

## ACCF/AHA CLINICAL COMPETENCE STATEMENT ON CARDIAC CT AND MR

# ACCF/AHA Clinical Competence Statement on Cardiac Imaging With Computed Tomography and Magnetic Resonance

A Report of the American College of Cardiology Foundation/  
American Heart Association/American College of Physicians  
Task Force on Clinical Competence and Training

*Developed in Collaboration With the American Society of Echocardiography, American Society of Nuclear Cardiology, Society of Atherosclerosis Imaging, and the Society for Cardiovascular Angiography & Interventions*  
*Endorsed by the Society of Cardiovascular Computed Tomography*

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**PREAMBLE**

The granting of clinical staff privileges to physicians is a primary mechanism used by institutions to uphold the quality of care. The Joint Commission on Accreditation of Health Care Organizations requires that the granting of continuing medical staff privileges be based on assessments of applicants against professional criteria specified in the medical staff bylaws. Physicians themselves are thus charged with identifying the criteria that constitute professional competence and with evaluating their peers accordingly. Yet the process of evaluating physicians' knowledge and competence is often constrained by the evaluator's own knowledge and ability to elicit the appropriate information, problems compounded by the growing number of highly specialized procedures for which privileges are requested.

The American College of Cardiology Foundation/American Heart Association/American College of Physicians (ACCF/AHA/ACP) Task Force on Clinical Competence was formed in 1998 to develop recommendations for attaining and maintaining the cognitive and technical skills necessary for the competent performance of a specific cardiovascular service, procedure, or technology. These documents are evidence-based, and where evidence is not available, expert opinion is utilized to formulate recommendations. Indications and contraindications for specific services or procedures are not included in the scope of these

documents. Recommendations are intended to assist those who must judge the competence of cardiovascular health care providers entering practice for the first time and/or those who are in practice and undergo periodic review of their practice expertise. The assessment of competence is complex and multidimensional; therefore, isolated recommendations contained herein may not necessarily be sufficient or appropriate for judging overall competence.

The ACCF/AHA/ACP Task Force makes every effort to avoid any actual or potential conflicts of interest that might arise as a result of an outside relationship or a personal interest of a member of the ACCF/AHA/ACP Writing Committee. Specifically, all members of the Committee are asked to provide disclosure statements of all such relationships that might be perceived as real or potential conflicts of interest relevant to the document topic. These changes are reviewed by the Committee and updated as changes occur. The relationship with industry information for the Writing Committee members is published in the appendix of this document.

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**INTRODUCTION**

The disciplines of cardiac imaging using computed tomography (CT) and magnetic resonance imaging (MRI) define unique areas worthy of competence. Existence of multi-disciplinary practitioners in the field, the complex nature of the imaging devices and anatomy, and the rapidly advancing uses of these modalities require credentialing guidelines for physicians in, hospital as well as private, outpatient settings. The guidelines are broad-based and applicable to cardiovascular practitioners from multiple medical backgrounds. This statement on clinical competence is designed to assist in the assessment of physicians' expertise in the ability to apply and interpret cardiovascular computed tomography (CCT) and cardiovascular magnetic resonance (CMR). The minimum education, training, experience, and cognitive skills necessary for the evaluation and interpretation of cardiac imaging using these newer approaches are specified. It is important to note that these are minimum training and experience requirements for the assessment of expertise in these approaches in the broadest sense. The specifications are applicable to most practice settings and can accommodate a number of ways in which physicians can substantiate expertise and competence in utility of either CCT or CMR.

Moreover, it is important to stress that competence levels for CCT and CMR are distinct and require separate training. This document specifically applies to cardiac applications of these two modalities. The official name for the discipline of magnetic resonance (MR) applied to the cardiovascular system per the Society for Cardiovascular Magnetic Resonance (SCMR) is "cardiovascular magnetic resonance" whether it is applied to the heart alone (includ-

ing the coronary arteries) or the heart and the peripheral blood vessels. Because of the complexities of the peripheral anatomy as well as the different methods of interpretation and acquisition, peripheral imaging using either modality is outside the scope of this document and will require separate attention and training.

The Writing Committee includes representatives from the American College of Cardiology (ACC), the American Heart Association (AHA), the American Society of Echocardiography (ASE), the American Society of Nuclear Cardiology (ASNC), the Society of Atherosclerosis Imaging (SAI), the Society for Cardiovascular Angiography and Interventions (SCAI), and the SCMR. Peer review included two official representatives from the ACC and AHA; organizational review was done by the ASE, ASNC, SCAI, Society of Cardiovascular Computed Tomography (SCCT), SCMR, and SAI, as well as 40 content reviewers. This document was approved for publication by the governing bodies of the ACC and AHA. In addition, the governing boards of the ASE, ASNC, SAI, SCAI, and SCCT have reviewed and formally endorsed this document.

**Rationale for developing a competence statement.** In this document, the term “cardiac disease” refers to acquired and congenital diseases of the heart muscle, valves, pericardium, coronary arteries and veins, pulmonary veins, and diseases of the thoracic aorta. Diseases of the pulmonary arteries (e.g., pulmonary embolism), peripheral vascular system, and carotid, renal, and intracranial vessels are outside the realm of this document. Furthermore, this document addresses other clinical imaging applications of both CCT and CMR. For CCT, anatomic, functional imaging, coronary calcium, non-calcified plaque assessment, and CCT use in congenital heart disease (CHD) will be included. For CMR, its use in anatomic, functional, and perfusion imaging, vasodilator or dobutamine stress imaging, viability, plaque assessment, valvular disease, and CHD will be discussed.

Coronary heart disease constitutes the most common cause of morbidity and mortality in Western society. Scientific advances have substantially increased the diagnostic capabilities of both CCT and CMR. Most cardiovascular and radiology programs do not provide formal post-training education in CCT and CMR, yet there is a strong need to establish competence guidelines for practicing physicians in these emerging fields. This document does not replace the Cardiovascular Medicine Core Cardiology Training (CO-CATS) document on CMR (1), which specifically addresses training requirements during cardiovascular fellowship, nor the recommendations made by the American College of Radiology (ACR) (2). This document is intended to be and is complementary to the SCMR statement regarding training requirements during fellowship and for practicing physicians (1,3) and to recommendations by the ACR (2). It must be understood that the SCMR guidelines, which require relatively more “in laboratory” training than the guidelines listed here, include the field of vascular imaging.

