Current Cardiology Diagnostic Modalities and Patient Dosimetry

COURSE BACKGROUND

Physicians today have many diagnostic modalities available to them to evaluate the heart, such as using radioactive materials, PET, PET/CT, CTA, and SPECT/CT. As each new modality is considered, questions on radiation safety and dosimetry limits are coming forth. How can we keep radiation exposure as low as reasonably achievable for the patient? Do the benefits always outweigh the risks involved? Which modality provides the most information at the least "risk" to the patient? This presentation will discuss these important issues for each imaging modality used to examine the heart. The discussion will highlight the levels of radiation exposure from currently used diagnostic modalities. A chart will show the advantages and disadvantages of each modality and its relative radiation dosimetry.

INTRODUCTION

Non-invasive imaging of the heart continues to evolve and improve. Several diagnostic medical modalities are frequently ordered in hospitals and clinics today. The decision when to use X-Ray, EKG(electrocardiogram), ETT (exercise tolerance test), Echocardiography, CT (CAT scan), Angiography (Cath Lab), Nuclear Medicine (SPECT), PET, or MRI is a challenge for the clinician. Each modality offers a different view into the patient's anatomy and physiology and each modality has its advantages and disadvantages. One modality may show anatomy while another shows perfusion and function. The clinician may choose to order one or more of these tests to provide a more comprehensive picture of the patient's health to predict the long-term and short-term outcomes for the patient.

It is general practice to begin a patient's cardiac work-up with an electrocardiogram and/or a chest X-ray.[1-3] Both of these tests may be ordered and performed in the physician's office. As the physician continues in exploration of the patient's cardiac condition, he/she may progress in the diagnostic algorithm. However as technology evolves and offers a different avenue toward patient management the key medical question remains: which test provides the most information with the least amount of patient risk?

The use of ionizing radiation still poses questions of risk to the medical community and to the public. The debate of how to limit radiation risk to the patient while performing imaging procedures is ongoingin the imaging community.
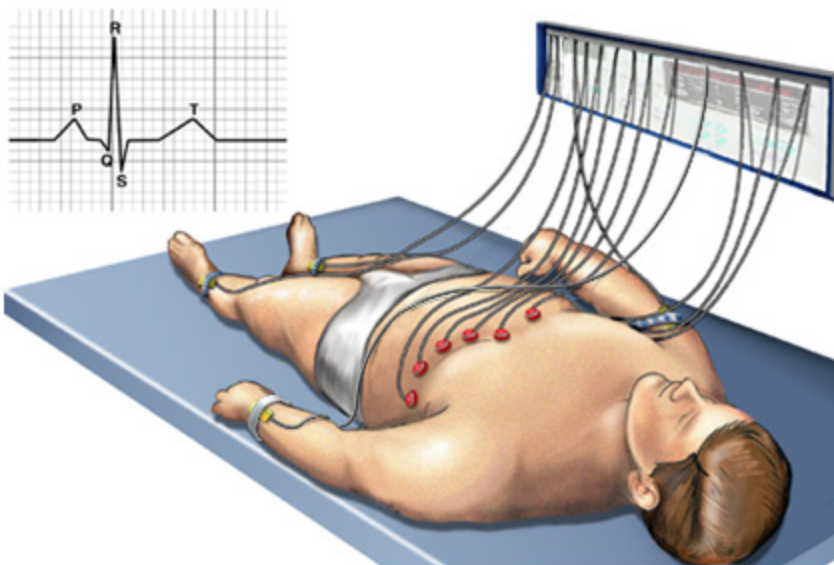
THE ELECTROCARDIOGRAM (EKG)

Figure 1.EKG electrode placement

Applications for the electrocardiogram include:

- To measure and diagnose heart rhythms
- To check the heart electrical activity
- To find the cause of unexplained chest pain
- To determine the effectiveness of mechanical devices implanted into the heart to establish a normal heart rate

The algorithm for exploring a cardiac issue may begin by examining the patient's cardiac rhythm. An electrocardiogram (EKG) may be ordered and performed by the requesting physician. Figure 1 demonstrates a 12-lead attachment for a resting EKG exam. This is the simplest cardiac exam; however, the information obtained may not answer all of the questions presented by the patient's signs and symptoms.[3]

Components of the Electrocardiogram (EKG)
An **electrocardiogram (EKG)** is a non-invasive recording via skin electrodes of the electrical activity of the heart over time produced by an electrocardiograph. Electrical impulses in the heart originate in the sinoatrial node and travel through the heart muscle where they impart electrical initiation of systole or contraction of the heart. The electrical waves can be measured at selectively placed electrodes (electrical contacts) on the skin.

