anatomic approach guided by invasive coronary angiography without significant differences in clinical outcomes. More recently, radionuclide imaging of myocardial blood flow with PET (and
SPECT) has been shown to be an indispensable tool for the evaluation and management of CAD. (7, 8) Furthermore, several recent advances in PET and SPECT hardware and software facilitate rapid, high-count imaging, and low-dose imaging. (9, 10) With these unique capabilities, the clinical benefits of an appropriately performed MPI are indisputable.

**The need to reduce radiation dose from MPI**

The primary concern of ionizing radiation from MPI relates to the stochastic effects and potential risk of the development of cancer decades later. (11) Cancer risk is estimated based on linear downward extrapolation of data from atom bomb survivors, to the ranges of medical imaging related radiation. (11) The risk from medical imaging related low level of radiation dose is small and difficult to estimate accurately. (2, 11) However, the overall radiation burden to the US population doubled, from the early 1980’s to 2006. While in the early 1980’s, medical imaging accounted for 15% of the US population’s per capita exposure to ionizing radiation from all sources (0.54 mSv of 3.6 mSv), in 2006, 48% of per capita exposure (3 mSv of 6.255 mSv) came from medical imaging. (12) Furthermore, the contributions of nuclear cardiology procedures to ionizing radiation increased 10-fold over this period (Figure 1). (2) A standard rest-stress Tc-99m MPI study can be performed with a dose of ~12 mSv, (13) compared to an average natural background radiation dose in the US of 3 mSv. The radiation dose from MPI is declining significantly with the use of new technologies. No data exist to relate an increased risk of cancer from ionizing radiation at these levels. (2) But, the performance of millions of procedures has raised concerns over increasing population radiation dose and the consequent minimal risk of future cancer related to radiation from diagnostic imaging. (12)

Efforts to reduce radiation dose from MPI are important, as long as the concomitantly increased level of image noise does not significantly compromise the ability of physicians to have confidence in making the correct diagnoses based on the images. Also, the risk of performing MPI must be balanced against the risk of missed or delayed diagnosis and treatment from not performing MPI. Radiation dose-reduction strategies and education may promote the safe and effective use of MPI. Informed patients and physicians may be more
accepting of MPI, allowing more patients to benefit from this technology. Indeed, a focus on reducing radiation dose from imaging may compel us to more closely scrutinize the need for MPI and reduce the volume of unnecessary tests, thereby reducing life time cumulative radiation dose to the patient.

I. Radiation dose reduction before MPI: Appropriate use

Radiation dose from medical imaging can be reduced before, at the time of the test, or after completion of the test (Figure 2). One of the main ways to reduce radiation dose, prior to the performance of a test, is to avoid tests which are not needed.

Over the last decade, several professional societies have developed “Appropriate Use Criteria” for various diagnostic tests and therapeutic procedures. Appropriate use is defined, by the RAND Corporation, as an indication wherein the expected clinical benefit of the test outweighs the risks of the procedure. Appropriate Use Criteria (AUC) for cardiac radionuclide imaging, first published in 2005, was most recently updated in 2009.\(^3\) Indications for MPI were categorized based on the median scores of 15 expert panelists. A range of 1-3 is considered rarely appropriate (also previously referred to as “inappropriate”), 4-7 may be appropriate (also previously referred to as "uncertain"), and 7-9 appropriate. Out of a list of 67 indications for MPI, 9 indications were considered uncertain, 25 inappropriate and the rest appropriate.\(^3\) Of note, the radionuclide AUC did not distinguish the indications for SPECT from PET MPI, the expert rating applied equally to SPECT and PET. The value of AUC in reducing radiation dose is obtained from avoiding the tests that may be rarely appropriate. When imaging is appropriate, the benefit of an optimal test generally outweighs its potential risk. The appropriateness of any given indication for MPI can be checked online using a radionuclide AUC app (https://itunes.apple.com/us/app/appropriate-use-criteria-auc/id391068250?mt=8).

