Recommendations for reducing radiation exposure in myocardial perfusion imaging

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INTRODUCTION

Radionuclide myocardial perfusion imaging (MPI) using single photon emission computed tomography (SPECT) or positron emission tomography (PET) for the detection of ischemia in patients with known or suspected coronary artery disease (CAD) has widespread clinical utilization and has been shown to have high accuracy and incremental prognostic value.[1-3] Amidst the recent publicity regarding the increasing use of all types of ionizing radiation in the United States, patients and medical professionals are scrutinizing the need for diagnostic testing and how radiation exposure can be reduced.[4,5] There are three critical questions that physicians must consider and answer with regard to radiation exposure and performing MPI in a particular patient:

- Is MPI testing appropriate and necessary in this patient?
- How can the MPI protocol be optimized to give the lowest possible radiation dose while maintaining diagnostic accuracy?
- How can new technologies be utilized to provide the lowest possible radiation dose while maintaining diagnostic accuracy?

Lowering the radiation dose while maintaining or improving image quality should be considered an improvement in quality of care; the lower the radiation and the higher the image quality, the greater the improvement in the quality of patient care. In general, all MPI studies should be performed in appropriate patients using relatively short-lived radionuclides, and using all possible measures to minimize radiation exposure. Under such circumstances, the benefits of the diagnostic and prognostic information outweigh the risks of radiation exposure.

This document identifies the best practice methods to optimize the benefits of MPI testing by obtaining the highest quality diagnostic images while minimizing radiation exposure. The focus will be on the appropriate selection of patients, the use of protocols that lessen total radiation exposure, and the use of equipment and processing methods that achieve the best image quality at the lowest possible radiation dose.

APPROPRIATE PATIENT SELECTION

Diagnostic radionuclide tracers are distributed over the entire body and are not associated with deterministic radiation effects which include skin burns, cataracts, and permanent sterility. They are related directly to the total dose received, have a latency of weeks to months, and there is a threshold below which effects will not occur. Theoretically, radionuclide tracers add a very small risk due to the stochastic effects of radiation, which are based on probability of chromosomal damage, independent of the dose; there is no threshold for the occurrence of cancer or genetic effects that may take years to decades to develop. Alternative diagnostic techniques such as computed tomography (CT) coronary angiography may expose the patient to a comparable or lower total body radiation dose, but the exposure to critical organs, such as the breast in female patients, is much higher. Since the currently favored model for stochastic effects does not acknowledge a lower radiation threshold, performance of MPI should be governed by the principle of ALARA (As Low As Reasonably Achievable).[6] Patient selection is the initial and most important component of managing radiation exposure

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from MPI, and is aided by the availability of appropriate use criteria (AUC).[7] When MPI is clinically appropriate, the benefits of accurate diagnosis and management are orders of magnitude greater than the potential risk from the radiation exposure.[8] Therefore, it would increase overall patient risk to avoid MPI or perform less optimal diagnostic testing in order to limit radiation exposure. When MPI is inappropriate, there is no amount of radiation exposure that can be considered acceptable. Inappropriate indications for cardiac radionuclide imaging are listed in Table 1.[7] MPI should be chosen for its ability to meaningfully advance clinical decision-making and care.

Once MPI is deemed appropriate, choosing the best diagnostic testing strategy for a patient requires evaluating the characteristics of both the patient and the test. With regard to radiation, the risk is greatest in the youngest patients. The latency period between radiation exposure and any measurable increase in cancer risk is believed to be 10-20 years for most cancers.[9] Accordingly, radiation exposure in younger patients results in a greater lifetime risk of potential radiation-induced cancer than in older patients. Older patients also are less sensitive to the oncologic effects of radiation than are children and young adults. Estimates of lifetime risk of cancer from a specific radiologic examination are four times greater for a 20-year-old woman than for a 50-year-old man.[10] The additional risk of malignancy from exposure to a 10 mSv dose is estimated to be approximately 1 in 2000, for the age distribution of the US population. This estimate includes children and young adults. Since most cardiac patients are older than the average assumed in this calculation, the estimated risk would be much smaller in the MPI population. The mean age of patients undergoing MPI in the United States is in the range of 60-65 years and the risks from their underlying suspected or known CAD are far greater than the theoretical risk from an appropriately ordered MPI study.