Electrodes on different sides of the heart measure the activity of different parts of the heart muscle. As the cardiac muscle contracts an EKG detects and displays the voltage between pairs of electrodes or vectors. This display indicates the overall rhythm of the heart and weaknesses in different parts of the heart muscle. It is the best way to measure and diagnose abnormal rhythms of the heart. Often abnormal rhythms can be caused by damage to the conductive tissue that carries electrical signals, or by levels of dissolved salts (electrolytes), such as potassium, that are too high or low. In myocardial infarction (MI), the EKG can identify damaged heart muscle. However, it can only identify damage to muscle in certain areas, so it cannot rule out damage in other areas. The EKG is used in conjunction with the ETT to assess exercise-induced irregular heartbeats. The EKG cannot reliably measure the pumping ability of the heart; for which ultrasound-based (echocardiography) or nuclear medicine tests are used. No ionizing radiation is used to produce an EKG study.

To determine if the patient can safely begin a home exercise program or to understand why the patient has shortness of breath while climbing stairs, the physician may next order an exercise tolerance test or ETT. The ETT using the Bruce protocol is the standard that incorporates the Duke treadmill score which gives the physician a good predictor of coronary heart disease in a patient with chest pain symptoms.

A Duke treatment score ≥ 5 indicates low risk for cardiovascular events and the patient does not need further investigation with coronary angiography(predicted 4 year survival is 99%). A score ≤ -10 indicates high risk for cardiovascular events and the patient requires further investigation with coronary angiography (predicted4 year survival is 79%). A score between 5 and -10 indicates intermediate risk and such patients may require further investigation with myocardial perfusion scanning or coronary angiography, or both, depending on the pretest probability.

EXERCISE TOLERANCE TEST (ETT)

Figure 2. Patient performing ETT www.radiologyinfo.org

Applications for the Exercise Tolerance Test include:

- Evaluate unexplained shortness of breath.
- Evaluate blood pressure response to exercise.
- Look for exercise-induced serious irregular heart beats.
- Evaluate patients with signs or symptoms suggestive of coronary heart disease.
- Evaluate patients with significant risk for coronary heart disease.

Components of the Exercise Tolerance Test (ETT)
The patient is asked to wear comfortable clothing and shoes for the ETT. Electrodes from the EKG machine are attached to the chest. The patient will walk slowly on the treadmill according to a prescribed protocol, such as a Bruce or modified Bruce protocol. These prescribed protocols will increase the speed and increase the incline of the treadmill at periodic intervals. The duration a patient can sustain following the protocol provides the physician with information concerning the health of the patient's heart.

If a patient is able to achieve the target heart rate, an ETT is capable of diagnosing coronary disease in approximately 67% or two-thirds of patients with coronary artery disease. The accuracy is lower (about 50%) when patients have narrowing in a single coronary artery or higher (greater than 80%) when all three major arteries are involved. Approximately 10% of patients may have a "false-positive" test (when the result is falsely abnormal in a patient without coronary artery disease). The physician may then refer the patient for further testing in echocardiology or nuclear medicine to determine coronary perfusion.

Before the patient is referred for a perfusion exam, the physician may also wish to examine some anatomical structures in the patient's chest. Does the patient have an enlarged heart? Is there fluid in the lungs or in the pericardium? The best tool to answer these questions is the chest X-ray. This is the first of several diagnostic imaging exams in which the patient is exposed to ionizing radiation.

THE CHEST X-RAY (RADIOGRAPHY)

Figure 3. Chest X-Ray (www.Wikipedia.com)

Applications for the Chest X-ray include:

- To determine size of the heart
- To determine if fluid is in the lungs (congestive heart failure)
- To rule out pneumonia
- To determine if fluid is around the heart (pericardial effusion)

Components of the Chest X-Ray Examination

As an x-ray tube beams x-rays at the patient's chest, film on the other side of the patient records the x-rays that pass through the patient's body. The x-rays are absorbed more by denser tissue such as bone, which appears white and less by soft tissue which appears black. This provides contrast and tissue differentiation. The patient is exposed to this penetrating radiation as long as the x-ray machine is on and beaming at the patient. When displayed, the pictures only show the patient's anatomy.