The AUC methodology has certain limitations. AUC were developed based on expert opinion and expert interpretation of existing clinical and trial evidence, while guidelines are developed based on clinical-trial evidence. They do not include a list of all possible clinical
scenarios. They are not directly based on the frequency with which the test reclassifies the extent or severity of a patient's disease, or directly affects the choice of treatment. Also, they do not take into account the costs of the test, cost-effectiveness, relative performance of one test versus alternative tests, ionizing radiation or the impact of repeat testing or layered testing.

**Frequency of appropriate MPI per AUC**

The frequency of appropriate use of MPI may vary from region to region and in different practices. In one study,(14) from 6 sites in United Health Care system, the majority of the studies were performed for appropriate indications (85.6%), and only 14.4% of the studies were performed for inappropriate indications (rarely appropriate). Inappropriate studies (or rarely appropriate) were more common in asymptomatic individuals, women and preoperative patients.(14) The American Society of Nuclear Cardiology (ASNC) incorporated some of these indications into the Choosing Wisely campaign to reduce inappropriate use of MPI. Choosing Wisely is an effort by the American Board of Internal Medicine (ABIM) partnering with Consumer Reports and in collaboration with several medical societies [including the Society of Nuclear Medicine and Molecular Imaging (SNMMI), ASNC, and others], developed to curb the growth in the use of unnecessary imaging tests. It uses the philosophy of “5 things that physicians and patients should question.” Table 1 lists the SNMMI and ASNC Choosing Wisely points related to MPI.(15, 16)

**Methods to increase the appropriate use of MPI**

Appropriate use of MPI can only be increased by improving knowledge about AUC for both referring provider and the imaging provider. Unfortunately, educational efforts to reduce the rates of rarely appropriate studies have had mixed results. Initial short-term declines in the proportion of “rarely appropriate” tests ordered, were not sustained in the long-term. (17)

The appropriateness of MPI can be tracked at the time of order entry using one of several online tools. The ACC Focus (Formation of Optimal Cardiovascular Utilization Strategies) is a web-based quality improvement tool developed to track and improve the appropriate use
of MPI. In a preliminary analysis, the proportion of rarely appropriate indications decreased from 10% to 5% for the sites participating in the FOCUS PIM (practice improvement module). (18) Also, decision support tools (DST), incorporated into physician electronic order entry systems, can guide the referring physicians through steps to ensure appropriate use of the test. One such system, the AUC-DST, showed that the frequency of appropriate tests increased from 49% to 61%, and the frequency of rarely appropriate tests decreased from 22% to 6% eight months after the implementation of the AUC-DST. (19) Ideally, the referring physician should ensure the appropriateness of the test at the time of order entry using clinical DST. Indeed documentation of appropriate use criteria using DST for ordering advanced imaging tests (including SPECT and PET MPI), is mandated by law as a prerequisite to receive payments for imaging services in Medicare patients by January 2017, (20, 21) and likely will increase the rate of appropriate studies.

As cardiovascular imaging has become fairly complex, choosing a suitable test from the many possible tests can be challenging for ordering physicians who may not be imaging experts. In complex cases, a discussion between the referring physicians and imaging physicians, who have expertise in multimodality imaging, can ensure that the most appropriate test is selected for a given indication and patient. In some cases, the most appropriate test may be an exercise treadmill test without imaging, stress echocardiography, or magnetic resonance imaging based MPI. This discussion is facilitated by a systematic review (“protocol”) of the patient’s history (Table 2), at least one day before the MPI, to change the test if needed and to contact the patient. Imaging laboratory personnel, fellows in training or experienced imaging staff members can prepare a protocol plan for the studies.