The greatest incremental value of diagnostic testing is obtained in the intermediate likelihood patient, and it is for this group of patients that MPI has the greatest utility.[1,2] MPI can also be used to obtain important management and prognostic information in patients, even when the diagnosis is established and the coronary anatomy is known.[3] In addition to establishing a diagnosis and providing prognostic information, MPI can also be of value in demonstrating the absence of disease in certain low-likelihood patients with persistent, unexplained symptoms that may indicate the presence of a life-threatening disease. Clinical judgment, therefore, must be patient specific. However, general principles of utility and appropriateness of diagnostic testing can be applied to clinical scenarios based on evidence. These scenarios have been described[7] and reviewed.[11]

Layered or serial testing should be avoided. Every effort should be made to select the best test based on the unique features of the patient and the specific clinical presentation in order to make a diagnosis or guide management without the need for multiple subsequent ''layered'' tests. Requests for serial testing in asymptomatic revascularized patients should be carefully scrutinized in light of appropriate use criteria and the likelihood of changing management. When appropriate repeat studies are performed in patients without interval myocardial infarction, repeating the rest study may not be necessary when a prior rest study is available.

Recommendations:

- **Apply appropriate use criteria.**
- **Consider alternative modalities with comparable diagnostic accuracy without radiation in younger patients.**
- **Consider utilization in the following patients in whom MPI has the most clinical utility: intermediate CAD risk, those requiring prognostic or management information, and those with persistent and unexplained symptoms.**
- **Layered or serial testing should be avoided.**

PROTOCOLS, RADIOTRACERS, AND IMAGING SYSTEMS

SPECT and PET MPI can be performed using several different protocols and radionuclide tracers.[12-14] Patient radiation exposure depends on the type and dose of injected radiotracer. Table 2 lists the effective dose estimates using tissue dose coefficients, E_1, or effective dose coefficients, E_2, for standard myocardial perfusion imaging protocols. Administered radiation dose may vary considerably based on patient weight and characteristics of the imaging system. There are a number of approaches available to significantly decrease patient exposure while maintaining diagnostic study quality.

SPECT

In general, Tc-99m-based SPECT protocols (sestamibi and tetrofosmin) offer lower patient radiation exposure than Tl-201 (stress/redistribution and stress/reinjection) or dual-isotope (Tl-201 rest/Tc-99m stress) protocols.[10] Patient radiation exposure per mCi is similar for the available Tc-99m-based tracers. For the diagnosis of ischemia, Tc-99m-based protocols are preferred.

Stress-only SPECT imaging. The use of stress-only imaging to exclude significant myocardial ischemia with Tc-99m-based tracers in appropriately selected

Table 1. Inappropriate indications (median score 1-3)

	Indication	Appropriateness score (1-9)
Detection of CAD: Symptomatic evaluation of ischemic equivalent (non-acute)		
1	Low pretest probability of CAD ECG interpretable AND able to exercise	I(3)
Detection of CAD: Symptomatic acute chest pain		
10	Define ACS*	I(1)
Detection of CAD/risk assessment without ischemic equivalent: Asymptomatic		
12	Low CHD Risk (ATP III Risk Criteria)	I(1)
13	Intermediate CHD risk (ATP III Risk Criteria) ECG interpretable	I(3)
Detection of CAD/risk assessment without ischemic equivalent: Syncope		
20	Low CHD risk (ATP III Risk Criteria)	I(3)
Risk assessment with prior test results and/or known chronic stable CAD, asymptomatic OR stable symptoms, normal prior stress imaging study		
23	Low CHD risk (ATP III Risk Criteria) Last stress imaging study done less than 2 years ago	I(1)
24	Intermediate to high CHD risk (ATP III Risk Criteria) Last stress imaging study done less than 2 years ago	I(3)
25	Low CHD risk (ATP III Risk Criteria) Last stress imaging study done more than or equal to 2 years ago	I(3)
Risk assessment with prior test results and/or known chronic stable CAD, asymptomatic OR stable symptoms, abnormal coronary angiography OR abnormal prior stress imaging study, no prior revascularization		
27	Known CAD on coronary angiography OR prior abnormal stress imaging study Last stress imaging study done less than 2 years ago	I(3)
Risk assessment with prior test results and/or known chronic stable CAD, asymptomatic, prior coronary calcium Agatston score		
33	Agatston score less than 100	I(2)
Risk assessment with prior test results and/or known chronic stable CAD, Duke treadmill score		
37	Low-risk Duke treadmill score	I(2)
Risk assessment: Preoperative evaluation for non-cardiac surgery without active cardiac conditions, low-risk surgery		
40	Preoperative evaluation for non-cardiac surgery risk assessment	I(1)
Risk assessment: Preoperative evaluation for non-cardiac surgery without active cardiac conditions, intermediate-risk surgery		
41	Moderate to good functional capacity (greater than or equal to 4 METs)	I(3)
42	No clinical risk factors	I(2)
44	Asymptomatic up to 1 year post normal catheterization, non-invasive test, or previous revascularization	I(2)
Risk assessment: Preoperative evaluation for non-cardiac surgery without active cardiac conditions, vascular surgery		
45	Moderate to good functional capacity (greater than or equal to 4 METs)	I(3)
46	No clinical risk factors	I(2)
48	Asymptomatic up to 1 year post normal catheterization, non-invasive test, or previous revascularization	I(2)
Risk assessment: Within 3 months of an acute coronary syndrome, STEMI		
49	Primary PCI with complete revascularization	I(2)
51	Hemodynamically unstable, signs of cardiogenic shock, or mechanical complications	I(1)
Risk assessment: Within 3 months of an acute coronary syndrome, ACS-asymptomatic post-revascularization (PCI or CABG)		
53	Evaluation prior to hospital discharge	I(1)