The radiation dose is limited to the number of repeated images taken, intensity (KeV) of the beam calibration of the x-ray machine and the expertise of the radiographer. A chest X-ray carries a dose of approximately 0.02to 0.2 mSv (miliSievert) compared to natural background radiation exposure which is approximately 0.01 mSv/day.

Because the chest x-ray is often the patient's first diagnostic imaging exam using ionizing radiation, the radiation dose received during a chest x-ray has become the unit with which to compare other exams.[4]

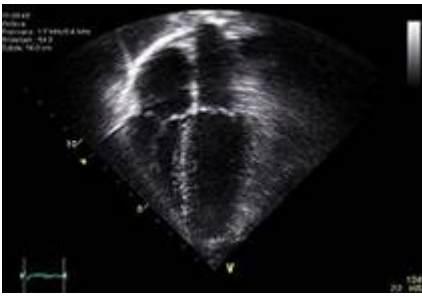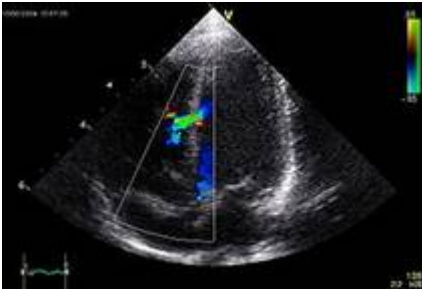**ECHOCARDIOGRAPHY (ULTRASOUND OF THE HEART)**

Figure 4: *Echocardiogram*

Figure 5: *Abnormal echocardiogram*

Some applications for the echocardiogram are:

- To evaluate all four chambers of the heart
- To determine the condition of heart valves
- To determine the strength of the heart muscle
- To detect enlargement of the heart
- To assess the lining of the heart (pericardium) and the aorta

Echocardiography uses sound waves to examine blood flow without exposing the patient to ionizing radiation. New digital echocardiography machines that useharmonics, bubble technology and color have greatly improved the quality and dependability of information gained from the echocardiogram.

An echocardiogram sometimes referred to as a cardiac ECHO or simply as an ECHO, is a sonogram of the heart. A cardiac ultrasound uses standard ultrasound techniques to image two-dimensional slices of the heart. The latest ultrasound systems employ 3D real-time imaging. In addition to creating two-dimensional pictures of the cardiovascular system, an echocardiogram can also produce accurate assessment of the velocity of blood and cardiac tissue at any arbitrary point using pulsed or continuous wave Doppler ultrasound. This allows assessment of cardiac valve areas and function, any abnormal communications between the left and right side of the heart, any leaking of blood through the valves (valvular regurgitation), and calculation of the cardiac output as well as the ejection fraction.[2-4]

The echo (ultrasound) examination may be ordered directly after the ECG or ETT in seeking new information about the patient's coronary arteries.

Components of the Echocardiogram Examination

A standard echocardiogram (resting state) is referred to as a transthoracic echocardiogram (TTE), or cardiac ultrasound. The echocardiography transducer (or probe) is placed on the chest wall (thorax) of the patient, and images are taken through the chest wall. This is a non-invasive, highly accurate and quick assessment of the overall health of the heart. The cardiologist can quickly assess a patient`s heart valves and degree of heart muscle contraction (an indicator of the ejection fraction). The images are displayed on a monitor and are recorded either by videotape (analog) or by digital techniques. The sonographer (echo technician) is the key to the quality of the resultant images. No radiation is applied to the patient or used in producing the images.

However, to produce quality images, several parameters must be considered:

- Selecting the appropriate transducer
- Adjusting the controls on the imaging unit
- Using the best technique
- Addition of a contrast agent, if necessary

The stress echo and dobutamine stress echo are ultrasound studies of the patient's heart muscle, heart valves and pericardium to determine how well the heart is working during exercise. During a stress echocardiogram, the patient walks a treadmill to increase the heart rate as in a standard ETT. Dobutamine stress echocardiograms are for patients who cannot exercise on a treadmill. Dobutamine is the stress agent pharmaceutical that makes the patient's heart beat faster and stronger while lying on the exam table.
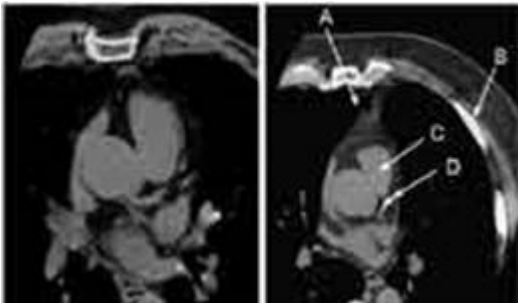
COMPUTERIZED TOMOGRAPHY (CARDIAC CT)