The appropriate use of MPI is expected eventually to reduce cumulative lifetime radiation exposure from imaging of patients with CAD, although this has not yet been studied directly on a large scale.
II. Radiation dose reduction during the test: Optimize MPI

SNMMI and ASNC recommend a patient-centered imaging approach taking into account radiation dose. ASNC issued an information statement on reducing radiation exposure in MPI and recommended several methods which, if used appropriately, can reduce radiation dose to ≤ 9 mSv in 50% of patients referred for SPECT or PET MPI studies. (22) Selection of protocols for MPI should also take into account: the clinical question, the image quality, potential risks incurred from future testing stemming from the results of MPI and from radiation, costs, patient convenience, and assurances that the patient and staff are receiving the lowest possible radiotracer dose. (23) However, image quality should not be significantly jeopardized by dose reduction. Patient characteristics such as body habitus, claustrophobia, ability to lie supine for imaging, and stress modality are also important considerations. Appropriate selection of radiotracer, the use of novel imaging protocols, and when available, the use of novel reconstruction methods, hardware, collimators and software are critical to reduce patient radiation dose.

A. Selection of radiotracers

Estimated whole-body effective radiation dose (averaged over various organs and averaged for men and women, and various organs) is directly related to the half-life of the radiotracer and dose of radiotracer administered (Table 3).

For SPECT MPI, $^{99m}$Tc agents are preferred due to their shorter half-life, significantly lower effective dose, and superior image quality compared to $^{201}$Thallium. For PET MPI, $^{82}$Rubidium and $^{13}$N-ammonia, when available, offer an even greater reduction in radiation dose compared to $^{99m}$Tc SPECT. Radiation dose from PET MPI can be further lowered with imaging in 3D mode, as this scan mode offers much higher count imaging and permits half-dose imaging, which may be especially useful in children. The mean estimated whole body effective dose from SPECT and PET perfusion tracers is listed in Table 3.

For SPECT and PET MPI, a weight or BMI-based adjusted radiotracer dose may be better than a fixed dose for all, to balance low radiation dose with optimal image quality. (24) Indeed, Marcassa et al, (25) recently documented a 58% radiation dose savings to patients, and a 50%
dose reduction to cardiologists performing the test, by switching from a fixed-dose protocol to weight-based $^{99m}$Tc dosing protocol and finally to low-dose MPI using novel software-based reconstructions. A sample table of weight-based $^{99m}$Tc dosing and estimated whole body effective dose is included in the Appendix Table 1. Radiation dose from MPI can be additionally reduced using any of the protocols and technologies described below.

**B. Stress-first or Stress-only imaging protocols for reduced dose MPI**

Stress-first or stress-only MPI as well as low radiotracer dose protocols (half-dose or less than half-dose) using novel scanners, collimators or novel software can significantly reduce radiation dose from SPECT MPI compared to standard dose rest/stress MPI protocols. Stress-first SPECT imaging has several other advantages (Appendix Table 2), and although supported by the imaging societies for over a decade now, the stress-first protocol has not been widely implemented due to a number of implementation challenges (Appendix Table 2). But, a decline in the frequency of abnormal scans to 8.7% in 2009 (41% in 1991)(26) combined with the soaring costs of medical imaging ( > 6 million SPECT MPI/year)(2) make a strong case for stress-only imaging.

A growing body of literature supports the utility of stress-first SPECT imaging.(24, 27-34) If the stress MPI is normal, the rest scan can be avoided, with significant cost, time and radiotracer exposure savings to the patient (35% dose reduction) and to the laboratory staff (40% dose reduction).(35) Stress-first and stress-only PET MPI has not been as widely studied as stress-first and stress-only SPECT MPI.

**Implementation of stress-first MPI.** A successful implementation of stress-only or stress-first protocols requires careful screening of patients ahead of the test. Experienced imaging physicians must be available to finalize the MPI report, definitively and unequivocally, before discharging the patient from the laboratory. A stress-only study is considered normal when the myocardial perfusion is homogeneous, the ejection fraction and left ventricular volumes are normal, during maximal stress, and with no ischemic ECG changes.(27) However, if the stress-
first images are not normal, a rest scan can be completed the same day with three times the stress radiotracer dose.