Whereas cardiologists, nuclear medicine specialists, and radiologists should possess core knowledge of cardiovascular physiology and imaging, it is unreasonable to expect the majority of such physicians to be fully conversant with all potential uses of CCT or CMR. Thus, there is a role for specialists who have more in-depth understanding of the utility and diagnostic capability of CCT and CMR.

Medical specialists trained in the distinct disciplines of cardiovascular medicine, radiology, and nuclear medicine are all involved in the imaging of cardiovascular diseases, albeit from differing perspectives. These perspectives, however, also share many common features, emphasizing the importance of a broadly based, multi-disciplinary approach for management. These specialist physicians also can be subdivided into those who have exposure or training in CCT and those who have exposure or training in CMR. Each of these subsets of physicians concerned with the care of the patient with cardiovascular disease must hold a specialized knowledge base that is applicable to one’s particular imaging discipline. This document addresses the minimal knowledge base required for expertise, the education and training pathways available to acquire that expertise, and the requirements to maintain expertise for each of the two related disciplines that involve tomographic cardiac imaging with CCT and CMR. Accordingly, this document is presented in two major sections: 1) CCT, and 2) CMR. Each section describes the cognitive, clinical, and/or procedural skills required for expertise, the training necessary for achieving competence, and the means for maintaining that expertise and competence.

## **COMPUTED TOMOGRAPHY (CT)**

### *Overview of X-Ray CT*

“Computed tomography” is a generic term that can apply to several methods currently employed in the evaluation of cardiovascular diseases. The first discussion must be one of semantics in defining CT derived in a specific manner using X-ray information from multiple sites. From here forward, CT will refer to the latter method partly by tradition and mostly by convention.

The development of CT, resulting in widespread clinical use of CT scanning by the early 1980s, was a major breakthrough in clinical diagnosis. Imaging a thin axial cross-section of the body avoided superposition of three-dimensional (3D) structures onto a planar two-dimensional (2D) representation, as is the problem with conventional projection X-ray. The basic principle of CT is that a fan-shaped, thin X-ray beam passes through the body at many angles to allow for cross-sectional images. The corresponding X-ray transmission measurements are collected by a detector array. Information entering the detector array and X-ray beam itself is collimated to produce thin sections and avoid unnecessary photon scatter. The transmission measurements recorded by the detector array are digitized into picture elements (pixels) with known dimensions. The



gray-scale information contained in each individual pixel is reconstructed according to the attenuation of the X-ray beam along its path using a standardized technique termed “filtered back projection.” Gray-scale values for pixels within the reconstructed tomogram are defined with reference to the value for water and are called “Hounsfield Units” (HU) (for the 1979 Nobel Prize winner, Sir Godfrey N. Hounsfield) or simply “CT numbers.” Air attenuates the X-ray less than water, and bone attenuates it more than water, so that in a given patient, the HU may range from -1,000 HU (air) through 0 HU (water) to approximately +1,000 HU (bone cortex). A range of 2,000 gray-scale values represents densities of various hard and soft tissues within the body and between these two extreme limits.

The CT technology has significantly improved since its introduction into clinical practice in 1973. Current conventional scanners used for cardiac and cardiovascular imaging now employ either a rotating X-ray source with a circular, stationary detector array (spiral or helical CT) or a rotating electron beam (electron beam computed tomography [EBCT]). Continuous or step increments of the patient table using electron beam methods allow imaging at 50 to 100 ms or continuous scanning (spiral or helical CT or multi-detector computed tomography [MDCT]), allowing for image reconstruction windows now on the order of 200 to 400 ms with short inter-scan delay. Today, 64-slice MDCT scanners provide enhanced scan modes of temporal resolution as low as 165 ms, and in multi-sector mode a range of temporal resolution as low as 100 ms. Improved temporal resolution should lead to lower motion artifacts and possibly higher diagnostic rates. Reconstruction algorithms and multi-row detectors common to both current EBCT and spiral/helical CT have been implemented, enabling volumetric imaging, and multiple high-quality reconstructions of various volumes of interest can be done either prospectively or retrospectively, depending on the method.

Although the purpose of this statement is to provide an overview of the requirements of competence in current CCT and MRI technology, continued efforts will be required to maintain competence as additional technological improvements and modifications are made in CCT hardware and software.

**Minimal knowledge and skills required for expertise in CCT.** Table 1 lists common CCT procedures performed currently in many hospital-based inpatient and outpatient imaging centers and in some private imaging clinics.

Cognitive skills required to demonstrate competence in CCT are summarized in Table 2. Candidates for competence in CCT shall have completed a formal residency in general radiology or nuclear medicine or will have completed an Accreditation Council for Graduate Medical Education (ACGME)-approved cardiovascular fellowship. A thorough knowledge and understanding of cardiac and vascular anatomy is required. Because cardiology, nuclear medicine, and radiology training is very much involved with

**Table 1.** Classification of CCT Procedures

<p>Cardiac:</p> <ul style="list-style-type: none"> <li>• Static tomographic and 3D non-contrast and contrast-enhanced anatomy of the heart, heart chambers, and pericardium (electron beam tomography [EBT] and multi-detector computed tomography [MDCT])</li> <li>• Dynamic contrast-enhanced assessment of left and right ventricular function (EBT and MDCT)</li> <li>• Quantitative coronary artery calcium scoring and interpretation (EBT and MDCT)</li> <li>• Performance and interpretation of tomographic and 3D contrast-enhanced CCT coronary angiography, including native and anomalous coronary vessels and coronary bypass grafts, aortic root, proximal pulmonary arteries, superior and inferior vena cavae, pulmonary veins (EBT and MDCT), and common congenital abnormalities involving the heart and central vasculature</li> </ul> <p>Thoracic Aorta:</p> <ul style="list-style-type: none"> <li>• Static tomographic and 3D non-contrast and contrast-enhanced anatomy of central vasculature (thoracic aorta) (EBT and MDCT)</li> <li>• Performance and interpretation of tomographic and 3D contrast-enhanced CCT central vascular angiography including aortic arch and thoracic aorta (EBT and MDCT)</li> </ul>
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anatomic definition, this requirement should be met or would have been met by individuals completing an ACGME-approved cardiovascular fellowship, nuclear medicine residency, or general radiology residency. Likewise, characteristics of the heart in health and disease by traditional cardiac imaging methods (echocardiography, nuclear medicine, and angiography) will provide a significant background for application to CCT. These dynamic tomographic or projection imaging techniques of the heart are commonplace in formal cardiology training, so little additional instruction is required when interpreting dynamic CCT sequences of the heart for cardiologists (e.g., evaluat-

