
A Report of the American College of Cardiology Task Force on Expert Consensus Decision Pathways

Developed in Collaboration With Mended Hearts

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**Formerly named ACC Task Force on Clinical Expert Consensus Documents.**

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ABSTRACT

The stimulus to create this document was the recognition that ionizing radiation-guided cardiovascular procedures are being performed with increasing frequency, leading to greater patient radiation exposure and, potentially, to greater exposure to clinical personnel. While the clinical benefit of these procedures is substantial, there is concern about the implications of medical radiation exposure. ACC leadership concluded that it is important to provide practitioners with an educational resource that assembles and interprets the current radiation knowledge base relevant to cardiovascular procedures. By applying this knowledge base, cardiovascular practitioners will be able to select procedures optimally, and minimize radiation exposure to patients and to clinical personnel.

“Optimal Use of Ionizing Radiation in Cardiovascular Imaging – Best Practices for Safety and Effectiveness” is a comprehensive overview of ionizing radiation use in cardiovascular procedures and is published online. To provide the most value to our members, we divided the print version of this document into 2 focused parts. “Part I: Radiation Physics and Radiation Biology” addresses radiation physics, dosimetry and detrimental biologic effects. “Part II: Radiologic Equipment Operation, Dose-Sparing Methodologies, Patient and Medical Personnel Protection” covers the basics of operation and radiation delivery for the 3 cardiovascular imaging modalities (x-ray fluoroscopy, x-ray computed tomography, and nuclear scintigraphy). For each modality, it includes the determinants of radiation exposure and techniques to minimize exposure to both patients and to medical personnel.

PREAMBLE

This document has been developed as an Expert Consensus Document by the American College of Cardiology (ACC) in collaboration with the American Society of Nuclear Cardiology, Heart Rhythm Society, Mended Hearts, North American Society for Cardiovascular Imaging, Society for Cardiovascular Angiography and Interventions, Society for Cardiovascular Computed Tomography, and Society of Nuclear Medicine and Molecular Imaging. Expert Consensus Documents are intended to inform practitioners, payers, and other interested parties of the opinion of ACC and document cosponsors concerning evolving areas of clinical practice and/or
technologies that are widely available or new to the practice community. Topics chosen for coverage by expert consensus documents are so designed because the evidence base, the experience with technology, and/or clinical practice are not considered sufficiently well developed to be evaluated by the formal ACC/American Heart Association practice guidelines process. Often the topic is the subject of considerable ongoing investigation. Thus, the reader should view the Expert Consensus Document as the best attempt of the ACC and document cosponsors to inform and guide clinical practice in areas where rigorous evidence may not yet be available or evidence to date is not widely applied to clinical practice.

To avoid actual, potential, or perceived conflicts of interest that may arise as a result of industry relationships or personal interests among the writing committee, all members of the writing committee, as well as peer reviewers of the document, are asked to disclose all current healthcare-related relationships, including those existing 12 months before initiation of the writing effort. The ACC Task Force on Expert Consensus Decision Pathways (formerly the ACC Task Force on Clinical Expert Consensus Documents) reviews these disclosures to determine which companies make products (on market or in development) that pertain to the document under development. Based on this information, a writing committee is formed to include a majority of members with no relevant relationships with industry (RWI), led by a chair with no relevant RWI. Authors with relevant RWI are not permitted to draft or vote on text or recommendations pertaining to their RWI. RWI is reviewed on all conference calls and updated as changes occur. Author and peer reviewer RWI pertinent to this document are disclosed in Appendixes A and B, respectively. Additionally, to ensure complete transparency, authors’ comprehensive disclosure information— including RWI not pertinent to this document—is available online (see Online Appendix). Disclosure information for the ACC Task Force on Clinical Expert Consensus Documents is also available online, as is the ACC disclosure policy for document development.

The work of the writing committee was supported exclusively by the ACC without commercial support. Writing committee members volunteered their time to this effort. Conference calls of the writing committee were confidential and attended only by committee members and ACC staff.

James L. Januzzi, MD, FACC
Chair, ACC Task Force on Clinical Expert Consensus Documents

1. INTRODUCTION

1.1. Document Development Process and Methodology

1.1.1. Writing Committee Organization

The writing committee consisted of a broad range of members representing 9 societies and the following areas of expertise: interventional cardiology, general cardiology, pediatric cardiology, nuclear cardiology, nuclear medicine, electrophysiology, cardiac computed tomography (CT), cardiovascular imaging, and the consumer patient perspective. Both a radiation safety biologist and physicist were included on the writing committee.

This writing committee met the College’s disclosure requirements for RWI as described in the Preamble.

1.1.2. Document Development and Approval

The Writing Committee convened by conference call and e-mail to finalize the document outline, develop the initial draft, revise the draft per committee feedback, and ultimately approve the document for external peer review. All participating organizations participated in peer review, resulting in 21 individual reviewers submitting 299 comments. Comments were reviewed and addressed by the writing committee. A member of the ACC Task Force on Expert Consensus Decision Pathways served as lead reviewer to ensure that all comments were addressed adequately. Both the writing committee and the task force approved the final document to be sent to the ACC Clinical Policy Approval Committee. This committee reviewed the document, including all peer review comments and writing committee responses, and approved the document in November 2017. The Heart Rhythm Society, North American Society for Cardiovascular Imaging, Society for Cardiovascular Angiography and Interventions, and Society of Cardiovascular Computed Tomography endorsed the document in January 2018. This document is considered current until the Task Force on Expert Consensus Decision Pathways revises or withdraws it from publication.

2. PURPOSE

This print-published document is part 2 of an abbreviated version of a larger, more comprehensive document that is published concurrently online. The online version contains additional technical detail for readers who wish to understand a topic in greater depth. The online published document, in addition to covering the topics in the 2 print-published documents in greater depth, also covers additional topics not covered in the print-published documents including 1) dose reduction strategies; 2) operator education and certification; 3) quality assurance; and 4) patient radiation tracking.
This document covers equipment operation for the 3 cardiovascular procedure classes that employ ionizing radiation: x-ray fluoroscopy, x-ray CT, and radionuclide scintigraphy. For the 3 modalities, it includes discussions of radiation delivery and strategies to minimize dose both to patients and to occupationally exposed medical personnel. In addition, it covers issues of quality assurance, radiation monitoring, and tracking.

The document’s purpose is to provide a comprehensive information source about ionizing radiation use in cardiovascular procedures. The writing group has assembled this information to assist cardiovascular practitioners to provide optimal cardiovascular care when employing ionizing radiation-based procedures. The goal is to enhance cardiovascular practitioners’ ability to select the optimal imaging technique for a given clinical circumstance, balancing a technique’s risk and benefits, and to apply that technique optimally to generate high-quality diagnostic images of greatest clinical value and minimal radiation exposure.

3. MODALITY-SPECIFIC RADIATION EXPOSURE DELIVERY

3.1. General Principles

3.1.1. Characteristics of Medical Diagnostic Radiation

For all 3 imaging modalities (x-ray fluoroscopy, x-ray CT, and nuclear scintigraphy), 95% to 99% of radiation energy that enters or is released within the subject is either absorbed or scattered within the subject. The remaining 1% to 5% of the incident x-ray penetrates the subject reaching the image detector to form the image.

3.1.2. Tools Used to Estimate Absorbed Dose

Estimates of absorbed dose for x-ray fluoroscopy and x-ray CT are based on models developed by exposing instrumented phantoms to incident x-ray beams that replicate the beams used in diagnostic imaging and measuring absorbed dose at different points within the phantom. Estimating absorbed dose from radionuclides is an entirely different discipline that is discussed in Section 4.4 of “Part I: Radiation Physics and Radiation Biology”.

3.2. X-Ray Fluoroscopy

3.2.1. X-Ray Fluoroscopy Subject and Operator Exposure Issues

X-ray fluoroscopy differs from other ionizing radiation imaging techniques in that the beam entrance port is relatively small. Consequently, the skin at the beam entrance port is the most intensely exposed tissue. Subject skin doses can reach levels that cause skin tissue reactions. X-ray photons are also scattered within the subject. These deliver dose to subject tissues outside of the imaging field (Figure 1). Scattered photons that exit the subject can expose nearby medical personnel (Figure 2). Consequently, assessment of the implications of subject exposure from x-ray fluoroscopy must consider entrance port skin dose, which is the dose received by internal structures within the imaging field and by other internal structures outside of the imaging field.