*Patient selection for stress-first imaging.* Patient selection is critical for a successful stress-first program. Patients without a prior history of MI and an intermediate pretest likelihood of CAD are well suited for stress-first MPI. The pre-test likelihood of CAD is calculated using the age, gender, and chest-pain characteristics (Appendix Table 3). A stress-first imaging protocol is feasible with either exercise or pharmacological stress. It may be used in diabetics(27) as well as in morbidly obese patients.(30) Patients with a low pretest likelihood of CAD, however, may be considered for treadmill testing alone without imaging. Indeed, the WOMEN study demonstrated, for women with an intermediate pre-test likelihood of CAD, and able to exercise on a treadmill, an initial diagnostic strategy of exercise treadmill testing with imaging, when compared to exercise treadmill testing alone, did not provide any incremental diagnostic or prognostic benefit and also reduced downstream costs.(36)

*Attenuation correction for stress-first SPECT imaging.* Accurate identification and correction of attenuation artifacts is important in stress-first imaging algorithms to avoid interpretation of attenuation artifacts as real perfusion defects. Although gated SPECT is not helpful to identify attenuation artifacts (as ischemic wall motion abnormalities typically resolve by the time of image acquisition), prone imaging can be used for troubleshooting fixed inferior wall perfusion defects. Attenuation correction, however, is the most direct and effective method for correcting attenuation artifacts.

Attenuation correction using radionuclide or CT-based transmission scans significantly reduced the need for rest MPI imaging, in as many as 37-48% of patients scheduled for stress-first SPECT imaging.(31, 37) Indeed, the primary application of cardiac CT with SPECT and PET MPI is for attenuation correction with a radiation dose ranging from 0.3 to 1.3 mSv with appropriate cardiac CT dose reduction methods (Appendix Table 4).(13) The use of attenuation corrected MPI with gated SPECT is essential for the best clinical application of stress-first or stress-only imaging.
Prognostic value of stress-only imaging. The excellent prognostic value of a normal stress-only SPECT imaging from conventional scanners is well-established (Appendix Table 5). In a pooled analysis including 10,438 patients with stress-only MPI, a normal stress-only image is associated with an annual event rate of 0.7%, with a relative risk comparable to a normal rest-stress MPI. This area has not been examined for PET MPI.

C. Novel reconstruction software, scanners, and collimators for MPI

Several recent advances in cardiac SPECT software, novel semiconductor detector solid state SPECT scanners [cadmium zinc telluride, CZT, Spectrum Dynamics, GE scanners or Thallium activated cesium iodide, CsI (Tl) (Digirad)], and novel collimator design, have substantially improved image resolution and lowered radiation-dose for MPI.

Novel iterative reconstruction methods [Astonish (Phillips, San Jose California), Wide beam reconstruction (UltraSPECT, Haifa, Israel), Flash 3D (Siemens, Hoffman Estates, IL), n-SPEED (Digirad), and Evolution (GE, Milwaukee, Wisconsin)] with resolution recovery and noise reduction provides higher image contrast (with sharper defects and borders) and significantly improve image quality, particularly for low-count imaging studies from half- and quarter-dose radiotracer protocols. Despite excellent image quality with shorter imaging times, not many studies have prospectively evaluated half-dose MPI with novel software. DePuey et al used half-dose \(^{99m}\)Tc MPI and showed that low dose MPI with conventional scanners using novel software (wide-beam reconstruction), provides good to excellent image quality in 93% of the patients. The value of the novel software is that existing scanners can be upgraded with advanced software to reduce radiation dose; a much smaller capital investment than buying a new scanner.

Novel solid-state SPECT scanners offer a several-fold higher count sensitivity compared to the conventional NaI(Tl) scanners because they utilize cardiofocal imaging and either large parallel hole or multiple-pinhole collimators. Also, attenuation correction is available for some of these scanners (Digirad and GE). Iterative-reconstruction protocols combined with
resolution recovery and noise reduction are standard for the novel scanners. Each of these enhancements enables low-dose and ultra low-dose MPI.