**Table 2.** Cognitive Skills Required for Competence in CCT

<p>General:</p> <ul style="list-style-type: none"> <li>• Knowledge of the physics of CT and radiation generation and exposure</li> <li>• Knowledge of scanning principles and scanning modes for non-contrast and contrast-enhanced cardiac imaging using multi-detector and/or electron beam methods</li> <li>• Knowledge of the principles of intravenous iodinated contrast administration for safe and optimal cardiac imaging</li> <li>• Knowledge of recognition and treatment of adverse reactions to iodinated contrast</li> <li>• Knowledge of the principles of image postprocessing and appropriate applications</li> </ul> <p>Cardiac:</p> <ul style="list-style-type: none"> <li>• Clinical knowledge of coronary heart disease and other cardiovascular diseases</li> <li>• Knowledge of normal cardiac, coronary artery, and coronary venous anatomy, including associated pulmonary arterial and venous structures</li> <li>• Knowledge of pathologic changes in cardiac and coronary artery anatomy due to acquired and congenital heart disease</li> <li>• Basic knowledge in ECG to recognize artifacts and arrhythmias</li> </ul> <p>Aorta:</p> <ul style="list-style-type: none"> <li>• Knowledge of normal thoracic arterial anatomy</li> <li>• Knowledge of pathologic changes in central arterial anatomy due to acquired and congenital vascular disease</li> </ul>
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ing ventricular function by watching the wall motion throughout a cardiac cycle). Cardiac physiology is also vital for CCT and CMR, and basic training should be part of both formal cardiology fellowship and radiology residency. Competence in peripheral CT is beyond the scope of this report. A brief overview of the technical aspects of CCT is included to facilitate understanding of the terms used in the subsequent sections of this report and is not intended to be comprehensive.

Coronary artery calcium quantification is now commonplace as a means of detecting coronary and peripheral vascular atherosclerotic disease, but will require specific CCT training in addition to traditional radiology residency, nuclear medicine residency, or cardiology fellowship training. A full discussion of computer workstation methods is beyond the scope of this document, but the candidate will be required to show competence in manipulation of the tomographic datasets.

Myocardial perfusion imaging can be performed using electron beam tomography (EBT) (4) and follows principles of first-pass kinetics and perfusion imaging by nuclear medicine methods; however, this application is not yet appropriately validated for routine use in cardiac CT. Because CCT is expected to undergo rapid technical evolution, current training requirements specifically cover non-contrast studies and contrast studies involving angiography and function, but not perfusion imaging. As this modality evolves and further matures, training requirements may change.

As many CCT studies are done before and after intravenous administration of iodinated contrast, a thorough understanding of contrast injection methods, adverse events and their treatments, and contrast kinetics in patients will be required. In particular, knowledge is needed in the methods of contrast-enhanced imaging of the pericardium, right ventricle (RV), right atrium, and superior and inferior vena cavae as well as imaging of the left heart, surrounding great vessels, and the central circulation.

**CT physics and nature of radiation exposure.** The physician will be required to demonstrate competence in the principles of CCT imaging using EBT and/or MDCT and tomographic imaging production. Candidates should receive didactic lectures from a qualified CT-trained physician and/or physicist on the basic physics of CT in general and of CCT in particular.

**EBT.** Electron beam tomography is a Food and Drug Administration (FDA)-approved body-imaging device developed over 20 years ago and is the only CT device specifically designed from inception for cardiac imaging. Since EBT first appeared in 1984, there has been significant validation for this approach for cardiac and body imaging, with imaging times as low as 50 ms. The EBT method is distinguished by its use of a scanning electron beam rather than a traditional X-ray tube and mechanical rotating device used in current "spiral" single and multiple detector scan-

ners. The electron beam (cathode) is steered by an electromagnetic deflection system that sweeps the beam across the distant anode, a series of fixed "target" rings. A stationary single or multi-level detector lies in apposition to the target rings. The technique can be used to quantify ventricular anatomy and global and regional function (5), for quantitation of coronary artery calcified plaque (6-8), non-invasive coronary angiography (9-12), and central and peripheral vascular anatomy and angiography. There have been three iterations for EBT since it was introduced clinically in the early 1980s. In addition to the standard 50-ms and 100-ms scan modes common to all EBT scanners, current generation units are capable of imaging speeds as fast as 33 ms per tomographic section, as well as multi-level image acquisition in the high resolution mode.

**MDCT.** Helical/spiral CT has undergone considerable changes in the past five years, from a single slice/detector to multiple slices/detectors. This modality employs a rotating X-ray source with a circular, stationary detector array. Continuous incrimination of the patient table has enabled continuous scanning (spiral or helical CT), allowing for image reconstruction windows on the order of 165 to 400 ms with shortened inter-scan delay. Reconstruction algorithms and multi-row detectors have been implemented, enabling volumetric imaging, and multiple high-quality reconstructions of various volumes of cardiovascular interest can be done in retrospect with even shorter image reconstruction windows (multi-sector reconstructions). Current generation MDCT systems are capable of acquiring data from 40 or 64 (and potentially greater) levels of the body simultaneously. Cardiac imaging is facilitated using electrocardiographic (ECG) gating in either a prospective or retrospective mode (11-13). The MDCTs differ from single-slice helical or spiral CT systems principally by the design of the detector arrays and data acquisition systems. The new design allows the detector arrays to be configured electronically to acquire multiple levels of various slice thickness simultaneously. Measurement of the true maximum (end-diastolic) and true minimum (end-systolic) volumes are more problematic with MDCT (as compared to EBT and especially CMR) owing to lower temporal resolution.