![Diagrammatic Representation of an X-Ray Fluoroscopy System to Illustrate X-Ray Exposure Modality](image-url)

The primary beam, collimated to a rectangular cross section, enters the patient, typically through the patient's back. It is attenuated and scattered within the imaging field. The primary beam exposes the subject within the imaging field. The scattered primary beam radiation can expose structures within the subject that are remote from the imaging field.
3.2.2. Basics of Operation of an X-Ray Cinefluorographic Unit

An x-ray cinefluorographic unit generates controlled x-rays in an x-ray tube that are collimated to regulate the size and shape of the beam. The beam passes through the subject forming images that are detected by a flat panel detector (Figure 1). The x-ray tube output (and accordingly the exposure to the subject) is modulated by feedback circuitry from the unit’s imaging chain to achieve an optimally exposed image.

X-Ray Cinefluorographic Unit Operating Parameters

There are multiple imaging parameters that influence the x-ray exposure associated with an x-ray cinefluorographic examination. These are:

1. X-ray image detector dose per pulse. The dose for each x-ray pulse (typically measured in nanogray [nGy]) that reaches the x-ray system detector. This parameter is set by the x-ray unit calibration. It determines image clarity and detail.

2. X-ray unit framing (pulsing) rate. The number of pulses that the x-ray system generates per unit time. This is an operator-selectable parameter that generally ranges between 4 and 30 pulses/s. It determines image temporal resolution.

3. Imaging field size. The area of the x-ray beam that impinges on the subject.

4. X-ray beam filtration. An x-ray tube produces a spectrum of x-ray photon energies. Photon energies <30 kiloelectron volts (keV) do not have sufficient penetrating power to reach the detector and, accordingly, expose the patient without contributing to image formation. Layers of aluminum and copper in the x-ray tube exit port filter out these “undesirable” photons.

3.2.3. Measures and Determinants of Subject and Operator Exposure

There are 2 different x-ray fluoroscopic system parameters (described in detail in Section 4.4.1 of Part 1) that characterize x-ray exposure and dose:

1) Cumulative air kerma at the interventional reference point. Kerma is an acronym for “kinetic energy released in material.”

2) Cumulative kerma-area product (KAP).

Cumulative Air Kerma at the Interventional Reference Point

A procedure’s cumulative air kerma at the interventional reference point is a more meaningful measure of subject exposure than the total fluoroscopic time, which does not account for selected detector dose, subject density, cine acquisition time, or changes in frame rate and angulation.

X-ray exposure to the subject is not uniform. As an x-ray beam passes through a subject, tissue absorption attenuates it. Tissue closer to the beam entrance port receives a larger dose than deeper-lying tissue (Figure 3). Tissue at the beam exit port receives the smallest dose. The magnitude of exposure from scattering to organs outside the x-ray beam area is considerably less than to
tissue within the imaging area, but is not negligible (Figure 1).

**Kerma-Area Product**

KAP, the product of air kerma output and image field size, is commonly used as a metric to estimate a subject’s total absorbed dose. It incorporates both dose intensity and exposed tissue volume into a single measurement. KAP is also directly related to the quantity of scattered radiation that leaves the subject’s body and, accordingly, to the magnitude of exposure to nearby medical personnel (Figure 2).

KAP is expressed in units of Gy·cm². It is calculated by multiplying the beam air kerma by its cross-sectional area. Some x-ray system manufacturers report KAP in units of μGy·m⁻² (1 Gy·cm² = 100 μGy·m⁻²). It should also be noted that air kerma and KAP represent cumulative doses from an exposure, not exposure rates.

**Application of KAP in Cardiovascular X-Ray Fluoroscopy to Estimates of Effective Dose to Medical Personnel**

The most commonly used estimate of the relationship between KAP exposure to the thorax in Gy·cm² and effective dose in Sieverts (Sv) is 0.20 mSv/Gy·cm² (1). By this estimate, a combination coronary arteriography and percutaneous coronary intervention that delivers a KAP exposure of 50 Gy·cm² would impart an effective dose to the subject of 10 mSv.

**3.2.4. Measures and Determinants of Physician Operator and Healthcare Worker Occupational Exposure**

**Application of KAP in Cardiovascular X-Ray Fluoroscopy**

Medical personnel who conduct x-ray fluoroscopic procedures are exposed by scattered radiation (Figure 2). The cumulative quantity of scattered radiation is directly related to the procedure’s cumulative KAP.

The quantity of scattered radiation that reaches and delivers dose to medical personnel is determined by:

1. The distance of the exposed medical personnel from the x-ray source—scattered x-ray intensity decreases proportionately to the square of the distance from the source.
2. The effectiveness of shielding employed by the exposed medical personnel.

**Physician and Medical Personnel Exposure Monitoring**

Estimates of radiation dose to exposed medical personnel are based on measurements made by personal radiation monitors (formerly known as “film badges”). The outside badge mounted at collar level outside protective garments measures the dose that reaches unshielded structures of the head. A badge worn underneath protective garments measures the dose that penetrates the protective apron reaching the subject. These measure total exposure in mGy. The personal radiation monitor readings are converted using an algorithm to estimate effective dose to the subject in mSv (2–5). The details of these measurements and calculations are included in the full version of this document published online.

**Exposure Levels for Operating Physicians**

Most studies of operating physician dosimetry find a range of 0.02 to 0.12 μSv/Gy·cm² KAP for the procedure with typical values clustering about 0.1 μSv/Gy·cm² (6,7). (Note that the estimated patient exposure is 200 μSv/Gy·cm², indicating that operator exposure is roughly 1/2,000 of patient exposure.) Applying these values, a “typical” combined coronary arteriogram and straight-forward coronary interventional procedure utilizing a cumulative KAP of 50 Gy·cm² would deliver a 5-μSv effective dose to the physician operator standing roughly 1 m from the center of the primary beam while delivering 10 mSv to the patient.

Special considerations for occupationally exposed workers who are pregnant or may become pregnant are discussed in Section 4.2 of this document and in greater detail in section 5.4.4 of “Part I: Radiation Physics and Radiation Biology” and in the longer, online-published version of this document.
3.3. X-Ray CT

3.3.1. X-Ray CT Subject and Operator Dose Issues

Although x-ray CT, like x-ray fluoroscopy, is an external beam exposure technique, unlike x-ray fluoroscopy the incident beam is distributed circumferentially around the subject. Consequently, x-ray CT subject skin doses should never approach levels that could cause skin injury, and subject-harm issues should be confined to stochastic risk. The dose delivered by an x-ray CT examination is not uniform, delivering greater dose to more superficial locations compared with deeper locations closer to the exposed volume center.

3.3.2. Basics of Operation of an X-Ray CT Unit

The dose delivered by an x-ray CT examination can vary substantially depending on patient characteristics and the settings of multiple scanner operating parameters. Configurable CT technique parameters that can affect dose include x-ray tube potential (measured in kV), x-ray tube current (measured in milliamperes [mA]), scan protocol (e.g., axial or helical), pitch, gating protocol, scan rotation time, beam width, scan length, and beam filtration.

Image quality is affected by imaging parameter selection. This selection involves a conscious balancing of image quality and dose. Other parameter selections, such as gating protocol, do not necessarily affect image quality but do affect the amount of radiation used to acquire an image set.

Electrocardiographic gating, which can have a major impact on dose, is important in cardiovascular imaging to minimize motion artifact. There are 2 types of gating (Figure 4):

- **Retrospective gating** involves x-ray exposure continuously over the cardiac cycle. Because exposure occurs continuously, retrospective gating delivers greater exposure than prospective triggering.
- **Prospective triggering** involves synchronizing exposure to a selected portion of the cardiac cycle. The goal of prospective triggering is for exposure to occur only when cardiac motion is minimal.

3.3.3. X-Ray CT Measures of Subject Exposure

The dose delivered by an x-ray CT examination should be considered from 2 perspectives:

- **Dose Intensity**: Dose per unit mass of tissue. This is a measure of the intensity of the dose used to generate the images.
- **Volume of Tissue Exposed**: The total dose delivered to a subject is the product of the dose intensity and the volume of tissue exposed.

Although CT dose metrics are derived from the measurement of x-ray tube air kerma, in the CT lexicon, the term “dose” is widely used.

**CT Dose Index—A Measure of Dose Intensity**

Computed tomography dose index (CTDI) was first defined in 21 CFR 1020.33(c) as the average dose detected...
over a 100-mm scan length from an imaging acquisition of
14 slices. It is a measure of dose intensity, that is, the dose
imparted by a unit scan length.

**CTDIcon**

CTDIcon is a refinement of CTDI that standardizes all dose
index measurements to a scan length of 100 mm.