Due to high count sensitivity, the novel scanners offer significant flexibility with imaging protocols. The initial focus of the novel high-sensitivity scanners was on rapid imaging (2-4 minute imaging times) which is well-suited for imaging patients with multiple comorbidities who may not otherwise tolerate longer imaging acquisition times. However, low-radiation dose, high quality imaging is the current focus of the novel scanners (Table 4). Half-dose or less than half-dose protocols [single-day 111-185 MBq (3-5 mCi)/333-555 (9-15 mCi) of $^{99mTc}$] with imaging times of 8 minutes and 6 minutes or longer using count-based imaging are used. The effective radiation dose from stress-only protocols with novel scanners is less than 2 mSv. However, enthusiasm for further dose reduction is tempered by the longer image acquisition times, which may be increase the likelihood of patient motion, especially if the acquisition duration is 27 minutes.

In multicenter studies, rapid scanning with dedicated cardiac SPECT scanners provided comparable or superior image quality, with much shorter scan duration compared to standard-time scanning with conventional scanners.(46, 47) However, only one study directly compared low-dose dedicated cardiac SPECT scanning with conventional-dose scanning in the same patients, and one other study simulated low radiation dose rest and stress imaging. Einstein et al.(48) directly compared rest ultra-low dose $^{99mTc}$ dedicated cardiac SPECT imaging (133.96 MBq/3.62 mCi) with standard-dose conventional SPECT in 110 patients [mean body mass index = 26.1 ± 2.8 kg/m$^2$, range (17.1-30.9 kg/m$^2$), mean acquisition time ranged from 9.7-15.2 minutes] from 3 sites, and showed comparable image quality with a very low radiation dose when using the dedicated cardiac SPECT scanner (1.15 ± 0.24 mSv). Nakazato et al.(49) recently simulated low-dose rest and stress SPECT MPI in 79 patients (mean body mass index = 30.0 ± 6.6, range 20.2-54.0 Kg/m$^2$) and showed that image quality is adequate even with very low count images (~ 1 million) and comparable to standard full count images. Finally, low-dose $^{99mTc}$ MPI with dedicated cardiac scanners is accurate for detecting obstructive CAD on invasive angiography (e.g., in one study visual analysis sensitivity 92%, specificity 56% and normalcy 98%).(50-52) Although the novel scanners offer significant advantages and high quality imaging
with low radiation dose, they are expensive, at this time, with clinical imaging applications limited to cardiac imaging. An algorithm for reduced dose SPECT MPI is shown in Figure 3.

**D. Dose reduction with PET.** Most current-generation PET scanners image in 3D mode and are equipped with advanced hardware and software capabilities for high resolution, low-dose imaging. With time-of-flight, high-definition iterative reconstruction and motion-frozen imaging, an effective spatial resolution as low as 2 mm can be achieved with PET MPI. When combined with the low dose from PET tracers, PET MPI offers significantly lower radiation dose compared to SPECT MPI. Stress-only imaging and low-dose CT imaging are additional dose reduction options for PET MPI, but have not been as widely studied or implemented.

Stress-only PET MPI in 3D mode with myocardial blood flow assessment can be performed with < 1 mSv radiation dose. Typical adult patients referred for PET MPI, however, are high-risk patients and are not always suitable for stress-only imaging. In addition, coronary flow reserve (CFR), an emerging risk marker of coronary vascular dysfunction, cannot be estimated with stress-only imaging. However, one recent study using \(^{15}\)O-water MPI suggests that hyperemic myocardial blood flow may be more accurate than CFR for the diagnosis of obstructive epicardial CAD (accuracy 86% vs. 78%, p < 0.01, respectively). On the other hand, another study suggested that while CFR and stress myocardial blood flow with \(^{82}\)Rubidium provide powerful risk stratification, estimates of CFR may be more robust and less variable than stress myocardial blood flow. If stress myocardial blood flow is validated to be superior to CFR with the clinical PET perfusion tracers, stress-only PET MPI may be more widely implemented. Combining stress-only MPI with low-dose CT coronary angiography (if CT is abnormal), or with calcium score can identify significant CAD that may warrant aggressive medical therapy. Despite significant advantages of superior image quality, better detection of CAD, and low radiation dose imaging, PET and PET/CT MPI is not widely available, remains expensive and is predominantly limited to pharmacological stress (as exercise stress can be challenging with PET).
III. Radiation dose reduction after the test