Figure 6: *Cardiac CT coronary plaque*

Applications for the computerized tomography (CT) exam include:

- To take detailed X-ray pictures of structures of the body (e.g. chest area to examine lungs, heart or aorta)
- To guide a needle during biopsy
- To stage cancer progression
- To calculate calcium deposit in heart structures (CT Angiography or CTA)

The measurement of coronary plaque has become another predictor of coronary heart disease and risk of myocardial infarct. Calcified plaque deposits in a patient's coronary arteries may become unstable (vulnerable plaque) and break off. Assessing vulnerable plaque has become a driving quest for the cardiologist and imagers.[4]Cardiac CT

This exam is a non-invasive test to evaluate coronary calcium or plaque. The cardiac CT determines the presence, location and extent of calcified plaque in coronary arteries. The patient is supine on the imaging table, while the electrodes of the EKG are applied to the chest. The table is slowly positioned into the field of the CT (x-ray). The patient is asked to be very still during the exam and may be asked to hold their breath for one 20-30 second period during the transmission scan. This breath hold technique is performed to compensate for the movement and position of the

diaphragm. Some newer CT machines may be able to perform the exam so quickly the breath hold step may be eliminated.[4, 16]

The use of calcium scoring is gradually becoming accepted as a diagnostic tool in coronary artery disease imaging; however, it is gaining greater acceptance as a predictor of coronary artery disease (CAD). Table 1 below shows the relationship of an increased reading of coronary calcium to the predictive value of coronary artery disease.

Score	CAD Finding
0	No evidence of CAD
1-10	Minimal evidence of CAD
11-100	Mild evidence of CAD
101-400	Moderate evidence of CAD
Over 400	Extensive evidence of CAD

Table 1. Calcium scores for presence of CAD[5]

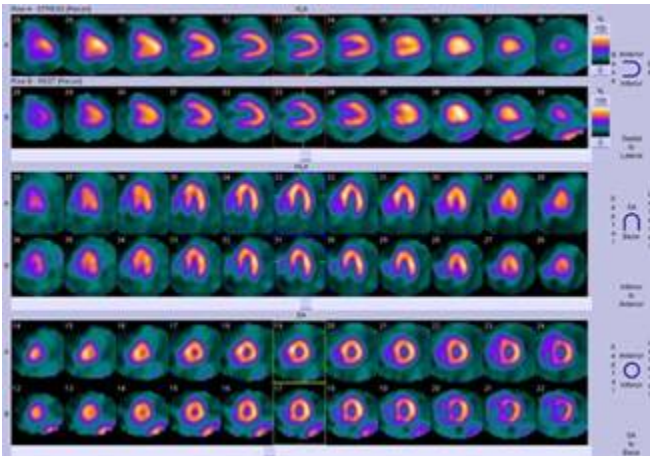**NUCLEAR CARDIOLOGY – MYOCARDIAL PERFUSION STUDY (MPS)**

Figure7: Rest/Stress MPS images www.radiologyinfo.org

Applications for the Myocardial Perfusion Study include:

- To measure blood flow of the heart muscle during rest and stress
- To determine the extent of a coronary artery blockage
- To determine the extent of damage to the heart muscle after a heart attack
- To determine the cause of chest pain (angina)
- To determine the safe level of exercise for a patient post-coronary event
- To determine the effectiveness of intervention provided to a patient to improve coronary circulation

The nuclear myocardial perfusion study may be the one exam that can answer many questions in a single test. The MPS provides images that depict coronary blood flow and highlight areas of decreased distribution as blockages. This exam can be performed with several different radioactive isotopes.

Myocardial perfusion imaging began by exploring the use of potassium (K+) analog agents. The first Food & Drug Administration (FDA) approved radiopharmaceutical for MPS was thallous (Tl-201) chloride. Thallous-201 chloride is still in use currently as a resting radiopharmaceutical agent and as an agent to determine myocardial viability.

With the advent of newer gamma cameras, technetium-99m has become the isotope of choice to decrease the imaging time for rest and stress exams.[11]

The nuclear cardiologist and radiologist can now choose from a menu of nuclear imaging protocols using one, two or a combination of several radiopharmaceuticals. Table 2 below lists several of the available radiopharmaceuticals used in nuclear cardiology. The dosimetry levels of these radiopharmaceuticals vary depending upon the dosage ranges used. Following the manufacturer's package insert (PI) only offers a starting point for calculating the radioactive effective dose to the patient. The information listed in the PI is Phase III study data performed on the radiopharmaceutical when it was first introduced. Since then the nuclear cardiology community, by common and best practices, has increased minimum doses for many reasons that include patients' increased body habitus and camera dynamics.