**Weighted CTDIcon**

The CTDIw or weighted CTDIcon, is an index developed to
approximate the average radiation dose delivered to a
cross section of a subject’s body, allowing for dose vari-
ation with depth.

**Volume CTDI**

CTDIcon is the weighted absorbed dose to air of a 1 cm
axial length of the examined subject located in the
middle section of a 100-mm length scan of an acrylic
cylinder for a specific CT technique. It accounts for both
the exposure directly delivered to the 1-cm thick slice
and the exposure to that slice by scatter from adjacent
imaged tissue.

**CTDIcon Special Considerations for Exposure in Children**

It is noteworthy that for identical techniques, smaller
subjects receive a higher dose than larger subjects. Esti-
mates of CTDIcon for body imaging made utilizing a 32-cm
thick phantom underestimate the dose received by
smaller individuals by a factor of 2.

**Size-Specific Dose Estimate**

Size-specific dose estimate is a normalization of CTDIcon
that takes into account subject size. Its incorporation into
practice is still to be determined.

**Dose-Length Product—A Measure of the Total Dose
Absorbed by the Subject**

Dose-length product (DLP) is the product of CTDIcon and
the axial scan length. It is a measure of total dose to the
subject and is analogous to KAP for x-ray fluoroscopy.
Accordingly, for x-ray CT, DLP is the best predictor of
stochastic risk.

**3.3.4. X-Ray CT Measures of Effective Dose**

For CT imaging, European Commission-sponsored
guidelines from 2000 (9) and 2004 (10) have suggested a
simple approximation of the effective dose that can be
obtained by multiplying the DLP by a conversion factor k
(unit: mSv·mGy⁻¹·cm⁻¹) that varies dependent on the
radiation sensitivity of different body regions and patient
ages. There are specified conversion factors for CT of the
head, neck, chest, abdomen, pelvis, and legs (11). The
most common conversion factor for adult chest CT is
0.014 mSv·mGy⁻¹·cm⁻¹ (12), with values for children
being greater. For CT examinations confined to the car-
diac region, estimated conversion factors are greater, with
an average value of 0.026 mSv·mGy⁻¹·cm⁻¹ (13-18).

**X-Ray CT Measures of Effective Dose in Children**

Pediatric CT dosimetry is complicated by the fact that
scanners and studies have variably used 32- or 16-cm
phantoms for the determination of DLP. For that reason,
when reporting CTDI or DLP in children, the phantom size
used should always be specified. In addition, in children,
sensitivity to a stochastic event varies substantially with
subject age. Consequently, in children, European guid-
elines for chest CT conversion factors (19), based on the 32-
cm phantom, range from 0.013 mSv·mGy⁻¹·cm⁻¹ (age 10
years) to 0.039 mSv·mGy⁻¹·cm⁻¹ (age 0 years). Only 2
studies using contemporary cardiac scanners have deter-
mined cardiac CT-specific conversion factors for children.
Normalized to the 32-cm phantom, conversion factors (20)
range from 0.092 to 0.099 mSv·mGy⁻¹·cm⁻¹ for age 1
year, 0.049 to 0.082 mSv·mGy⁻¹·cm⁻¹ for age 5 years,
(19) and 0.049 mSv·mGy⁻¹·cm⁻¹ for age 10 years.

**3.4. Patient and Medical Personnel Exposure in
Nuclear Cardiology**

**3.4.1. Patient Exposure in Nuclear Cardiology**

Unlike x-ray imaging, which principally exposes the
imaged structures, an injected radioactive tracer exposes
the entire body. Organs receiving the highest radiation
dose may not be the imaged structures. The patient’s
behavior after study completion can alter the rate of
radiopharmaceutical excretion, affecting the overall ra-
diation dose.

Estimating the effective dose from a radiopharmae-
tical exposure incorporates:

1. Quantity of radioactivity administered.
2. Radiopharmaceutical distribution within the subject.
3. Kinetics of distribution to and elimination from each
organ.
4. Radiosensitivity of each exposed organ.
5. Physical half-life of the radionuclide and its emitted
photon or particle energy.

Medical internal radiation dose is a commonly used
framework for estimating the radiation dose from radi-
opharmaceuticals. The medical internal radiation dose
method uses the radiopharmaceutical’s “effective” half-
life—the combination of radionuclide organ residence
times and physical decay rates—to estimate the total dose
(in mGy) received by each organ. These values are
multiplied by the individual organ radiation sensitivities
to yield the individual organ equivalent doses, which are
then summed to calculate the whole-body effective dose for
the subject in mSv.

Additional dose issues:

1. A renally excreted radiopharmaceutical will deliver a
radiation dose to the bladder wall. If the subject voids
infrequently, the dose to the bladder will be higher.
2. Radiopharmaceutical imaging studies, both positron
imaging (positron emission tomography [PET]) and
single-photon emission computed tomography
variables affecting personnel exposure: differences, compared with x-ray environments, in the proximity to radioactive patients. There are substantive handling radiopharmaceutical doses and from their Nuclear cardiology personnel receive exposure both from exposure is to perform a radiation-based procedure only The most effective way to reduce patient radiation 4.1.1. Case Selection Procedures.
The examination should be conducted such that the dose received by the patient and attendant medical personnel is the smallest necessary to yield satisfactory diagnostic efficacy. Core Principles for the Use of Medical Ionizing Radiation for Diagnostic and Therapeutic Procedures 2. Diagnostic and therapeutic efficacy should not be compromised in the interest of sparing radiation dose. 3. If the study’s purpose can be achieved employing a modality that does not employ ionizing radiation, serious consideration should be given to the alternative modality.

4.1.1. Case Selection

The most effective way to reduce patient radiation exposure is to perform a radiation-based procedure only when it is the preferred choice among alternative modalities that do not involve radiation exposure (e.g., stress echo or stress cardiac magnetic resonance). Appropriate use criteria should be applied to select patients to undergo diagnostic and therapeutic procedures. Although it is important always to seek to minimize patient radiation exposure (this is a particular consideration in younger patients who have long natural life expectancies), it is equally important to not withhold appropriate studies due to undue concern of the radiation-related risk.

4.1.2. Dose-Determining Variables

The radiation dose delivered to patients and medical personnel (regardless of modality) is affected by 3 variables that are under the operator’s control. These are:
1. Equipment quality and calibration
2. Equipment operating protocols
3. Operator conduct

As each of these variables influences the dose delivered to the patient (and also, potentially to operating medical personnel), each provides an opportunity to reduce dose.

4.1.3. Image Quality Issues

Image quality is a major determinant of an examination’s diagnostic accuracy. Inadequate image quality may cause either incorrect diagnoses or a need to repeat an examination—requiring additional patient exposure. Consequently, it is imperative that radiological equipment meet current image quality standards, be maintained in prime working order, and are operated properly to produce high-quality diagnostic images.

Radiological image quality is strongly influenced by the detector dose—the quantity of radiation that reaches the image detector. Overall image quality is determined by spatial and temporal resolution, the signal-to-noise ratio, the contrast-to-noise ratio, and presence of imaging artifacts. Most tactics that increase either spatial resolution (by improving signal-to-noise ratio and contrast-to-noise ratio) or temporal resolution (by increasing framing rate) do so at the cost of increased dose. The challenge is to optimize these properties by balancing the tradeoffs between dose and image quality. There are circumstances in which the “best” image that the system can deliver is better than needed for diagnosis. Consequently, operators can choose to accept a lower image quality, which is still sufficiently diagnostic, to reduce patient (and operator) radiation dose.
detector doses ranging from 10 to 1,200 nGy/frame. As the number of photons reaching the detector increases, image noise decreases and the image becomes smoother. Over a defined range, as image noise decreases, perceptible image spatial resolution increases. For each imaging modality there is an upper limit of dose beyond which further dose increase, although it may produce a smoother-appearing image, does not yield greater image detail of diagnostic importance.

Similarly, the image noise in x-ray CT images is determined in part by detector dose. Larger doses will yield images with less noise and, within limits, greater spatial resolution. For x-ray CT, the spatial resolution required to assess myocardial contours, and, accordingly, the dose needed to achieve it, is smaller than that required to image coronary arteries.

For nuclear scan images, the number of gamma ray counts that are acquired to construct the image determines the image noise and, accordingly, its spatial resolution, which improves as the number of counts acquired increases. The number of counts acquired is determined by the amount of radioactivity administered for the examination, which determines the number of counts per unit time, and the image acquisition time, with longer acquisition times acquiring a larger number of counts.