In MDCT systems, like the preceding generation of single-slice helical scanners, the X-ray photons are generated within a specialized X-ray tube mounted on a rotating gantry. The patient is centered within the bore of the gantry such that the array of detectors is positioned to record incident photons after traversing the patient. Within the X-ray tube a tungsten filament allows the tube current to be increased (in mA) which proportionately increases the number of X-ray photons for producing an image. This ability to vary the power is a substantial design difference with current generation EBT systems, which has only two mA settings (14). The attenuation data (after passing from the source, through the body, and incident on the detector

array) are recorded and transformed through a filtered back-projection into the CT image. This final step is common to both EBT and MDCT.

**Radiation dose.** The CCT utilizes X-rays, a form of ionizing radiation, to produce the information required for generating CCT images. Although ionizing radiation from natural sources is part of our daily existence, a role of health care professionals involved in medical imaging is to understand the potential risks of the test and balance those against the potential benefits. This is particularly true for diagnostic tests which are applied to healthy individuals as part of a disease-screening or risk-stratification program. Health care professionals must have an understanding of the exposure involved in CCT to effectively advise candidates for imaging.

Because of the dangers of ionizing radiation, a comprehensive understanding must be obtained in physics and radiation safety for anyone involved with CCT. Patient doses for CCT acquisition should be set at the lowest values that are consistent with satisfactory image quality. Most candidates will likely have had some didactic training regarding radiation physics during radiology residency, nuclear medicine residency, or cardiology fellowship. However, specific instructions in the need to keep radiation exposure to the patient to a minimum when performing CCT will be required.

In general, there are differences in radiation exposure depending on the examination performed and the CT method (EBT vs. MDCT). Adoption of the *effective dose* as a standard measure of dose allows comparability across the spectrum of medical and non-medical exposures. “The effective dose is, by definition, an estimate of the uniform, whole-body equivalent dose that would produce the same level of risk for adverse effects that results from the non-uniform partial body irradiation. The unit for the effective dose is the milliSievert (mSv)” ([www.fda.gov/cdrh/ct/rqu.html](http://www.fda.gov/cdrh/ct/rqu.html)). The typical radiation dose for calcium scanning using EBT is 0.5 to 0.7 mSv, increasing with 4- to 16-slice MDCT (prospective gating) to 0.8 to 1.5 mSv, and for MDCT (retrospective gating) is up to 6.2 mSv (13–17). Radiation dose exposure for coronary angiography is much higher. Using EBT coronary angiography yielded effective doses of 1.5 and 2.0 mSv for male and female patients, respectively (15). Effective doses delivered during 16-slice MDCT coronary angiography are reported to be 6.7 to 10.9 mSv for male patients and 8.1 to 13.0 mSv for female patients (15,16).

In MDCT coronary angiography, the dose can be reduced by 30% to 50% using ECG-controlled dose modulation techniques (18). For both EBT and MDCT, the radiation dose increases with thinner slices and more overlapping images (13). In comparison, routine conventional diagnostic X-ray coronary angiography is associated with effective doses of 2.1 and 2.5 mSv for male and female patients, respectively (15). Depending on the operator and the nature of the diagnostic procedure, the effective dose of

X-ray coronary angiography can be significantly higher. Understanding the appropriate use of prospective triggering (EBT), prospective gating (MDCT), and retrospective gating (MDCT), especially given the patient radiation dose implications is important (9,13–16).

The current EBT configuration has two power (mA) settings and performs prospective triggering through only 210° of arc, so radiation dose is reduced, and there is limited opportunity either to increase or decrease radiation dose to the patient with varying protocols. However, this is not the case with MDCT angiography, which images through 360° of radiation exposure.

There are various choices with MDCT that can dramatically change the patient radiation dose during coronary computed tomography angiography (CTA). Because of rapid technical advances, scanning protocols for MDCT have not yet been standardized. Controversies about optimal tube current and voltage are ongoing. Dose (in mA) can be increased or decreased, and this is most often based upon the body habitus of the patient (16). Furthermore, slice thickness can be decreased. However, one 16-slice MDCT study that utilized high mA and 0.5-mm slice thickness for CTA (thus achieving nearly isotropic imaging) reported radiation doses as high as 24.2 mSv per patient (13). This can be reduced by using dose modulation (turning down the radiation exposure during parts of the cardiac cycle that imaging is not useful) during systolic cardiac phases; however, this is also dependent upon the patient’s heart rate (17), and cannot be applied in all cases. Although the efficacy of dose modulation depends on the heart rate, it can theoretically be applied to any heart rate with the 64-detector CT scanner. Beta-blockade to achieve heart rates below 60 beats/min is still most often part of the MDCT angiogram (10,11,18,19).

**CT laboratory requirements.** Defining the specific requirements for a valid CCT laboratory is beyond the scope of this physician competence document. However, some general aspects of the appropriate CT environment can be considered. A continuous quality control (QC) program must be established for all CT units with the assistance of a qualified medical physicist and a Level 3-trained physician (training levels are described in the following text). The scanners must be staffed by qualified CT technologists with appropriate background and/or training in CCT imaging.

Several states require all CT operators to qualify for a state permit. A current permit should be held by all technologists and Level 2- and 3-trained physicians, when required by state law.

**Training to achieve clinical competence in CCT (Table 3).**

The recommendations for all levels of training in the following text represent a cumulative experience, and it is expected that for many practicing clinicians the training will not be continuous. A summary of the training requirements is given in Table 3. Time spent at didactic continuing T3 medical education courses specifically targeting CCT can contribute to the total time. Due to the advancement in the



**Table 3.** Requirements for CCT Study Performance and Interpretation to Achieve Level 1, 2, and 3 Clinical Competence

	Cumulative Duration of Training	Minimum Number of Mentored Examinations Performed	Minimum Number of Mentored Examinations Interpreted
Level 1	4 weeks*	—	50†
Level 2—non-contrast	4 weeks*	50	150†
Level 2—contrast	8 weeks*	50	150†
Level 3	6 months*	100	300†

\*This represents cumulative time spent interpreting, performing, and learning about CCT, and need not be a consecutive block of time, but at least 50% of the time should represent supervised laboratory experience. In-lab training time is defined as a minimum of 35 h/week. †The case load recommendations may include studies from an established teaching file, previous CCT cases, journals and/or textbooks, or electronic/on-line courses/CME.

sophistication and widespread availability of electronic training medias, the committee felt that some training can now be obtained outside the laboratory setting. However, for all Level 2 and 3 requirements, minimum time in a CCT laboratory is half of the time listed, with the other half garnered by supervised time, CT exposure and other courses, case studies, CD/DVD training, time at major medical meetings devoted to performance of CCT, or other relevant educational training activities, as a few examples. Several aspects of CCT can be learned from the general CT expert, including use of the workstation, tomographic imaging, and radiation physics, among others. The caseload recommendations may include studies from an established teaching file, previous CCT cases, and electronic/on-line experience or courses.