Finally, several steps after completion of MPI will minimize the lifetime radiation dose. First, an accurate, clear, and unambiguous report, and timely communication to the referring physician will reduce repeat, layered testing. Next, the MPI report should accurately list the administered radiotracer dose; in the near future estimates of lifetime radiation exposure from medical imaging on the report may become a requirement. Periodic quality reviews of the laboratory for doses administered for MPI, image quality with low-dose MPI, and evaluation of the number of MPI procedures below ASNC recommended dose parameters of < 9 mSv are suggested.(22) Further, quality control of the scanners will optimize image quality and facilitate low radiation-dose MPI. Lastly, staff radiation-exposure should be followed according to ALARA principles, including rotation of duties for nuclear medicine technologists to avoid high radiation exposure to any individual technologist. A recent scientific statement on Approaches to Enhancing Radiation Safety in Cardiovascular Imaging,(57) highlights the need to educate referring physicians and health care providers on performing low-dose medical imaging and provides a list of online resources for radiation dose reduction from the various societies.

Conclusions:

The rising barriers to radionuclide MPI from ionizing radiation and high costs mandate a change in the traditional practice of nuclear cardiology. The time to change is now. Novel imaging protocols and powerful imaging technologies have emerged to facilitate low-dose high-quality MPI. A secondary benefit of this change is that in the current challenging fiscal environment, medical facilities, practitioners and practices can differentiate themselves by producing superior image quality, at a faster pace, and at a low-dose. The state of the art nuclear cardiology practice requires embracing best practices for appropriate patient selection, patient centered imaging protocols, use of novel protocols for traditional scanners, and adoption of laboratory practices to reduce life time radiation exposure for patients and staff members. The move to lower radiation dose for MPI brings nuclear cardiology into the 21st century spreading new best practices across the country and the world.
Acknowledgements:

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References:

1. Office USGA. Rapid Spending Growth and Shift to Physician Offices Indicate Need for CMS to Consider Additional Management Practices.


Figure 1. Increasing radiation burden in the US and contributions from medical imaging. The collective dose from medical imaging increased 3-fold in 2006 compared to the early 1980’s.
Figure 2. Practical Ways to Implement a Reduced Radiation Dose MPI Program

Before MPI: Justify MPI

- Check appropriate use criteria
- Protocol studies

At the time of MPI: Optimize MPI

- Use patient centered protocols (for each patient select an imaging protocol, radiation dose, stress type)
- Weight based radiotracer; Use Tc-99m tracers
- Stress only MPI when feasible
- Low dose protocols: novel software; novel hardware
- Consider PET MPI

After MPI: Reduce life-time radiation dose

- Minimize layered testing: Report MPI accurately, definitively and in a timely manner and provide easy access to reports and images
- Scanner quality control: optimize image quality
- Radiation safety education: minimize dose error, rotate staff to minimize radiation exposure
Figure 3. Patient Centered Protocols for Low Radiation Dose MPI. Traditional SPECT (Orange), Traditional SPECT with Novel Software (Purple), Novel SPECT Scanners (Green). Most MPI procedures which employ novel protocols or novel technologies provide < 9 mSv radiation dose from rest/stress $^{99m}$Tc protocols. To achieve 50% of the laboratory volume with < 9 mSv dose, practices can implement several of the above options into their practice. LD = low dose; HD = high dose.
Table 1. Five Things Physicians and Patients Need to Know