The cardiovascular system moves. This imposes additional requirements on cardiovascular imaging systems. Spatial resolution is also determined by x-ray pulse width. Images acquired with pulse durations >8 ms will be degraded by motion unsharpness just as photographs of moving objects are blurred if acquired at slower camera shutter speeds. Typical pulse durations are 2 to 8 ms.

**Temporal Resolution—Pulse Frequency**

If an image series (such as an x-ray fluoroscopy cine acquisition) is acquired at too slow of a frame rate, events that occur during time periods shorter than the framing rate will not be resolved and object motion will cause the image to have a jerky quality.

### 4.2. X-Ray Fluoroscopy

Of the 3 imaging modalities, x-ray fluoroscopy has the greatest variability in dose per procedure and has the potential to deliver the largest dose to patients, operators, and nearby medical personnel. Dose is substantially lower than for nuclear scan imaging; however, it is still important to minimize the dose and to optimize the imaging technique to achieve diagnostic images with the lowest possible dose.
affected by operator choices, behavior, equipment quality, and calibration.

4.2.1. General Principles
For an x-ray fluoroscopic examination, the total skin dose (in Gy) is determined by the sum of air kerms of all the frames (fluoroscopy and cine acquisition) in the examination. The total effective dose is proportional to the sum of the KAPs of all of the examination’s frames.

4.2.2. Digital X-Ray System Operating Modes
Digital x-ray imaging systems operate in 3 modes that employ different detector doses to achieve different image spatial resolution.

1. Fluoroscopy—the lowest-dose imaging protocol that yields images with the lowest spatial resolution. Typical fluoroscopic detector doses range between 20 and 40 nGy/frame.

2. Cine acquisition—an intermediate-dose imaging protocol intended to provide diagnostic quality images for archiving and diagnostic interpretation. Cine acquisition images have less image noise than fluoroscopic images but should still have visible noise. Typical cine acquisition detector dose rates are 200 nGy/frame.

3. Digital subtraction—Digital subtraction algorithms are highly sensitive to image noise and require high doses to function effectively. Consequently, digital subtraction algorithms per frame dose rates are the largest (typically 1,200 nGy/frame).

4.2.3. X-Ray System Calibration, Operation, and Dose
The goals and purposes of an examination determine the optimal balance between radiation exposure and image spatial and temporal resolution. For example, for x-ray fluoroscopy, the spatial and temporal resolution required for general catheter placement and manipulation is less than that required to perform cardiac interventional procedures. Current x-ray fluoroscopy systems are capable of imaging at multiple frame rates and can adjust detector gain to utilize variable detector doses (21,22). These capabilities enable the operator to select an optimal imaging protocol for a particular situation.

Temporal Resolution Issues and Dose Tradeoffs
Because the cardiovascular system moves, x-ray fluorographic imaging requires short pulse durations to limit image motion unsharpness (typically between 3 and 8 ms for adults, as short as 2 ms for children).

Fluoroscopic temporal resolution requirements vary substantially depending on the examination’s purpose. In less demanding circumstances, the operator can decrease dose by utilizing slower frame rates and lower doses per frame without compromising effectiveness. General catheter placement can be accomplished with fluoroscopic frame rates as slow as 4 frames/s. More complex procedures such as coronary and structural interventions require greater temporal resolution and employ frame rates between 10 and 15 frames/s.

Cine acquisition frame rates also vary with the purpose of the examination. For coronary arteriography, a frame rate of 10 to 15 frames/s is generally adequate. For adult ventriculography, 30 frames/s is preferred to achieve more precise identification of end diastole and end systole. In pediatric applications, framing rates as fast as 60 frames/s are occasionally needed.

4.2.4. Determinants of Total Dose for an Exposure
Dose per Frame and Framing Rate
The optimal parameter settings for a fluoroscopic examination or a cine acquisition run are determined by the patient’s particular circumstance’s and requirements for spatial and temporal resolution. For fluoroscopy mode, current x-ray units typically provide tableside-selectable fluoroscopy detector dose per frame levels that produce different degrees of image noise. They also provide tableside fluoroscopy and cine acquisition frame rates ranging from 4 to 30 pulses/s. For cine acquisition mode, the detector dose per pulse is set by the service engineer but the operator is able to select the frame rate.

X-Ray Imaging Field Size and System Positioning
Whereas the dose per pulse and the number of pulses determine the total dose intensity (in mGy) delivered to the patient, the product of the total dose and the imaging field size determines the total amount of radiation energy (expressed as the KAP in Gy-cm²) that the patient receives. In addition to the examination’s total number of pulses and the detector dose per pulse, the KAP is affected by 2 additional parameters that are under the operator’s control: the imaging field size selected and system positioning.

X-Ray Imaging Field Size
Current x-ray systems link brightness stabilization detection to a collimator position that samples only the detector area receiving the collimated x-ray beam. Consequently, the dose per pulse to the detector is not affected by collimator position. However, the KAP is directly related to the size of the imaged area. The consequence of this phenomenon is that, for a given detector zoom (magnification or input phosphor size) mode, smaller image area sizes deliver proportionately smaller KAPs. Thus, at a given detector zoom mode, reducing exposed field size by collimation to the smallest size necessary minimizes the KAP that the patient receives. This is not true for changing detector zoom modes. Detector dose per pulse increases as the zoom magnification increases.
X-Ray System Positioning
There is an optimal distance between the patient’s skin surface and the x-ray source (typically approximately 70 cm). If the patient is positioned too close to the x-ray source, the x-ray output is concentrated on a smaller area of the patient’s skin, increasing the patient’s beam entrance port exposure rate. This can increase the patient’s skin injury risk. If the patient is positioned too far from the x-ray source, the image receptor necessarily must also be positioned further away from the source and the inverse square law requires a greater x-ray output to achieve the requisite detector dose, requiring increased kVp and decreasing image contrast.

X-ray detector positioning is also an important determinant of dose to the patient as well as the exposure to medical personnel from scattering. If the detector is positioned substantially above the thorax, the image magnification caused by beam divergence will decrease the size of the beam entrance port, causing the patient to receive a larger skin dose. In addition, the x-ray image detector, when positioned close to the patient’s chest, intercepts a substantial portion of the radiation scattered within the patient that would otherwise reach medical personnel; accordingly, x-ray detector positioning contributes to medical personnel protection (Figure 6).

4.2.5. Procedures and Practices to Minimize Patient and Personnel Exposure

X-Ray Equipment Quality, Calibration, and Maintenance
Invasive cardiovascular x-ray imaging facilities have a responsibility to maintain and update x-ray equipment to produce quality images at the minimum detector dose. Equipment should be well maintained and its calibration should be surveyed periodically to verify that it is operating within appropriate specifications. The x-ray system should provide beam spectral filtering that is consistent with current standards.

The x-ray system should provide reduced-dose operating protocols for low-dose and low frame rate fluoroscopy imaging programs. Cine acquisition detector input doses range should be set at the smallest detector dose that provides satisfactory diagnostic quality images.

FIGURE 6 Diagrammatic Representation of the Effect of System Positioning on Patient and Operator Radiation Exposure During X-Ray Fluoroscopy

System Positioning Affects the Dose to Both the Patient and the Operator

OPTIMAL

TABLE TOO LOW

TABLE TOO LOW
Detector Too High

Note that in the “table too low” circumstance, the entrance port dose delivered to the patient is increased compared with optimal positioning. In the “table too low, detector too high” circumstance, the entrance port dose to the patient is further increased. In addition, in the “table too low” circumstance, the scattered dose to the operator increases because less of the scattered dose is intercepted by the detector (23).
Physician Operator Conduct

Dose Awareness and Monitoring

Appropriate physician operator conduct begins with a commitment to minimize radiation exposure to patients and to healthcare personnel. Operators should be cognizant of the variables that determine image quality and dose to achieve the best balance of image quality and radiation exposure (24,25).

Current x-ray units display real-time values for air kerma dose rates, and cumulative air kerma and KAP. The physician operator should be aware of these values and their interpretation throughout a procedure and consider total accumulated dose in making procedure conduct decisions.

X-Ray System Operational Issues

Imaging modality, imaging time, and image field size are 3 important dose-affecting parameters that are under the operator’s direct control. Operators should select the lowest-dose imaging modality that is appropriate for a particular application. This includes using an image field size that confines exposure to the structures of interest, using the lowest-dose fluoroscopy program, and using the slowest fluoroscopy pulse rates that yield appropriate quality images (26).