For all levels of competence, it is expected that the candidate will attend lectures on the basic concepts of CCT and include parallel self-study reading material. A basic understanding of CCT should be achieved, including the physics of CCT imaging, the basics of CCT scan performance, safety issues in CCT performance, post-processing methods, and the basics of CCT interpretation as compared with other cardiovascular imaging modalities, which include echocardiography, nuclear medicine, CMR, and invasive cardiac and peripheral X-ray angiography.

**LEVEL 1 TRAINING.** Level 1 is defined as the minimal introductory training for familiarity with CCT, but is not sufficient for independent interpretation of CCT images. The individual should have intensive exposure to the methods and the multiple applications of CCT for a period of at least four weeks. This should provide a basic background in CCT for the practice of adult cardiology or for general radiology. During this cumulative four-week experience, individuals should have been actively involved in CCT interpretation under the direction of a qualified (Level 2- or Level 3-trained) physician-mentor. There should be a mentored interpretative experience of at least 50 cases for all studies in which other cardiovascular imaging methods are also available; correlation with CCT findings and interpretation is strongly encouraged and should be included if possible. As much as possible, studies should consist of procedures outlined in Table 1. Independent performance of CCT is not required for Level 1, and the mentored interpretive experience may include studies from an estab-

lished teaching file or previous CCT cases and also the potential for CD/DVD and on-line training.

**LEVEL 2 TRAINING.** Level 2 is defined as the minimum recommended training for a physician to independently perform and interpret CCT. This is an extension of Level 1 training and is intended for individuals who wish to practice or be actively involved with CCT performance and interpretation.

**COMPETENCE IN NON-CONTRAST CCT.** For those physicians only interested in the ability to interpret non-contrast CT studies (the “heart scan”), there are separate requirements for non-contrast Level 2 training (Table 4). The successful candidate will demonstrate competence in analysis and interpretation of cardiac and proximal aorta calcification data. The acquisition, post-processing, and interpretative learning curve for this procedure is rapid, but competence must be defined. A specific requirement for the physician only credentialed to interpret non-contrast CCT studies will be training for a minimum of four weeks (including coursework, scientific meetings and continuing medical education [CME]/on-line training) with 150 cases interpreted, with a minimum of 50, which should be interpreted with a mentor.

**COMPETENCE IN CONTRAST CCT.** Physicians seeking Level 2 training inclusive of contrast and non-contrast studies will need to interpret 50 non-contrast cases with more time and cases specifically targeting contrast. Training in contrast and non-contrast CT may occur concomitantly.

The minimum requirement for the dual credentialing is eight weeks of cumulative experience in a program actively performing CCT examinations in a clinical environment. In-lab training time is defined as a minimum of 35 h/week. Twenty hours of didactic CME courses specifically targeting CCT can contribute to the total time. The variety of exposure should include as much as possible the list of studies outlined in Table 1.

During this training experience, each candidate should actively participate in CCT study interpretation under the direction of a qualified (preferably Level 3-trained) physician-mentor. Some supervision can be by an expert non-cardiac CT physician for some of the basics of CT/reformatting, workstation, radiation physics, and so forth. The candidate should be involved with the interpretation of at least 150 CCT examinations (with contrast enhance-

T4

**Table 4.** Requirements for Level 2 and Level 3 Clinical Competence in CCT

	Level 2	Level 3	
Initial Experience	<ul style="list-style-type: none"> <li>● <b>NON-CONTRAST REQUIREMENTS</b></li> <li>● Board certification or eligibility, valid medical license, and completion of 4 weeks of training (to include coursework, scientific meetings, and courses/on-line training)</li> <li>● AND 150 non-contrast CCT examinations (for at least 50 of these cases, the candidate must be physically present, and be involved in interpretation of the case)</li> <li>● AND completion of 20 h of courses/lectures related to CT in general and/or CCT in particular</li> </ul>	<ul style="list-style-type: none"> <li>● <b>FULL CCT REQUIREMENTS</b></li> <li>● Board certification or eligibility, valid medical license, and completion of 8 weeks (cumulative) of training in CCT</li> <li>● AND 150 contrast CCT examinations. For at least 50 of these cases, the candidate must be physically present, and be involved in the acquisition and interpretation of the case</li> <li>● AND evaluation of 50 non-contrast studies</li> <li>● AND completion of 20 h/lectures related to CT in general and/or CCT in particular</li> </ul>	<ul style="list-style-type: none"> <li>● Board certification or eligibility, valid medical license, and completion of 6 months (cumulative) of training in CCT,</li> <li>● AND 300 contrast CCT examinations. For at least 100 of these cases, the candidate must be physically present, and be involved in the acquisition and interpretation of the case</li> <li>● AND evaluation of 100 non-contrast studies</li> <li>● AND completion of 40 h of courses/lectures related to CT in general and/or CCT in particular</li> </ul>
Continuing Experience	50 non-contrast CCT exams conducted and interpreted per year	50 contrast CCT exams conducted and interpreted per year	100 contrast CCT exams conducted and interpreted per year
Continuing Education	20 h Category I every 36 months of CCT		40 h Category I every 36 months of CCT

ment). The candidate should be physically present and involved in the acquisition and interpretation of the case in at least 50 studies. Cases should reflect the broad range of anticipated pathology. Didactic studies should include advanced lectures, reading materials, and formal case presentations. These didactic studies should include information on the sensitivity, specificity, accuracy, utility, costs, advantages, and disadvantages of CCT as compared with other cardiovascular imaging modalities. Each physician should receive documented training from a CCT mentor and/or physicist on the basic physics of CT in general and on CCT in particular. Lectures will include discussions of anatomy, contrast administration and kinetics, and the principles of 3D imaging and post-processing. The physician should also receive training in principles of radiation protection, the hazards of radiation exposure to both patients and CT personnel, and appropriate post-procedure patient monitoring. Finally, the physician should be thoroughly acquainted with the many morphologic and pathophysiologic manifestations and artifacts demonstrated on CCT images.