<table>
<thead>
<tr>
<th>SNMMI</th>
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<tr>
<td>• Do not perform routine annual stress testing after coronary artery revascularization.</td>
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<th>ASNC</th>
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<tr>
<td>• Do not perform stress cardiac imaging or coronary angiography in patients without cardiac symptoms unless high-risk markers are present.</td>
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<tr>
<td>• Do not perform cardiac imaging for patients who are at low-risk.</td>
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<tr>
<td>• Do not perform radionuclide imaging as part of routine follow-up in asymptomatic patients.</td>
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<tr>
<td>• Do not perform cardiac imaging as a pre-operative assessment in patients scheduled to undergo low- or intermediate-risk non-cardiac surgery.</td>
</tr>
<tr>
<td>• Use methods to reduce radiation exposure in cardiac imaging, whenever possible, including not performing such tests when limited benefits are likely.</td>
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Adapted from references (15, 16)
Table 2. Steps to Plan a Protocol for MPI

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<table>
<thead>
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<tbody>
<tr>
<td>1</td>
<td>Review the electronic medical records to define the clinical question</td>
</tr>
<tr>
<td>2</td>
<td>Check for recently performed cardiac evaluations to avoid duplicate testing and</td>
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<td></td>
<td>layered testing for similar clinical symptoms</td>
</tr>
<tr>
<td>3</td>
<td>If the clinical question is not clear or if the test ordered is not the most</td>
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<td></td>
<td>appropriate test, discuss with the referring physician for clarification</td>
</tr>
<tr>
<td>4</td>
<td>Plan the appropriate stress technique</td>
</tr>
<tr>
<td>5</td>
<td>Plan the appropriate imaging technique</td>
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Table 3: Estimation of effective radiation dose from the various myocardial perfusion radiotracers

<table>
<thead>
<tr>
<th>Radiopharmaceutical</th>
<th>Effective Dose mSv/MBq</th>
<th>Adm. Activity Full dose MBq</th>
<th>Adm. Activity Half dose MBq</th>
<th>Adm. Activity Full dose mCi</th>
<th>Adm. Activity Half dose mCi</th>
<th>Estimated Dose Full dose study mSv</th>
<th>Estimated Dose Half dose study mSv</th>
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</thead>
<tbody>
<tr>
<td>$^{82}$Rubidium*</td>
<td>0.0017</td>
<td>1480</td>
<td>740</td>
<td>40</td>
<td>20</td>
<td>2.52</td>
<td>1.26</td>
</tr>
<tr>
<td>$^{13}$N-Ammonia</td>
<td>0.0027</td>
<td>740</td>
<td>370</td>
<td>20</td>
<td>10</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$^{99m}$Tc Sestamibi-rest</td>
<td>0.0079</td>
<td>296</td>
<td>148</td>
<td>8</td>
<td>4</td>
<td>2.34</td>
<td>1.17</td>
</tr>
<tr>
<td>$^{99m}$Tc Sestamibi-stress</td>
<td>0.009</td>
<td>888</td>
<td>444</td>
<td>24</td>
<td>12</td>
<td>8.0</td>
<td>4.0</td>
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<tr>
<td>$^{99m}$Tc Tetrofosmin-rest</td>
<td>0.0069</td>
<td>296</td>
<td>148</td>
<td>8</td>
<td>4</td>
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<tr>
<td>$^{99m}$Tc Tetrofosmin-stress</td>
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<td>888</td>
<td>444</td>
<td>24</td>
<td>12</td>
<td>6.13</td>
<td>3.1</td>
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<tr>
<td>$^{201}$Thallium</td>
<td>0.14</td>
<td>148</td>
<td>74</td>
<td>4</td>
<td>2</td>
<td>20.72</td>
<td>10.36</td>
</tr>
</tbody>
</table>