Operators should use the x-ray system collimator to minimize the exposed field size. Operators should optimize system positioning with the procedure table at the optimal distance from the x-ray tube and the image detector as close to the patient as possible. In addition, operators should employ radiation-sparing tactics including “last image hold,” virtual collimator position adjustment, and virtual patient positioning aides.

Physician and Medical Personnel Shielding and Protection

Protective shielding of operators and personnel provides substantial protection. Standard shielding for diagnostic x-ray ranges between 0.25 and 0.5 mm of lead or equivalent. A 0.5-mm lead-equivalent apron absorbs 95% of 70 kVp x-ray and 85% of 100 kVp (27,28).

Medical personnel working in an x-ray procedure room should wear 0.25- or 0.5-mm equivalent lead aprons augmented with neck thyroid shields and humeral shields. The protection provided by thyroid collars is particularly important. The thyroid collar shields the thyroid and the cervical bone marrow–2 highly radiosensitive structures that are located in an area of high radiation scatter. By attenuating the dose to these structures, the thyroid collar decreases the effective dose to the operator by approximately one-half. In addition to lead aprons, medical personnel who work close to the x-ray source should wear leaded eye protection with side shields. Lead or lead-equivalent hats may reduce cranial dose, but potential benefits are, to date, theoretical, based upon anecdotal reports of increased left-sided brain tumors in interventional cardiologists (29).

The protection afforded by lead garments should be augmented by portable shielding. Typical in-room shielding includes a ceiling-mounted lead-impregnated poly (methyl methacrylate) shield that can be placed between the patient’s thorax and the operator’s upper body. The importance of ceiling-mounted shields cannot be overstated. Proper use of these shields reduces operator eye exposure by a factor of 19 (30). Under-table mounted 0.5-mm lead-equivalent shielding intercepts backscatter off of the patient and the x-ray table that would otherwise strike the operator’s lower body.

The inverse square law is one of the best sources of protection. X-ray intensity decreases as the square of the distance from the source. This relationship has implications for physician operators, because the operator’s position in relation to the x-ray source can make a large difference in exposure magnitude.

Circulating personnel should be positioned remotely from the x-ray source and, as a result, should receive negligible exposure. When circulating personnel need to approach close to the patient, the physician operator has a responsibility to not operate the x-ray system (22,31).

4.2.6. Pregnant Occupationally Exposed Workers

Uterine Exposure Considerations for Pregnant or Potentially Pregnant Occupationally Exposed Workers

As discussed in Section 5.4.4 of Part 1, no measurable increase in adverse fetal outcomes has been detected at fetal or embryonic exposures below 50 mGy. For occupationally exposed workers in an x-ray fluoroscopy environment, proper shielding and practices should keep accumulated uterine exposures well below this level. Because the uterus is a deep structure and is inside of protective garments, the dose to the uterus delivered by scattered x-ray is greatly attenuated. Measurements made in phantoms indicate that the uterine dose in a subject wearing a 0.25-mm lead apron is <2% of the collar dose (outside protective garments).

Radiation Protection and Monitoring Practices for Pregnant or Potentially Pregnant Occupationally Exposed Workers

A pregnant occupationally exposed worker should wear, in addition to the customary collar film badge, an abdominal badge worn under the apron to estimate the uterine dose. This will verify that the uterine dose is within the range that is considered to be safe for the fetus (32,33). (This material is discussed in greater detail in the online version of this document.)
4.2.7. Alternative Imaging Techniques

Alternative imaging techniques, such as intracardiac ultrasound and electromagnetic mapping, can provide structural and guidance information that can supplement or replace x-ray fluoroscopic imaging. These should be employed in place of fluoroscopy when appropriate.

4.2.8. Summary Checklist for Dose-Sparing in X-Ray Fluoroscopy

<table>
<thead>
<tr>
<th>Checklist of Dose-Sparing Practices for X-Ray Fluoroscopy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case selection</td>
</tr>
<tr>
<td>○ Consider appropriateness and utility of nonradiation-based imaging techniques</td>
</tr>
<tr>
<td>Equipment calibration</td>
</tr>
<tr>
<td>Procedure conduct</td>
</tr>
<tr>
<td>○ Use lowest-dose fluoroscopy setting suitable for a particular task</td>
</tr>
<tr>
<td>○ Collimate imaging field size to the area of interest</td>
</tr>
<tr>
<td>○ Use the slowest framing rates suitable for a particular task</td>
</tr>
<tr>
<td>○ Minimize cine acquisition run durations</td>
</tr>
<tr>
<td>○ Minimize patient-detector distance</td>
</tr>
<tr>
<td>○ Maximize employment of operator shielding</td>
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</tbody>
</table>

4.3. X-Ray CT

4.3.1. X-Ray CT General Principles

Achieving optimal images at minimal dose requires an expert team to coordinate patient management and protocol selection including image acquisition, reconstruction, and interpretation. The team needs to select the imaging protocol most likely to acquire diagnostic-quality images that achieve the examination’s goals while exposing the patient to the smallest necessary radiation dose (34-36).

The keys to minimizing radiation exposure in cardiac CT are:

1. Appropriate case selection.
2. Scanner capability and protocol selection.
4. Appropriate examination conduct.

Greater detail of how to implement these procedures is discussed in depth in the complete document published online.

Case Selection Appropriateness

The first principle to reduce patient radiation exposure due to CT examinations is to avoid performing examinations that will prove to be nondiagnostic either because of poor image quality or because the images will not answer the clinical questions posed. Case selection should incorporate the appropriate use criteria formulated collaboratively by the American College of Cardiology and other organizations (37-39).

4.3.2. Equipment Quality and Calibration

Equipment calibration and preventive maintenance as part of quality assurance and control programs play an important role in reducing radiation dose by facilitating dose optimization. This is discussed in greater detail in the full online document.

4.3.3. Variables That Affect Patient Dose for X-Ray CT

The radiation dose to a patient is determined by a combination of the patient’s physical characteristics and scanner protocol selection. Larger patients require larger exposures.

Operator-selectable imaging protocols that influence patient dose include:

1. Scan length. Scan length should be kept to a minimum to encompass only the anatomy of interest.
2. X-ray beam intensity. Dynamically modulated tube current should be used for cardiovascular acquisitions

**Tube potential**: The single most important factor in controlling radiation dose is adjustment of x-ray tube voltage (in kV) (40-42). Increasing tube voltage increases the x-ray beam’s mean photon energy level, and increases radiation dose roughly proportionally to the square of the voltage. Increasing x-ray tube voltage decreases image noise.

**Tube current**: The x-ray tube current (in milliamperes [mA]) is proportional to the number of x-ray photons produced per unit time and is linearly proportional to radiation dose. Image noise is inversely proportional to the square root of the tube current. Thus, decreasing tube current at a given tube potential decreases the radiation dose at the expense of increased image noise.

3. Rotation time. The time required for the gantry to perform 1 rotation is a selectable parameter. Exposure increases linearly with rotation time.
5. **Scan acquisition mode.** This is a major determinant of radiation dose. There are 3 principal CT scan modes: 

**Axial scanning** images a portion of the anatomy during a single gantry rotation while the table is stationary. The table advances to the next contiguous position for the next scan.

**Helical scanning** combines continuous gantry rotation with continuous table advancement. Scan “pitch” (ratio of the detector array width to the distance that the table advances per complete gantry rotation) is a major determinant of dose, with pitches <1 causing greater exposure (43,44).

**Fixed table scanning** A complete acquisition in a single gantry rotation, performed when using a CT scanner with a detector array width greater or equal to the length of the anatomy of interest.

6. **Cardiac motion compensation.** When imaging the heart or aortic root, cardiac motion compensation is critical to avoiding motion-related artifacts. Depending upon the scan mode, 1 of 2 cardiac compensation methods is used.

**Prospective ECG triggering:** The operator “prospectively” selects an imaging window within the cardiac cycle (45). Scans are triggered to coincide with the selected scan window. This minimizes dose, but has the disadvantage that image quality may prove to be unsatisfactory.

**Retrospective gating:** Images are acquired across the entirety of a cardiac cycle, with the ECG signal providing a 4-dimensional dataset. This allows image reconstruction at any point in the cardiac cycle. Retrogressive gating has many advantages over prospective gating, including the ability to construct cine loops to examine global and regional left ventricular function. However, it necessarily delivers a higher radiation dose.

**ECG-triggered tube current modulation:** Tube current is modulated using ECG triggering and is at nominal value only during the portion of the cardiac cycle likely to be used for reconstruction (typically end diastole) (see Figure 4). During the remainder of the cardiac cycle, the tube current is reduced to reduce radiation output (46-48). Tube current modulation has the advantages of retrospective gating at reduced total dose to the patient.