Table 1. continued

	Indication	Appropriateness score (1-9)
Risk assessment: Within 3 months of an acute coronary syndrome, cardiac rehabilitation		
54	Prior to initiation of cardiac rehabilitation (as a stand-alone indication)	I(3)
Risk assessment: Post-revascularization (PCI or CABG), asymptomatic		
59	Less than 2 years after PCI	I(3)
Risk assessment: Post-revascularization (PCI or CABG), cardiac rehabilitation		
61	Prior to initiation of cardiac rehabilitation (as a stand-alone indication)	I(3)
Evaluation of ventricular function, evaluation of left ventricular function		
65	Routine use of stress FP RNA in conjunction with rest/stress gated SPECT MPI	I(3)

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patients provides the lowest radiation dose for SPECT.[15-18] The accuracy of stress-only studies can be enhanced using attenuation correction. The prognostic value of an unequivocally normal stress-only gated Tc-99m SPECT study performed with attenuation correction and employing careful quality control and experienced readers has been demonstrated to be equivalent to that obtained from a conventional rest/stress study in a large single-center study of 16,854 patients.[19]

Performing stress first, reviewing the images, and if the stress portion is normal, canceling the rest portion, minimizes radiation exposure for one-day studies. Rest-stress sequences are acceptable. In obese patients requiring two-day studies, the stress study should be performed first, using attenuation correction if available, and the rest study canceled when the stress portion is normal.

Dual-isotope protocol. A dual-isotope protocol is most useful when myocardial viability is an overriding clinical consideration in patients with advanced CAD, when there is substantially impaired left ventricular systolic function, and when PET is not available. The patient dose for the detection of myocardial ischemia using this protocol involves a higher patient radiation exposure than is necessary to obtain the diagnostic information by other protocols. The use of PET with a flow tracer and fluorodeoxyglucose (FDG) for viability can achieve a lower patient exposure than existing thallium protocols. However, in patients in whom viability is an important clinical issue, the risk of short-term cardiovascular mortality is much higher and should be the predominant focus of clinical decision making.

Dose adjustment for patient weight. Injected doses for SPECT studies are typically adjusted for patient weight in order to maintain acquired count statistics. In obese patients, the consideration of performing PET rather than SPECT MPI may allow for lower patient radiation exposure with maintained (or even improved) diagnostic performance.[20] In lighter-weight patients, reducing the injected dose can still allow adequate counts statistics while reducing exposure.

Reduction of injected activity with new SPECT camera technologies. SPECT studies performed with higher sensitivity solid-state cameras with high sensitivity crystal material and utilizing advanced reconstruction algorithms permit lower doses of injected activity for diagnostic studies compared with Anger gamma cameras using sodium iodide crystals.[21] Dose reductions on the order of 50% compared with conventional doses appear to be feasible.