Drug	T ½	Energy Level
Thallium 201 Chloride	73 hours	66-80 KeV
Tc-99m (sestamibi or tetrofosmin)	6 hours	140 KeV
Rb-82 chloride	75 seconds	511 KeV
F-18 FDG	110 minutes	511 KeV

Table 2. Radiopharmaceuticals for nuclear cardiology[8-11]

The determination of the myocardial viability in the CAD patient provides the cardiologist with vital information, which will lead to better patient management. Thallium-201 and single photon emission computer tomography (SPECT) imaging have been major tools in the determination of myocardial viability for a number of years. However, the low photon energy of thallium-201, (66-80 KeV) has significant limitations in the quality of the images using standard gamma cameras.

Imaging cameras have greatly improved over the past 5 -10 years, allowing nuclear medicine to incorporate β⁻ emitting and high-energy gamma emitting isotopes as imaging agents. Positron emission tomography (PET) for cardiac imaging is well validated to assess myocardial perfusion, left ventricular function and viability. The use of Rb-82 chloride and F-18 labeled radiopharmaceuticals in PET has been both advantageous and problematic.[10,14-15]

Cardiac PET imaging opened a new frontier for nuclear medicine. The ability to detect CAD and lesions not seen in SPECT and to provide better myocardial viability information has made cardiac PET vital in the cardiologist's diagnostic toolbox. The higher energy levels of the PET agents have been offset by the shorter physical half-life.

Components of the MPS

There are many approaches to performing the nuclear cardiac exam. The standard format is to perform the study first in a rest state, then repeat the process after a form of exercise or stress to the patient. This means the patient will be exposed to radiation twice.

The nuclear cardiac study begins with the patient entering the department without taking any cardiac medicines or caffeine for 12-24 hours per physician's orders. Most laboratories also have the patient in a fasting state 4-6 hours prior to testing.[1] The exam may then proceed using one of several protocols using various radiopharmaceuticals.

Each protocol listed in Table 3 below offers advantages in diagnostic imaging for the interpreting physician[1-3]. No imaging protocol is perfect, especially if the resultant images show excessive motion and artifacts. Many techniques have been used to compensate for both of these troublesome issues. The use of transmission imaging using isotopes or CT x-rays has helped eliminate some of the impact from both patient motion and other attenuation artifacts. However,

the addition of attenuation correction techniques using either of these methods adds more exposure to the patient. These additional exposures must be included in the patient's risk assessment.[6-7,13]

	Rest	Stress
Dual Isotope Imaging:	Thallium-201	Tc-99m (sestamibi or tetrofosmin)
Dose:	2-4 mCi	25-35 mCi
Single Isotope Imaging:	Tc-99m (sestamibi or tetrofosmin)	Tc-99m (sestamibi or tetrofosmin)
Dose:	8-15 mCi	25-35 mCi
2 Day protocol	Tc-99m (sestamibi or tetrofosmin	Tc-99m (sestamibi or tetrofosmin
Dose	25-35 mCi	25-35 mCi
Rb-82	40-60 mCI	40-60 mCi
F-18 FDG	5-15 mCi *Viability study*	

Table 3. MPS imaging protocols [8-11]

Images created using transmission imaging improve interpretation by fusing anatomy of x-ray derived images with perfusion and functional images of PET or SPECT. [14-15]

During the actual acquisition of a cardiac study using hybrid imaging, whether SPECT/CT or PET/CT, the patient is exposed externally to the x-ray from the CT and internally from the injected radiopharmaceutical. The patient's effective dose of radiation must be calculated as a result of both occurrences. If using CT as the transmission technique, a "scout scan" is initiated to ascertain correct positioning. Each sweep of the patient into the field of ionizing radiation increases the cumulative exposure.