7. **Image reconstruction.** Filtered back-projection has historically been used to reconstruct CT images from projection data. Iterative reconstruction has recently become practical for CT. This reconstructs images with lower noise values, permitting lower radiation dose (49,50).

8. **Image postprocessing filters.** These may also be applied to acquired images to reduce image noise while preserving image contrast and edges (51).

### 4.3.4. Summary Checklist of Dose-Sparing Practices for X-Ray CT

<table>
<thead>
<tr>
<th>Checklist of Dose-Sparing Practices for X-Ray Computed Tomography</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case selection</strong></td>
</tr>
<tr>
<td>- Consider patient age, comorbidities, natural life expectancy</td>
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<tr>
<td>- Consider appropriateness and utility of nonradiation-based imaging techniques</td>
</tr>
<tr>
<td><strong>Equipment calibration</strong></td>
</tr>
<tr>
<td>- Acquisition detector doses as low as compatible with diagnostic image quality</td>
</tr>
<tr>
<td>- Use ECG-gated variable tube output if retrospective gating is used</td>
</tr>
<tr>
<td>- Use the lowest x-ray tube voltage compatible with adequate diagnostic quality image acquisition</td>
</tr>
<tr>
<td>- Use the lowest x-ray tube current compatible with diagnostic quality image acquisition. Use toplogram-based tube current modulation</td>
</tr>
<tr>
<td>- Use the largest scan pitch compatible with adequate diagnostic quality image acquisition</td>
</tr>
<tr>
<td><strong>Procedure planning</strong></td>
</tr>
<tr>
<td>- Select lowest-dose acquisition protocol compatible with study goals. Retrospective gating should be selected when feasible</td>
</tr>
<tr>
<td><strong>Study conduct</strong></td>
</tr>
<tr>
<td>- Minimize patient heart rate</td>
</tr>
<tr>
<td>- Confine scanned body area to the area relevant to the study’s diagnostic purpose</td>
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</table>

### 4.4. Nuclear Cardiology Techniques

#### 4.4.1. Nuclear Cardiology General Principles

There are 2 categories of nuclear cardiac imaging:

1. **Single photon imaging (SPECT)—** an intrinsically planar format technique in which images can be acquired in either planar or tomographic formats.

2. **Positron imaging (PET)—** an obligatory tomographic format.

PET generally administers a smaller radiation dose to the patient and is less affected by patient attenuation. It is currently more expensive to perform than SPECT because the scanners are more expensive and some of the radiopharmaceuticals are currently more expensive than those used in SPECT.

Like x-ray imaging, nuclear image quality is, in part, determined by the quantity of radiation that reaches the detector to form the image. This presents dose-image quality tradeoffs that are similar to the tradeoffs in x-ray imaging.

#### 4.4.2. Nuclear Cardiology Equipment Quality, Calibration, and Maintenance

In nuclear cardiology imaging, achieving an optimal balance of image quality and patient dose requires that the imaging equipment be in good operating order. Newer detector designs and better electronics both for PET and SPECT confer greater count detection efficiency permitting smaller patient doses. Nuclear cardiology facilities should endeavor to have recent-generation equipment and have an organized program of equipment performance surveillance.
4.4.3. Nuclear Cardiology Spatial Resolution and Image Detector Dose

To be of diagnostic quality, an image should be properly collimated and formed from a requisite number of counts. Typically, image noise is approximately proportional to the square root of number of counts (52).

Three variables affect the number of registered counts:

1. The imaging system's sensitivity.
2. The amount of radioactivity administered to the subject, which determines the dose the subject receives.
3. The duration that counts are acquired.

Achieving an optimal balance of patient exposure and image quality requires a judicious balancing of radiopharmaceutical dose, image acquisition parameters, and imaging time. Decreasing radiopharmaceutical dose decreases subject radiation dose but requires longer scan acquisition time.

4.4.4. Procedures and Practices to Minimize Patient Exposure

Radiopharmaceutical Choice

**SPECT Imaging Agents: Technetium-99m and Thallium-201**

The most commonly used SPECT radiopharmaceuticals use technetium (Tc)-99m bound either to sestamibi or tetrofosmin. These radiopharmaceuticals have largely supplanted thallium-201 chloride because of Tc-99m's superior imaging characteristics and lower subject radiation dose. A typical effective dose range for a 1-day Tc-99m rest-stress imaging protocol is 9.8 to 16.3 mSv (53). However, thallium-201 has a pharmacological advantage in that it redistributes over time, providing viability assessment without additional radiation exposure.

**PET Imaging Agents: Rubidium-82 Chloride, N-13 Ammonia, F-18 Fluorodeoxyglucose**

PET myocardial perfusion imaging can be done with a number of radiopharmaceuticals. All positron emitters yield photons with energies of 511 keV, which is ideal for imaging.

The most commonly used agent is rubidium (Rb)-82 chloride. Rb-82 has a 75-s physical half-life. It is generator-produced. It provides a viable alternative to Tc-99m SPECT imaging in centers that have PET scanners and sufficient clinical volume to amortize the generator cost. Rb-82's short half-life delivers a rest-stress study radiation dose of 3.3 to 3.8 mSv, a small fraction of a Tc-99m sestamibi 1-day rest-stress study (54,55).

Rb-82's short half-life confers an advantage, an operational challenge, and a disadvantage. The advantage is that rapid physical decay enables high count rates with a substantial decrease in subject dose. The disadvantage is that the short half life means that Rubidium imaging cannot be performed in conjunction with exercise stress. The operational challenge is that the radionuclide dose must be administered promptly after it is generated and the patient must be imaged immediately after nuclide administration.

Other PET imaging agents used less commonly in nuclear cardiology are nitrogen-13 ammonia and F-18 fluorodeoxyglucose. These agents are discussed in greater detail in the full online version of this document.

**PET Imaging requires attenuation correction, which requires a small (compared to the radionuclide dose) x-ray CT exposure. Many centers currently perform CT attenuation correction for SPECT as well, so this is not a major distinguishing difference between SPECT and PET total dosimetry.**

**Imaging Protocol Choice**

**Imaging Agent**

There are a variety of imaging protocol strategies that provide different opportunities to reduce subject dose. Each involves compromises and tradeoffs.

As Tc-99m imaging agents and Rb-82 do not redistribute, separate radiopharmaceutical injections are needed for the stress and the resting scans. Because of Rb-82's short physical half-life, both injections can utilize the same dose (typically 20 to 30 millicuries [mCi]), as the first dose will have decayed by the time the second dose is administered. However, for a Tc-99m same-day stress-rest protocol, the first administration is with a lower dose (typically 10 mCi) and the second employs a higher dose (typically 30 mCi). The basis of this strategy is that the higher dose of the second administration overwhelms the residual counts from the first administration. This necessarily means that the lower-dose administration may be count-poor and possibly nondiagnostic, particularly in larger patients.

**Rest-Stress Versus Stress-Rest Protocol**

Stress-first and rest-first acquisition protocols have different merits. Choosing between them involves balancing the important goal of reducing patient dose against the requirement to assure acquisition of a fully diagnostic study. A low-dose stress-first protocol offers the potential to acquire a diagnostic study at reduced total patient dose. If the stress images are normal and of good quality, there is no need to do a rest image and the study can be completed with a single low-dose injection. Use of stress-first imaging in some patients has been recommended as a best practice protocol by the International Atomic Energy Agency (52) and is widely practiced effectively in Europe. However, although stress-first imaging offers the potential of saving dose when the stress images are normal, it also means that the stress image, arguably the more important of the 2, is acquired with a
lower radiopharmaceutical activity, which may compromise its image quality, particularly in obese patients, limiting the study’s diagnostic accuracy. If the stress image is abnormal, the rest image is also needed for a complete study.

The American Society of Nuclear Cardiology imaging guidelines balance these competing priorities in protocol selection (53,56). While noting that “in patients without a high pre-test probability of a stress perfusion defect or left ventricular dysfunction or dilatation, a low-dose stress/high-dose rest Tc-99m protocol is advantageous because a significant percentage of these patients will have normal stress imaging, thereby obviating the need for the rest imaging with its additional radiation exposure,” the guideline allows that in “larger patients (e.g. >250 lbs or BMI >35) or in female patients where significant breast attenuation is anticipated, a low dose of Tc-99m radiotracer may result in suboptimal images and a 2-day imaging protocol with higher activities (18 to 30 mCi) for each injection may be preferable.”