PET

For PET MPI, the tracers currently in use are Rb-82 and N-13 ammonia, in decreasing frequency of clinical utilization. Protocols most commonly involve both rest and stress imaging on a single day. Injected dose and resulting patient radiation dose depends in part on the system sensitivity and mode of operation (two-dimensional [2D] vs three-dimensional [3D]). In general, the newer lutetium oxyothosilicate (LSO) systems will require less injected activity than older bismuth germinate (BGO)-based systems. Systems operating in 3D acquisition mode require lower injected activity than those acquiring in 2D mode.

Because of their short half lives, PET studies potentially offer a lower patient radiation dose compared to SPECT, and may result in more favorable patient dosimetry, especially in obese patients. The issue of stress-only PET MPI has not been widely investigated but is worthy of consideration.

Attenuation correction. For both PET and SPECT MPI, the use of either radionuclide or CT-based transmission scans for attenuation correction contributes a negligible component of the radiation exposure received by the patient when the dose from the injected tracer is considered. The use of attenuation correction is

Table 2. Estimates of effective doses of standard myocardial perfusion imaging protocols

Protocol	Injected activity (mCi)		Effective doses (mSv)			
			From ICRP tables		From manufacturers' PIs	
	Rest	Stress	E_1	E_2	E_1	E_2
^{99m}Tc Sestamibi rest-stress	10.0	27.5	11.3	11.4	14.6	NR
^{99m}Tc Sestamibi stress only	0.0	27.5	7.9	8.0	10.0	NR
^{99m}Tc Sestamibi two day	25.0	25.0	15.7	15.6	20.6	NR
^{99m}Tc Tetrofosmin rest-stress	10.0	27.5	9.3	9.9	9.7	12.9
^{99m}Tc Tetrofosmin stress only	0.0	27.5	6.6	7.1	6.7	8.8
^{99m}Tc Tetrofosmin two day	25.0	25.0	12.8	13.5	13.7	18.3
^{201}Tl stress-redistribution	0.0	3.5	22.0	22.0	28.7, 9.3, 28.4	46.6, NR, 46.6
^{201}Tl stress-reinjection	1.5	3.0	31.4	31.5	43, 14.0, 42.6	69.9, NR, 69.9
Dual isotope ^{201}Tl-^{99m}Tc Sestamibi	3.5	25.0	29.2	29.3	37.8, 18.4, 37.5	NR, NR, NR
^{99m}Tc labeled erythrocytes	22.5	0.0	5.7	5.8	2.3	NR
^{82}Rb	50.0	50.0	13.5	12.6	3.0	NR
^{13}N-ammonia	15.0	15.0	2.4	2.2	n/a	n/a
^{15}O-water*	29.7	29.7	2.5	2.4	n/a	n/a
^{18}F-FDG	10.0	0.0	7.0	7.0	n/a	n/a

*American Society of Nuclear Cardiology guidelines do not prescribe a recommended dose. Stress and rest doses of 1100 MBq (29.7 mCi) used, as per European Association of Nuclear Medicine/European Society of Cardiology guidelines.
PI, Package Insert (or product information).
E_1 = Effective dose estimated from tissue dose coefficients, using ICRP Publication 60 tissue weighting factors. Calculations performed using the "splitting rule," arithmetic averaging rather than mass averaging of individual remainder organ dose contributions, and upper large intestine rather than extrathoracic airways as a remainder organ, as was originally specified in ICRP Publication 60. If dose to the colon was not specified in a data source, then the average of the upper large intestine and lower large intestine doses was substituted.
E_2 = Effective dose estimated from whole-body dose coefficients, using ICRP Publication 60 tissue weighting factors.
NR, Not Reported in PI (Total body dose provided rather than effective dose); *n/a*, Not available for cyclotron-produced tracers.
Reproduced with permission from Estimates of Effective Doses of Standard Myocardial Perfusion Imaging Protocols.[10]

desirable, especially when stress-only imaging is performed.[18,22]

Recommendations:

The clinical indications and physical stature of each patient should be reviewed and the best combination of radiotracers and protocols selected using the following guidelines:

- **Use radionuclides with shorter half-life such as Tc-99m and PET tracers.**
- **Perform stress-only testing.**
- **Use weight-based dosing.**

TECHNOLOGY

Once the appropriate patient, radiotracer, and protocol have been selected, technological considerations can further reduce radiation exposure. The various hardware and software options are discussed below, and the recommendations that can be made based on the existing data are listed in Table 3.