Modality	Effective Radiation Dose (mSv)	Chest X-Ray Equivalents	Approx. Period of natural Background yrs.
Electrocardiogram	0	0	0
Exercise Treadmill Test (ETT)	0	0	0
Chest X-Ray	0.02	1	3 days
Stress Echo	0	0	0
Angiogram	2.1-7	105-350	0.9-2.9
Cardiac CTCA-16 slice	6.5-10.7	325-635	2.7-4.4
Dual Isotope Exam	26.5-43.9	1275-2145	10.7-14.7
Single Isotope-1 day	12.75-23	850-890	5.2-6.2
PET w/ Rb-82	10-15	600-750	4-6.2
PET w/ F-18	7-10	350-600	3.1-4
+ CT 4-slice	2-10	100-600	1.8-4
+ CT 16-slice	7-18	350-900	3-8

Table 4. Effective Dose for Cardiac Diagnostic Modalities (estimates) [7]

Because dosimetry calculations use many variables they can only provide estimated effective ranges. Body sizes, length of scanning times, and actual administered dosages all contribute to the calculations. However, the clinician will continue the use of hybrid imaging systems to acquire the best quality and most accurate imagine of a patient's study without artifacts of motion and attenuation. The decision to send a patient on for the "next" imaging test using ionizing radiation is now a more deliberate one. Table 4 listed above demonstrates the wide variability of radiation dose from several imaging modalities using ionizing radiation. Even a limited observation can result in very high exposure for certain diagnostic tests.

VALUE OF DIAGNOSTIC CARDIAC EXAMS

Once the patient presents with signs and symptoms of suspected coronary artery disease, steps are taken that will lead to an accurate diagnosis and ultimate treatment. Information acquired from the patient`s history, physical examination, ECG, echocardiogram and stress test enable adequate evaluation of the degree of left ventricular dysfunction and the extent of angina and ischemia.[16]

The interpretation of these various diagnostic exams may indicate the need for the patient to have an invasive test, a cardiac catheterization or angiogram performed. The angiogram has been stated to be the "Gold Standard" of cardiac imaging for coronary artery disease. In patients undergoing cardiac catheterization, once the number and severity of diseased vessels are known, the optimal treatment can be determined.

ANGIOGRAPHY (CATH LAB)

Figure 10. Angiogram (www.wikopedia.com)

Applications for the angiogram include:

- To localize lesions in coronary arteries
- To diagnose blockages of the arteries outside the heart - peripheral artery disease (PAD)
- To diagnose enlargements of the arteries - aneurysms
- To diagnose problems in the arteries that branch off the aorta - aortic arch conditions
- To diagnose malformed arteries - vascular malformations
- To examine problems with your veins, such as deep venous thrombosis (DVT) or blood clots in the lungs called pulmonary emboli
- To direct placement of intracoronary stents

Components of the Angiogram Examination

During an angiogram the radiologist threads a thin flexible catheter into the desired artery or vein from an access point. The access point is usually in the groin but it can also be in the arm or, less commonly, a blood vessel in another location. To create the x-ray images, the radiologist will inject contrast media through the catheter. The contrast makes the blood inside the blood vessels visible on an x-ray. The contrast media is eliminated from the body through the kidneys and urine.

For guidance regarding catheter position during the examination, the physician relies on a detailed knowledge of internal anatomy, guide wire and catheter behavior. Intermittently, fluoroscopy and low x-ray dose are used as an aide in visualization. This is done by activating the equipment to apply a significantly higher x-ray dose (cine) to the patient. This creates better quality motion picture images, with sharper radio density contrast, captured at typically 30 frames per second. The physician controls the contrast injection, fluoroscopy and cine application timing to minimize the total amount of injected contrast media and the total amount of x-ray used. Dosages of contrast media and x-ray exposure times are routinely recorded in an effort to maximize safety.

Radiation doses to the patient depend greatly on the size of the patient as well as length of the procedure, with typical skin dose rates quoted as 20-50 mGy/min. Exposure times vary depending on the procedure being performed, but procedure times up to 75 minutes have been documented.[2-3]

CONCLUSION

Exposure to ionizing radiation during medical procedures is a small but real risk. These levels should be kept as low as reasonably possible while providing the needed clinical information. Single isotope protocols using Tc-99m agents or PET agents appear to be associated with the lowest amount of effective dose. Introduction of the newer fast imaging cameras also allow for the administered dosage of radiopharmaceuticals to be decreased.

AUTHOR INFORMATION AND DISCLAIMER

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The author has over 35 years of experience in Nuclear Medicine with the last 20 years devoted to nuclear cardiology. She has served as a Clinical Specialist, an independent ICANL consultant and currently assists cardiology facilities to achieve accreditation. She holds certifications in the NMTCB and Radiopharmacy Technology. She is an active member of the Society of Nuclear Medicine and is a Fellow of the Society of Nuclear Medicine, Technologist Section.

The author is currently employed by Cardinal Health, Nuclear Pharmacy Services.

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