Thus, stress-first imaging is advisable in subjects who are good imaging subjects and who do not have a high pretest probability of an abnormal study.

**Image Acquisition Practices**

The required patient radionuclide dose is determined by the imaging equipment capabilities, how it is used, and the time period to acquire images.

There are a number of image acquisition practices that can decrease the radionuclide dose needed to acquire high-quality images.

1. **Camera positioning.** Emission intensity decreases with the square of distance from the source to the detector. Consequently, position the camera as close to the patient as possible.

2. **Iterative image reconstruction.** Iterative reconstruction techniques yield improved image quality from a given dataset compared to filtered back projection. This enables diagnostic-quality images from fewer counts, permitting smaller doses.

3. **Attenuation correction x-ray dose.** The x-ray dose used for attenuation correction adds to the exposure from the radionuclide. It is important to minimize the magnitude of the additional radiation exposure. Rod-source is intrinsically low dose (typically <1 mSv). CT source, depending on the CT acquisition protocol, can be substantially greater (24,25,57,58).

**4.4.5. Procedures and Practices to Protect Occupationally Exposed Healthcare Workers in Nuclear Cardiology Facilities**

Occupationally exposed healthcare workers are at exposure risk from 3 sources:

1. Handling radiopharmaceuticals prior to administration.
2. Ambient radiation from the radioactive patient.
3. Radiation from an unrecognized contamination or spill.

Contained doses of radiopharmaceuticals should be properly shielded to minimize the escape of radiation into the environment. While some radiation emanating from a patient who has received a radiopharmaceutical dose inevitably escapes into the environment, the magnitude of exposure to healthcare workers can be managed by minimizing the time that workers are in close proximity to radioactive subjects.

The consequences of contamination or a radiopharmaceutical spill can be severe. It is necessary to have in place rigorous spill-protective practices; rigorous safety protocols that govern personal conduct in “hot” areas; and rigorous surveillance of equipment, work surfaces, and personnel for radioactive contamination.


<table>
<thead>
<tr>
<th>Checklist of Dose-Sparing Practices for Nuclear Cardiology</th>
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<tr>
<td><strong>Modality selection</strong></td>
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<tr>
<td>□ Select the appropriate technique and radionuclide that provides diagnostic quality information at the least patient radiation dose.</td>
</tr>
<tr>
<td>Dose relationships: N-13 H, PET &lt; Rb-82 PET &lt; Tc-99m SPECT &lt; Ti-201 SPECT</td>
</tr>
<tr>
<td><strong>Equipment calibration</strong></td>
</tr>
<tr>
<td>□ Use scanners with cadmium zinc telluride [CZT] detectors</td>
</tr>
<tr>
<td><strong>Procedure planning</strong></td>
</tr>
<tr>
<td>□ Use stress-rest protocol in preference to rest-stress when the overall clinical situation (clinical scenario and patient imaging characteristics) is appropriate</td>
</tr>
<tr>
<td>□ Use the smallest radionuclide dose compatible with adequate count acquisition rates</td>
</tr>
<tr>
<td>□ Position camera head as close to the patient as possible</td>
</tr>
<tr>
<td>□ Use iterative reconstruction</td>
</tr>
<tr>
<td>□ Minimize radiation exposure for attenuation correction</td>
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4.5. Summary of Dose Minimization Strategies in X-Ray Fluoroscopy, X-Ray CT, and Cardiovascular Nuclear Scintigraphy

Table 2 summarizes dose minimization strategies for the imaging modalities discussed in this document.

<table>
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<th>TABLE 2 Dose Minimization Strategies</th>
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<tbody>
<tr>
<td><strong>X-Ray Fluoroscopy</strong></td>
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<tr>
<td>Use alternative nonradiation-based imaging techniques (ultrasound, magnetic resonance imaging, electromagnetic mapping) when appropriate.</td>
</tr>
<tr>
<td>Radiological equipment: Current state-of-the-art equipment calibrated for minimal dose exposures.</td>
</tr>
<tr>
<td>Operator conduct: Optimal system positioning, minimal imaging field size, minimal exposure time.</td>
</tr>
<tr>
<td>X-ray system operating modes: Slowest frame rate and the smallest dose per frame consistent with diagnostic quality imaging and appropriate procedure guidance.</td>
</tr>
<tr>
<td>Medical personnel protection: Optimal use of protective garments and shields, maximize distance from the x-ray source, and minimize patient exposure (which, in turn, minimizes medical personnel exposure).</td>
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</table>

| **X-Ray CT**                        |
| Study appropriateness: Ensure that an x-ray CT examination is the optimal imaging technique to answer the clinical question. |
| Radiological equipment: Equipment should be current state of the art, in good working order, and calibrated for minimal dose exposures. |
| Scan protocol: Select the lowest-dose scan protocol that will provide images of diagnostic quality to answer the clinical question. |
| Scan size: Confin e the imaged body region to the smallest area needed to answer the clinical question. |

| **Nuclear Cardiology**               |
| Study appropriateness: Ensure that nuclear cardiology study is the optimal imaging technique to answer the clinical question. Consider PET rather than SPECT imaging if feasible and appropriate. |
| Imaging equipment: Equipment should be current state of the art, in good working order, and calibrated for minimal dose exposures. |
| Scan protocol: Select a stress-rest protocol when appropriate (according to ASNC guidelines). |
| Radiopharmaceutical choice: Tc-99m is preferred for SPECT. Avoid Tl-201 except for studies focused particularly on myocardial viability issues. |
| Radiopharmaceutical dose: Use the smallest injected dose that will provide sufficient counts for imaging in a practical time period. |

5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1. The Issue

While engineering refinement of imaging equipment has yielded better image quality at lower patient doses, on balance, the increased utilization rates and procedure complexity have combined to increase the quantity of medical radiation exposure both at the population and the individual level. This creates the potential for greater radiation-induced harm including both tissue reactions and cancer.

Radiation-related hazard presents an additional variable to weigh when considering whether to undertake a given procedure, when making choices among alternative procedure modalities, and when weighing procedure conduct decisions. The healthcare profession is responsible to be aware of this issue and to work to optimize the risk-benefit relationship.

5.1.1. Patient Participation in Clinical Imaging Decisions

Patients should participate with their physicians in the decision to undertake any medical procedure that involves risk, and the radiation risk is no exception. Patients should understand the radiation component of a procedure’s overall risk and interpret it in the context of the procedure’s overall risk-benefit relationship. Physicians are responsible to explain the radiation risk of a medical procedure as well as the other risks. These explanations, which should be comprehensive and rigorous, can be challenging to conduct given that many patients have limited understanding of radiation metrics and effects. Current understanding is that the incremental stochastic risk associated with a particular procedure is almost always an extremely small component of the procedure’s total risk and can generally be discounted.

5.2. Clinical Value of Radiation-Based Imaging Studies and Radiation-Guided Therapeutic Procedures

A procedure’s risk-benefit relationship determines its overall clinical value (and, consequently, its appropriateness). The risk conferred by radiation exposure is a component of a procedure’s overall risk complement. The established benefit to patient health outcomes of radiation-based cardiovascular diagnostic and therapeutic procedures is substantial. The radiation-associated hazard is generally very small in absolute terms and certainly in comparison to hazards from other
components of a procedure. In appropriate circumstances, radiation-based cardiovascular procedures have substantial clinical value that justifies the attendant risk, including the small associated radiation-associated hazard. Nonetheless, the radiation component is real and should be assessed in considering a proposed procedure’s appropriateness.

The risk of radiation-caused cancer is not uniform across the entire population. Patient characteristics, particularly age, gender, and comorbidities, modulate the risk associated with a particular radiation exposure. Because most radiation-induced cancer requires a minimum of 5 years to emerge (some as early as 2 years) (60), the potential for radiation-induced cancer is less relevant in patients with shorter life expectancies and important comorbidities. It is most important for children and young adults with a long life expectancy, particularly females, in addition to those with congenital heart disease who have an ongoing need for evaluation and risk an increased lifetime cumulative exposure.

5.3. Individual Patient Risk and Population Impact (Including Occupationally Exposed Workers)

Medical radiation cancer risk has 2 potential impacts: a categorical effect on the exposed individual and an aggregate probabilistic effect on the exposed population.

Individual patient risk is linearly related to the total effective dose in mSv and is modulated by patient characteristics including age, gender, and life expectancy.

The overall population risk is the potential for an increase in population cancer rates caused by the population’s aggregate medical radiation exposure. This effect is difficult to detect because of cancer’s large background frequency and the comparatively small magnitude of accumulated medical doses. Nonetheless, now that the U.S. population’s aggregate medical radiation exposure exceeds background, there is reason for concern that medical radiation may become a contributor to overall cancer incidence.