A physician with Level 2 training should demonstrate clear understanding of the various types of CT scanners available for cardiovascular imaging (EBT and MDCT) and understand at a minimum the common issues related to imaging, post-processing, and scan interpretation, including:

- Important patient historical factors (indications and risk factors that might increase the likelihood of adverse reactions to contrast media, if applicable)
- Radiation exposure factors
- CT scan collimation (slice thickness)
- CT scan temporal resolution (scan time per slice)

- Table speed (pitch)
- Field of view
- Window and level view settings
- Algorithms used for reconstruction
- Contrast media
- Post-processing techniques and image manipulation on work stations
- Total radiation dose to the patient

**LEVEL 3 TRAINING.** Level 3 training represents the highest level of exposure/expertise that would enable an individual to serve as a director of an academic CCT section or director of an independent CCT facility or clinic. This individual would be directly responsible for QC and training of technologists and be a mentor to other physicians seeking such training. The minimum cumulative training period will be six months, to include all of the didactic requirements of Level 2 training as well as participation in CCT study interpretation under the direction of a qualified (Level 3-trained) physician-mentor. In-lab training time is defined as a minimum of 35 h/week. Level 3 candidates should be involved with interpretation of at least 100 non-contrast and 300 contrast CCT examinations. For at least 100 of these cases, the candidate must be physically present and be involved in the acquisition and interpretation of the case. Cases should reflect a broad range of pathology.

In addition to the recommendations for Level 1 and Level 2 training, Level 3 training should include active and ongoing participation in a basic research laboratory, clinical research, or graduate medical teach-



ing. This level also requires documented and continued clinical and educational experiences. Additionally, Level 3 CCT physicians should have appropriate knowledge of alternative imaging methods, including the use and indications for specialized procedures including echocardiography and vascular ultrasound, CMR, and nuclear medicine/positron emission tomography (PET) studies. A summary of the training requirements is given in Table 3.

#### *Competence Considerations Unique to Specific Applications*

**Non-contrast cardiac CT including coronary artery calcium.** Quantification of coronary artery (as well as central and peripheral artery) calcification has been established as a means to estimate atherosclerotic plaque burden. Calcification scores have been shown to provide individualized cardiovascular risk assessment independent of and incremental to conventional cardiovascular risk factors (6-8).

It is to be emphasized, however, that a study done primarily to quantify coronary artery calcification (EBT or MDCT) will require not only separating native coronary calcification from aortic and mitral valvular and pericardial calcification, but also defining the potential for gross cardiac chamber abnormalities as well as potential abnormalities of the pericardium. Proximate calcification and/or enlargement of the ascending aorta and the descending thoracic aorta, included in the heart in the imaging field, should also be recognized if imaged. Tables 3 and 4 discuss the recommended number of cases for proficiency for non-contrast studies (not included in the totals for contrast CT).

Physicians must demonstrate competence in analysis and interpretation of cardiac and proximate aorta calcification data. The learning curve for this procedure is rapid, but competence must be defined. For those physicians interested in full Level 2 competence (to include contrast studies), this non-contrast requirement can be done concomitantly with training for contrast studies. Specific requirements are outlined in Table 4.

**Non-invasive coronary CT angiography (CTA).** Performance and interpretation of CTA involving the intravenous administration of 60 to 140 ml of iodinated contrast during a prolonged breath-hold is significantly more challenging than coronary calcium assessment. Understanding the anatomy, which is learned most directly from conventional coronary arteriography, is vital to the applicant, and it is expected that all the candidates will have adequate understanding of the coronary distribution and anatomy. The tortuosity of the vessels and limited temporal resolution (MDCT) or spatial resolution (EBT) contributes to this difficulty. However, studies have demonstrated a high sensitivity and specificity in the major epicardial segments for the diagnosis of significant (greater than 50% diameter) obstructive coronary artery disease (CAD) as compared to conventional X-ray coronary angiography using EBT and 16-slice MDCT scanners (9-12,18,19). The successful candidate will demonstrate competence in analysis and

interpretation of cardiovascular angiographic data. The post-processing and interpretive learning curve is not rapid, and much of the overall time spent training in CCT should thus be directed at non-invasive angiography training. This is necessary for clinicians to obtain both clinical expertise and to become technically competent in 2D and 3D rendering using a computer workstation. For clinicians to obtain expertise in performance of CTA, a majority of the cases must be directed at the performance of these contrast studies. Cases should reflect the broad range of coronary artery and bypass graft pathology.

**CHD evaluation by CCT.** Use of CCT is an important resource for the evaluation of known or suspected CHD in children and adults. Echocardiography and CMR are the most commonly used technologies for assessment of CHD. Cardiovascular computed tomography can provide accurate 3D assessment of the heart, offering additional clarity when findings are in question. The ability to assess CHD quickly allows for studies either without any sedation in most cases, or with markedly reduced sedation requirements, which is particularly useful in children. However, CCT requires exposure to ionizing radiation and iodinated contrast. The CCT technique has excellent spatial resolution, and can be utilized to assess the great vessels, including anomalies of the aorta, pulmonary artery, patent ductus arteriosus, pulmonary or tricuspid valve atresia, persistent left superior vena cava, anomalous pulmonary veins, assessment of intracardiac shunts, and the presence of bronchial collaterals.

A properly trained CCT practitioner at Level 2 should be able to determine the appropriate indications for echocardiography, CCT, or CMR in CHD assessment. This is especially true in the assessment of pediatric CHD patients, where the information gained from the CCT examination does not require the risks associated with the general anesthesia or conscious sedation required to perform CMR, but does expose the young patient to ionizing radiation (where radiation exposure may be more clinically important than in adults) and iodinated contrast.