Image Reconstruction

Filtered back projection (FBP) has been the standard method for reconstructing SPECT MPI. FBP has problems with low-count SPECT images due to the inevitable amplification of image noise, and mandates higher radiation doses or longer acquisition times. It is unable to correct for photon attenuation and scatter.[23,24]

Iterative reconstruction (IR) refers to a broad category of SPECT and PET reconstruction techniques that estimate the distribution of the radioactivity being imaged by mathematically generating projections that such a distribution would produce.[23,24] The generated projections are compared to the actual acquired projections and the difference is used to improve the estimate of the estimated distribution. If the algorithm is designed correctly, the estimate approaches the actual distribution being imaged and the difference is minimized. Using IR allows the injection of a lower radiation dose and correction for the Poisson nature of the noise as well as attenuation and scatter.

Table 3. Recommendations for achieving MPI radiation reduction

Feature	Potential for dose reduction	Recommendation
Patient selection	Significant	Apply appropriate use criteria. Consider alternative modalities with comparable diagnostic accuracy without radiation in younger patients. Consider utilization in the following patients in whom MPI has the most clinical utility: intermediate CAD risk, those requiring prognostic or management information, and those with persistent and unexplained symptoms. Layered or serial testing should be avoided
Protocols, radiotracers and imaging systems	Significant	The clinical indications and physical stature of each patient should be reviewed and the best combination of radiotracers and protocols selected using the following guidelines: use radionuclides with shorter half-life such as Tc-99m and PET tracers, perform stress-only testing, and use weight-based dosing
Reconstruction-FBP	Standard	No recommendation
Reconstruction-iterative	Potential for significant	Strongly recommend
Multi-detector systems	Significant	Strongly recommend minimum of two detectors
New camera geometries	Significant (same effect as multi-detector systems)	Use when available. Consider for new equipment purchase
Solid-state detector systems	Minor unless part of a multi-detector or new geometry system.	No recommendation
Collimators-custom	Unproven, probably minor	Further exploration and research
Energy settings	Probably minor	Further exploration and research
Step and shoot	Minor	No recommendation
Count consistency	Minor	No recommendation

Clinical acceptance of IR had been limited due to the computationally intensive nature of the algorithms and resultant slow reconstruction times. With the increased computation speed currently available, IR is now practical for clinical use. Studies have been performed to identify the potential lower bounds of the required count density that is needed with IR techniques compared to the established protocols using FBP. The results have shown that with IR techniques, image quality comparable to FBP can be obtained with as little as 50% to 75% of the counts; the degree of reduction is dependent on the software vendor's implementation of the algorithm.[18,25-27] Since the detected count density for a SPECT study is dependent on the injected radioactivity, IR techniques hold the promise of significantly reducing administered dose and patient radiation exposure. PET protocols routinely use IR with attenuation and scatter correction.

IR techniques are very dependent on the manufacturer, class of algorithm, the geometry of the imaging system, and other models incorporated into the reconstruction (e.g., photon attenuation). As a result, not all algorithms will provide the same results for the same acquisition protocol. It is advised to follow the manufacturer's recommendations and review the results and protocols that clinically validated the technology.

Recommendation:

- **IR should be used for SPECT and PET MPI processing.**

Imaging Systems

The majority of imaging laboratories perform SPECT using conventional Anger cameras with NaI(Tl) crystals

and parallel-hole collimators with protocols optimized to acquire high-quality SPECT MPI with the minimum radiation dose.[28] The following suggestions minimize injected radiation dose, and therefore deliver less radiation to the patient, while maintaining high image quality.

Multiple detector systems. Multi-detector imaging systems are able to obtain high-quality diagnostic images using lower radionuclide doses than a single-detector system. Two-detector systems are widely available and enable a routine reduction by half of the injected dose while imaging for the same time as a one-detector system. Since 180-degree acquisition is preferable with FBP and comparable results are obtained with IR using 180-degree and 360-degree acquisitions (with correction for patient attenuation, detector response characteristics, and radiation scatter), 180-degree acquisition is recommended.[29] Some of the newer, unconventional radiation detector designs, especially those that employ arrays of small solid state detectors,[30] have the equivalent of many more ''heads'' than two-detector or three-detector gamma cameras. The potential for these newer SPECT systems to reduce radiation dose are discussed below.