5.4. The ALARA Principle

The ALARA (as low as reasonably achievable) principle has long been the guiding principle governing medical radiation exposure. It is based on the linear-no threshold model of radiation cancer risk and states that medical radiation exposure should be employed judiciously and that healthcare professionals are responsible to minimize radiation exposure both to patients and to healthcare personnel.

5.5. The Potential to Minimize Exposure to Patients and Personnel

Physicians have 2 options available to minimize patient medical radiation exposure:

1. Choice of procedure modality
2. Choice of procedure conduct

5.5.1. Imaging Modality Choice

Procedure modality choice is based on the purpose and goals for the procedure. Often more than a single modality can be employed to address a clinical issue. If alternative modalities provide truly comparable diagnostic utility, a modality that does not employ radiation is preferable to a radiation-based modality. For example, for some stress testing circumstances both nuclear perfusion imaging and echocardiographic imaging can have equivalent utility. On the other hand, depending on patient characteristics affecting echocardiographic image quality, the ability of a patient to exercise, or on the clinical question to be addressed, nuclear perfusion imaging may be sufficiently superior to echocardiographic imaging to offset the small attendant risk of radiation exposure.

5.5.2. Procedure Conduct Choice

Procedure conduct choices can also have a substantial impact on the attendant radiation dose. With current imaging technology, the best image achievable may actually be better than needed. In some circumstances, employing a smaller radiation dose, although degrading image quality somewhat, will yield images of sufficient quality for diagnosis. Examples include X-ray fluoroscopy at lower detector doses and/or slower framing rates, CT scanning at lower detector doses, and nuclear perfusion imaging employing smaller tracer doses.

5.5.3. Protecting Occupationally Exposed Workers

It is important to be vigilant to minimize healthcare worker occupational exposure. Healthcare workers who work in radiation environments are typically young and therefore more susceptible. Someone working in a radiation environment for an extended period has the potential to accumulate a substantial exposure. There is a synergistic incentive to minimize patient X-ray fluoroscopy exposure because the same practices that decrease patient exposure also decrease occupational exposure. X-ray fluoroscopic environments also have ample opportunity to control occupational exposure through standard protective practices.

5.6. Physician Responsibilities to Minimize Patient Exposure

All physicians, whether or not they work in a radiation environment, have a responsibility to minimize patient exposure. This responsibility falls into 3 domains: procedure selection, procedure conduct, and facility management.

5.6.1. Case Selection

When selecting a diagnostic or therapeutic procedure, a physician is responsible to understand the procedure’s complete risk-benefit relationship and, when there are alternative procedures to choose among, select the most
appropriate procedure. Radiation exposure is an important consideration that must be weighed in this choice. It is important to consider the patient characteristics that modulate that risk, including patient age, comorbidities, and natural life expectancy. For younger patients without comorbidities, radiation-based imaging is less preferred than for older patients with limited life expectancies. Physicians should employ the ACC appropriate use criteria as a point of departure in making these judgments. When feasible, particularly in younger patients, an alternative imaging procedure that does not use ionizing radiation may be preferable (e.g., cardiac magnetic resonance or echocardiography).

5.6.2. Procedure Conduct
Physicians who perform radiation-based procedures are responsible for understanding the determinants of patient dose and adjusting procedure conduct to achieve successful diagnosis or therapy while employing the minimal necessary dose. In x-ray fluoroscopy, this begins with attention to beam-on time, beam collimation, and system positioning to minimize dose to both the patient and to nearby clinical personnel. In addition, physicians should select the imaging protocol (detector dose, frame rate) that minimizes dose while providing diagnostic quality images. In x-ray CT it is important to select the lowest dose imaging protocol that will yield diagnostic quality images. In addition, care should be taken to limit the examination to the body region of interest. Similarly, in radionuclide scintigraphy, it is important to consider radiation dose and endeavor to minimize it when selecting a protocol. It is important to select the radionuclide species that delivers least radiation exposure while best answering the clinical question(s) at hand, and to administer the smallest radiopharmaceutical activities likely to ensure diagnostic image quality. Stress-first imaging is preferred for subjects who have a reasonable pretest probability of a normal study and who are good imaging subjects. Rest-first imaging is appropriate for subjects who are more challenging to image and are likely to have abnormal studies.

5.6.3. Facility Management
Physicians who manage facilities that use ionizing radiation are responsible to ensure that those facilities generate high-quality images at minimal radiation exposure to patients and personnel. These responsibilities include radiological equipment selection, calibration and maintenance, establishing imaging protocols that optimally balance image quality and exposure, and fostering a culture of minimizing patient radiation exposure and maximizing personnel protection.

Radiological equipment should be capable of generating diagnostic-quality images at minimal dose. A unit that requires a greater than current state-of-the-art dose to generate quality images should be considered obsolete and either renovated or replaced. The facility’s managing director should collaborate with the equipment company’s service engineers and the institution’s radiological physicist to verify that equipment is optimally calibrated. The equipment should provide user control of imaging dose parameters so that operators can select the imaging protocol that best balances image quality and dose.

The facility’s physician director should monitor the facility’s overall radiological performance by tabulating patient procedure doses and personnel doses to ascertain that these doses are within guideline levels. Individual large outlier exposures should be investigated and explained, and corrective action taken if indicated.

5.7. Patient Radiation Dose Tracking
Technology now exists that could be applied to create a comprehensive patient dose tracking system. There has been some advocacy to create such systems. However, current understanding of the biological basis of cancer induction by radiation does not support a clinical utility to the patient of longitudinal dose tracking. Based on the linear-no threshold concept, the incremental cancer risk associated with a particular medical exposure is independent of prior exposure magnitude. Knowing a patient’s lifetime accumulated radiation exposure provides no additional information of value for clinical decision-making with respect to the incremental stochastic risk that would be conferred by a contemplated radiation exposure (although knowledge of prior exposure can aid in predicting the tissue reaction risk). The risk that should be weighed when choosing to perform a procedure is the incremental risk that the procedure’s exposure adds to the patient’s background risk. Consequently, knowing the amount of prior exposure is not a factor in the decision.

Accordingly, tabulating a patient’s aggregate radiation exposure adds little practical clinical value. The principal value of a radiation tracking program would be to provide data for future clinical research to define the dose-stochastic risk relationship for doses in the medical range more precisely.

5.8. Need for Quality Assurance and Training
Properly conducted quality assurance is essential to consistent facility operation to provide reliable high-quality imaging while minimizing radiation exposure. Quality assurance requires verifying equipment performance and calibration and monitoring metrics of patient and personnel exposure. Proper training of all personnel is essential. Good training ensures that all clinical personnel have the requisite understanding of
radiation physics, radiation biology, and radiation protection. In addition, training should create a culture of respect for radiation hazard and a commitment to minimize exposure and maximize protection.

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ABIM — American Board of Internal Medicine; ACC — American College of Cardiology; ACPC — Adults with Congenital Heart Disease and Pediatric Cardiology; AHA — American Heart Association; ASNC — American Society of Nuclear Cardiology; HRS — Heart Rhythm Society; NASCI — North American Society for Cardiovascular Imaging; SCAI — Society for Cardiovascular Angiography and Interventions; SCCT — Society of Cardiovascular Computed Tomography; SNMMI — Society of Nuclear Medicine and Molecular Imagine; UT — University of Texas.
APPENDIX C. ABBREVIATIONS

CT = computed tomography  
CTDI = computed tomography dose index  
CTDIvol = volume computed tomography dose index  
Gy = gray  
KAP = kerma-area product  
kerja = kinetic energy released in material  
mSv = milliSieverts  
nGy = nanogray  
PET = positron emission tomography  
SPECT = single-photon emission computed tomography  
RWI = relationship with industry

APPENDIX D. OPERATOR EDUCATION, QUALITY ASSURANCE, RADIATION DOSE MONITORING, AND TRACKING

Modality-Specific Operator Education and Certification
This section may be found in Section 8 of the online version of this document. It covers education and certification requirements for physicians who operate or supervise the operation of radiological equipment.

Quality Assurance
This section may be found in Section 9 of the online version of this document. It covers quality assurance practices for facilities that operate radiological equipment.

Patient and Medical Personnel Radiation Dose Monitoring and Tracking—Programmatic and Individual Considerations
The issue of the value and appropriateness of patient radiation dose monitoring and tracking is discussed in depth in Section 10 of the online published version of this document.