A cardiologist, nuclear medicine specialist, or radiologist with Level 2 or Level 3 CCT competence should be capable of recognizing simple CHD. However, as with echocardiography, few adult cardiology or radiology training programs have a sufficient case load and case mix of complex CHD lesions to ensure an adequate level of training. Although those trained in CCT may be able to recognize the presence of a complex congenital lesion, most CCT programs will be unable to provide enough experience to trainees to develop the special skills necessary to evaluate complex CHD, post-surgical appearance, and post-surgical complications. Practitioners who wish to perform CCT for adult and pediatric CHD patients need special experience. A recommended case load (as part of the total number recommended for competence) for Level 2 is 25 cases; for Level 3 it is 50 cases, with an additional 20 cases annually to maintain competence.

**Cardiac function and structure assessment by CCT.** Electron beam tomography was initially validated for quantification of LV and RV global and regional systolic and diastolic function—demonstrating similarities to other methods. Lower temporal resolution MDCT data results in lower ejection fraction (EF) estimates than reference methods such as CMR. A thorough knowledge of the utilization of CCT reconstructions of short axis, long axis, and trans-axial imaging is necessary. These imaging planes have been standardized for multiple imaging methods (20).

The use of CCT has been demonstrated to be accurate for the measurement of RV and LV mass, volumes, and EF (5,21), and has been used to quantify calcified plaque on the aortic and mitral valve (22). However, it is inferior to specially sequenced CMR and echocardiography for assessing valvular function and volumes. For clinicians to obtain expertise in performance of CCT functional assessment, a minimum number of cases must be directed at the performance of these contrast studies. As part of the total cases necessary for Level 2 competence, at least 25 cases should be performed and 50 cases interpreted with mentorship. Cases should include assessment of the thoracic aorta.

**Nuclear/CT hybrid devices.** Hybrid devices are rapidly evolving to incorporate state-of-the-art, high-speed MDCT technology, along with the latest PET and single-photon emission computed tomography (SPECT) detector systems. Dual-modality imaging presents an opportunity to use a single piece of equipment for distinctly different purposes, such as the determination of perfusion, function, and metabolism (PET-SPECT) or coronary calcification and CTA. Therefore, a laboratory may use these hybrid devices for multiple purposes, thereby reducing space requirements compared to installation of two separate systems, and also reducing overall financial cost involved in the purchase of both CT and PET-SPECT cameras. There is the potential for a hybrid system to provide attenuation correction for SPECT, thereby further improving the diagnostic accuracy of more traditional radionuclide techniques.

Furthermore, the combination of SPECT-CT or PET-CT may provide an evaluation of coronary anatomy in

the same setting as perfusion imaging. The functional imaging (PET or SPECT) combined with anatomic imaging (CT calcium or CTA) may also offer superior prognostic information, although this has not yet been demonstrated. Current hybrid systems available do not include state-of-the-art MDCT systems. As the CT hardware in hybrid systems becomes more robust, the feasibility of combining CTA, coronary calcium scoring, and SPECT- or PET-gated perfusion imaging will become a reality. Given that hybrid devices or sequential scintigraphic and CCT imaging will result in increased radiation exposure, expertise is needed to know in whom to apply these complementary techniques (23).

To facilitate the availability of new technology in all regions of the country, eventually including rural areas where there is frequently limited access to individuals trained in the latest technologies, consideration should be made to allow “cross-over” training for CT and nuclear medicine technologists. Similarly, “cross-over” may occur for physicians, including cardiology fellows, radiology residents, and nuclear medicine residents as well as for cardiologists, nuclear medicine physicians, and radiologists currently in practice. Each of these specialties incorporates radiation safety into their training programs. However, those trained in nuclear cardiology will require additional training in CCT detector physics and instrumentation, because individuals trained primarily in CCT will require additional time to learn physics and instrumentation of scintillation techniques and to review aspects of radionuclide handling and safety. Otherwise, requirements for the performance and interpretation of radionuclide, PET, and CCT studies should follow previously established guidelines and the recommendations set forth in this document.

**PROOF OF TRAINING.** Documentation of training can be achieved by means of letters or certificates from the director of a fellowship training program or from individuals who are Level 2 or Level 3 qualified in hospital-based or independent imaging centers or clinics. This documentation should state the dates of training and that the candidate has

**Table 5.** Documentation and Maintenance of Clinical Competence in CCT

Documentation of Competence	Training Guidelines	Proof of Competence
Training completed after July 1, 2008	Level 2 or Level 3 training as outlined	Letter of certification from training supervisor OR letter attesting to competence from Level 2- or 3-trained physician
Training completed before July 1, 2008	Level 2 training OR interpretation of at least 150 studies (in which 50 where the candidate is physically present, involved in the acquisition and interpretation of the case) and attendance in at least 20 h of devoted CCT classes Level 3 training OR interpretation of at least 300 studies (in which 100 where the candidate is physically present, involved in the acquisition and interpretation of the case) and attendance in at least 40 h of classes devoted to CCT	
Maintenance of competence	Contrast CCT examinations per year be performed and interpreted: Level 2: 50 Level 3: 100	

successfully achieved or surpassed each of the training elements (Levels 1, 2, and 3) (Table 5).

Practicing physicians can achieve appropriate training in CCT without enrolling in a formal CCT training program. However, the same prerequisite medical knowledge, medical training, and goals as outlined in the previous text are required. Directly working with a mentor on an ad-hoc basis is acceptable, but formalized time of cumulative exposure for Levels 1 to 3 competence will be maintained. Currently, a practicing physician seeking this training should have completed an ACGME-approved cardiovascular diseases fellowship, a general radiology residency, or a nuclear medicine residency.

**Maintaining expertise in CCT.** All individuals are required to provide evidence of continuing expertise in CCT. Individuals who are currently at Level 1 or Level 2 training can advance to Level 2 or Level 3 by pursuing independent advanced studies from either an academic center or an independent center specializing in CCT. No formal mechanisms currently exist regarding assurance of continuing competence. The field of CCT has expanded rapidly, and ongoing procedural and technical improvements are expected.

Maintenance of CCT expertise requires both ongoing continuing education and regular performance and interpretation of clinical and research CCT examinations. Physicians should periodically attend postgraduate courses and workshops that focus on clinical applications of CCT, especially those that emphasize new and evolving techniques and developments. In addition, physicians should seek to compare the quality, completeness, and results of their own examinations with those presented at scientific meetings and in professional publications. Level 2- and 3-trained individuals will be required to document and continue Category I CME in the area. The recommendations for maintaining Level 2 training is a minimum of 20 h of coursework devoted to CCT over a 3-year period of time. The recommendations for maintaining Level 3 training is a minimum of 40 h of coursework devoted to CCT over a 3-year period.