Solid-state detector-based SPECT systems. New technology based on innovative detector designs using semiconductors have greater count sensitivity and the potential for reducing radiation dose relative to conventional anger cameras.[30]

Improved sensitivity. New imaging geometries using solid-state detectors offer increased sensitivity compared to conventional parallel collimated Anger cameras. While conventional Anger cameras have count sensitivities on the order of 0.5-0.7 kcps, new SPECT system geometries using cadmium-zinc-telluride (CZT) have sensitivities of 2.2-4.7 kcps.[31,32] Some detector designs have reported a 10 fold greater count sensitivity than Anger cameras, without a reduction in energy or spatial resolution.[33] Anger cameras have 9-10% Tc-99m energy resolution while CZT-based SPECT cameras have energy resolution of 5.7%. Similarly, Anger cameras have system spatial resolution on the order of 9-10 mm, while CZT SPECT systems have system spatial resolution of 4-5 mm. Consequently, it is feasible to acquire high-quality MPI images with solid-state detector-based SPECT systems using greatly reduced injected radioactivity.[31,34,35]

Overall image quality. Initial reports indicated the image quality achieved with CZT cameras in 5-6 min is comparable to or better than conventional parallel hole collimated Anger camera acquisitions of 14-15 min.[36,37] A subsequent analysis of 168 patients showed that CZT studies with 4-minute rest and 2-minute stress CZT acquisitions produced image quality comparable to that of 14-minute rest and 12-minute stress Anger camera studies.[38] CZT imaging devices can acquire images of similar quality as Anger cameras in 12-14 minutes studies using only 15%-30% of the current standard injected isotope dose. In clinical trials the newer detectors produce images that are at least comparable to those obtained with conventional SPECT cameras,[21,37,39,40] so that significant radiation dose reduction is feasible.

Collimation. *Conventional collimators*. Most cardiac Anger cameras use low-energy high resolution parallel-hole collimators with a collimator resolution of about 7 mm at 10 cm from the collimator surface. ''General purpose'' collimators typically have 2× higher sensitivity, but a reduced collimator spatial resolution of 9 mm. ''High sensitivity'' collimators have 4× higher sensitivity than ''high resolution'' collimators, but a collimator spatial resolution of only 13 mm. Incorporating the intrinsic camera resolution, going from a ''high resolution'' to a ''general purpose'' collimator acquisition would allow a reduction of the injected dose by 50% while achieving the same number of counts, but the system spatial resolution would decline from 8-8.5 to 9.5-10 mm.[28]

Custom-designed collimators. An alternative approach is to use specially designed focusing collimators for cardiac imaging. The geometry of the collimator holes and septa are not parallel, but are variably aligned across the face of the collimator to achieve higher spatial resolution and higher sensitivity in the area of the heart. Special reconstruction software is required. Because of their higher extrinsic sensitivity compared to conventional parallel-hole collimators, the injected dose can be reduced and quality images obtained using standard imaging times. Pin-hole collimators have the greatest spatial resolution, and a solid-state based detector has been constructed that uses multiple pin-hole collimators, as described below. Other specialized collimator designs include multiple simultaneous pin-hole collimators that are used in conjunction with standard Anger camera technology, which also require special reconstruction software.

Considerable development over the past several years has been devoted to creating sophisticated IR algorithms that incorporate physical details of the collimators. These algorithms are designed to account for their different spatial resolution with depth.[34,41]

Recommendations:

- **Anger camera MPI studies should be performed using a minimum of 2 detectors with 180-degree acquisition.**
- **High sensitivity SPECT imaging geometries should be used whenever available and considered at the time of new equipment purchase.**
- **High sensitivity and custom designed collimators have the potential for reducing injected radiation**

dose .but require further validation before implementation into clinical practice.

Imaging System Acquisition Parameters

Energy settings, energy resolution. One method for increasing the total number of counts from a lower injected radiation dose is to widen the energy window. This results in a larger total number of acquired counts, but also increases the percentage of scattered gamma rays, which will reduce spatial resolution and reduce image contrast. For institutions that routinely employ scatter corrections as part of IR,[42,43] this may have a less deleterious effect than for those that use FBP. If the attempt is made to obtain acceptable myocardial perfusion studies by widening the energy window, institutions that have more than one Anger camera should use the one with the best intrinsic energy resolution, in order to minimize the blurring effect of including a larger percentage of scattered radiation.

When using Tl-201, acquiring the 167 keV peak increases counts by about 5%, which can be used to reduce the injected activity. The higher energy Tl-201 gamma rays improve the spatial resolution compared to the lower energy Tl-201 photons.