Adm = administered; Recommended MPI radiotracer dose for conventional scanners\(^{(58, 59)}\): $^{99m}$Tc Sestamibi Rest (8-12 mCi) and Stress (24-36 mCi); $^{82}$Rubidium (40-60 mCi 2D; 20 mCi 3D)(\(^{(60)}\)); $^{13}$N-Ammonia (20 mCi 2D; 10 mCi 3D)(\(^{(60)}\)); $^{201}$Thallium (2.5-4 mCi)(\(^{(59)}\))

* New estimates of $^{82}$Rubidium dose are significantly lower (0.00126 mSv/MBq).(\(^{(61)}\)) Full dose PET radiotracer is used for 2D imaging and half dose for 3D imaging, typically equal dose of radiotracer is administered for rest and for stress PET MPI. 1 mCi = 37 Bequerels; Average activities are listed.

Estimated Dose (mSv) = Effective dose times administered activity. Calculate dose for rest and stress scans separately and, if attenuation correction is used, add 0.3 – 0.7 mSv for CT and 0.3 mSv for radionuclide transmission scan (13).

Adapted with permission from reference. (13)
Table 4. Radiation dose from low-dose protocols for novel SPECT scanners

<table>
<thead>
<tr>
<th>First Author</th>
<th>Rest MBq (mCi)</th>
<th>Stress MBq (mCi)</th>
<th>Number of patients</th>
<th>BMI kg/m² (mean±SD or range)</th>
<th>Radiotracer</th>
<th>Protocol (one day)</th>
<th>Radiation dose for the study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duvall (24)</td>
<td>296-481 (8-13)</td>
<td>462.5; 925-1332 (12.5; 25-36)</td>
<td>717</td>
<td>Weight &lt; 200 lb</td>
<td>⁹⁹ᵐ Tc sestamibi</td>
<td>LD str only; HD str only; Stress/Rest</td>
<td>LD str-only = 4.2 mSv; HD str-only = 8.0 mSv; Stress/Rest = 11.8 mSv</td>
</tr>
<tr>
<td>Duvall (62)</td>
<td>185 (5)</td>
<td>555 (15)</td>
<td>131</td>
<td>&lt; 35</td>
<td>⁹⁹ᵐ Tc sestamibi</td>
<td>Rest/Stress</td>
<td>5.8 mSv</td>
</tr>
<tr>
<td>Nkoulou (63)</td>
<td>320.05+639.73 (8.65 + 17.29)</td>
<td>320.05 (8.65)</td>
<td>50</td>
<td>19-32</td>
<td>⁹⁹ᵐ Tc tetrofosmin</td>
<td>Stress/Rest</td>
<td>Stress only = 2.21 mSv; Stress + Rest = 6.62 mSv</td>
</tr>
<tr>
<td>Gimelli (52)</td>
<td>185-222 (5-6)</td>
<td>370-444 (10-12)</td>
<td>137</td>
<td>39±7</td>
<td>⁹⁹ᵐ Tc tetrofosmin</td>
<td>Stress/Rest</td>
<td>5.10-6.12 mSv</td>
</tr>
<tr>
<td>Esteves (51)</td>
<td>222 (6)</td>
<td>740 (20)</td>
<td>285</td>
<td>29±5</td>
<td>⁹⁹ᵐ Tc tetrofosmin</td>
<td>Rest/Stress</td>
<td>6.0 mSv; rest = 1.4 mSv; Stress = 4.6 mSv</td>
</tr>
<tr>
<td>Einstein (48)§</td>
<td>129.5 (3.5)</td>
<td>N/A</td>
<td>101</td>
<td>17.1-30.9</td>
<td>⁹⁹ᵐ Tc sestamibi</td>
<td>Rest only</td>
<td>1.2 mSv</td>
</tr>
</tbody>
</table>

Variable scan times for count based acquisition. Str = stress; LD = low dose; HD = high dose; BMI = body mass index; Most studies used Discovery NM530c; § = Discovery NM/CT 570c; ¶ = D-SPECT.