Continuous acquisition. Continuous acquisition is an alternative to conventionally used step-and-shoot protocols where the detectors are not acquiring counts while moving from one projection to the next. Continuous acquisition protocols acquire additional data for only a few seconds per projection.[44] Step-and-shoot protocols are used instead of continuous acquisition, because reconstruction algorithms are designed for input data that are assumed to be a sequence of images acquired at discrete angles.[45] However, using reconstruction software designed to accommodate true continuous acquisitions allows a reduced injection dose while obtaining the same target count rate. The reduction is on the order of 5%.

Count consistency. One means to reduce total radiation dose for sites that use multiple injections of the same isotope involves obtaining consistent counts for the rest and stress portions of the study. By performing a one-minute anterior-view myocardial image for the initial injection, it is possible to adjust the amount of time per projection in order to obtain a target information density.[46] This approach could be extended to enable acquiring the initial tomogram for a standardized initial total number of myocardial counts and then, for the second injection, to reduce the injected activity so as to acquire the second tomogram for a longer period of time that is still tolerable for the patient. This would be most feasible for two-day protocols, and would be more likely useful in imaging smaller patients rather than larger patients.

Recommendations:

- **Widening the energy window requires further validation before implementation into clinical practice.**
- **Continuous acquisition, and count consistency methods require further validation before implementation into clinical practice.**

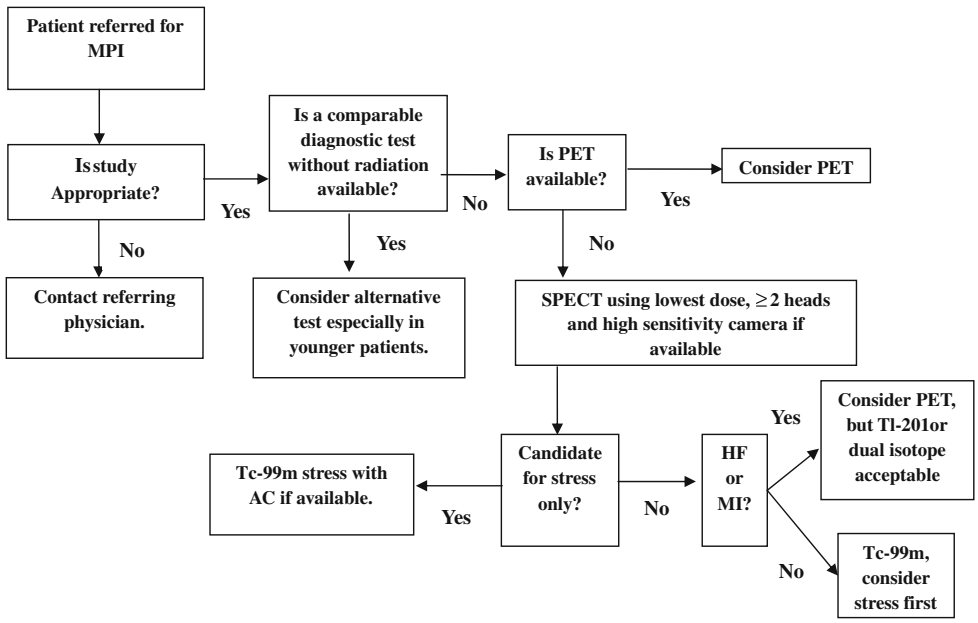

Figure 1. Proposed algorithm for maximal reduction in patient radiation exposure.

SUMMARY

Figure 1 illustrates the patient flow resulting from the above discussion. It is consistent with the concept of lowering the radiation dose while maintaining or improving image quality which should be considered an improvement in quality of care. The lower the radiation and the higher the image quality the greater the improvement in the quality of patient care. This approach combines the radiation reduction factors, which if implemented correctly, will provide the highest quality MPI studies at the lowest possible radiation dose. It must be recognized that such an approach requires moving away from the comfortable, familiar, time-tested, and efficient protocols adapted in most nuclear cardiology laboratories. It requires patient assessment at the time of scheduling, flexibility in patient flow as each patient will potentially go through a different protocol, and ultimately modifying existing imaging systems or purchasing new equipment.

Based on these recommendations, we expect that for the population of patients referred for SPECT or PET MPI, on average a total radiation exposure of ≤9 mSv can be achieved in 50% of studies by 2014.

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