In conjunction with guidelines provided for other cardiovascular imaging modalities, it is recommended that at least 50 CCT examinations annually be performed and interpreted for those at Level 2 and 100 CCT examinations for those at Level 3 (Table 5).

**Prior experience to qualify for Levels 2 and 3 clinical competence for CCT.** It is expected that a substantial number of practitioners from multiple specialties have been performing these studies for some time before the creation of these guidelines. Thus, these practitioners can qualify for completion of Level 2 or Level 3 training by having achieved the minimum criteria set forth below by July 1, 2008, as well as board certification and completion of an ACGME-approved radiology or nuclear medicine residency or cardiology fellowship, or at least two months of formal training in CCT. Proof of competence can be obtained by a

letter of attestation by a Level 3-trained physician who has overread studies, or by letters or certificates from the training supervisor (Table 5).

Level 2 training: substantive activities in CCT over the last 3 years, with documented involvement in the performance and interpretation of at least 150 studies (at least half with contrast enhancement), and at least 20 h of coursework devoted to CCT.

Level 3 training: activities in CCT to include directing a CCT laboratory with documented involvement in the performance and interpretation of at least 300 studies (at least half with contrast enhancement), accrual of at least 40 h of coursework devoted to CCT, and peer recognition to include at least one of the following: 1) faculty lecturer for at least two CME courses on the topic of CCT, 2) fellowship/residency teaching activities, or 3) three or more peer-reviewed publications in the area of CCT.

## **CMR IMAGING**

### *Overview of CMR*

Cardiovascular magnetic resonance is well established in clinical practice for the diagnosis and management of a wide spectrum of cardiovascular disease. Use of CMR represents the specialized application of MR to the cardiovascular system, employing specialized receiver coils, pulse sequences, and gating methods.

A brief overview of the technical aspects of CMR (24) is included to facilitate the understanding of the terms used in the subsequent sections of this report and is not intended to be comprehensive. A CMR scanner has six major components. The magnet, which is usually superconducting, produces the static magnetic field whose strength is measured in Tesla (e.g., 1.5-T or 3-T; 1.5-T is equivalent to 15,000 Gauss, and the Earth's magnetic field is approximately 0.5 Gauss). A stable, homogeneous field is required about the area of interest. Resistive gradient coils within the bore of the magnet produce the gradient fields, and the currents within these coils are driven by the gradient amplifiers. The performance of the gradient system determines the speed of the MR acquisition. A radiofrequency (RF) coil (antenna) is coupled to an RF amplifier to excite the patient's protons with RF pulses, and this (or another more localized surface coil) is coupled to the receiver to measure the resultant signal. A computer is required to control the scanner and generate the images, which are then displayed in static, dynamic (cine) modes. Post-processing tools are extensive and used both for quantitation and for image display.

Like echocardiography, MR is fundamentally safe and does not interfere with the electron shells involved in chemical binding (e.g., DNA) that can be altered by ionizing radiation methods such as X-rays or CT. The phenomenon of MR is restricted to atomic nuclei with unpaired spin and includes hydrogen, carbon, oxygen, sodium, potassium, and fluorine; these latter elements are rarely used for imaging in clinical practice owing to their



low abundance or sensitivity to RF stimulation. Phosphorus is used for clinical CMR spectroscopy, but the majority of clinical CMR imaging involves the hydrogen nucleus, which is abundant in water, fat, and muscle.

In the presence of an external magnetic field (primary magnet), the hydrogen nucleus acts like a small magnet, which can align itself parallel to an external magnetic field, processing about the field in a manner analogous to a spinning top in a gravitational field. The frequency of precession is 63 MHz for field strength of 1.5-T and is in the RF range. Hydrogen nuclei can be excited by radio waves only at this resonant frequency, which has the effect of rotating the net magnetization vector by an amount termed the “flip angle.” After this excitation, the net magnetization vector precesses around the direction of the main field, returning to its former position (relaxation) during which energy is transmitted as a radio signal that can be detected by a receiver coil. The return of the net magnetization vector to equilibrium has two components. The vector component parallel to the main field relatively slowly returns to equilibrium by interacting with surrounding molecules, and this is known as “T1 relaxation.” Recovery of the vector component transverse to the field is more rapid and is termed “T2 relaxation.” The CMR images can be weighted to show the distribution of T1 or T2 (proton density). In order to localize the signals coming from the body, gradient magnetic fields are required that are switched on and off at appropriate times.

An MR pulse sequence is a combination of RF pulses and magnetic gradient field switches controlled by the scanning computer. For CMR, spin echo, gradient echo, steady-state free precession, phase velocity, and inversion recovery, pulse sequences are the most commonly used sequences. Spin echo sequences are routinely used for multi-slice anatomical imaging; rapidly moving blood is typically suppressed/dark while gradient echo and steady-state free precession sequences are used for physiological assessment of cardiac function through cine acquisitions, and rapidly moving blood is typically bright/white. Inversion recovery sequences are typically used in concert with MR contrast agents for infarction/viability imaging, where myocardium is purposefully nulled/black, infarct is bright/white, and blood is an intermediate/gray. Images may be performed with ECG gating/triggering (less preferred is peripheral pulse gating) and with respiratory suppression (breath holding or navigator gating). This reduces image artefacts.

As compared with CCT in which images are acquired in the axial plane and reconstructed in oblique orientations, with CMR, the data are often directly acquired in oblique imaging planes.

Some specialized sequences exist that have particular application for the cardiovascular system. For example, magnetic resonance angiography (MRA) is usually performed with 3D coverage of the vessel during a short breath-hold and after intravenous injection of a gadolinium-based contrast agent. Gadolinium has seven unpaired elec-

trons in its outer shell, and it hastens T1 relaxation, thereby increasing signal in the area of interest. Gadolinium alone is cytotoxic, but not if chelated with diethylenetriamine pentaacetic acid (DTPA). Gadolinium-chelate has similar pharmacokinetic properties to iodinated X-ray contrast but with minimal nephrotoxicity and anaphylaxis risk. Several FDA-approved gadolinium-DTPA preparations have been used for over a decade, and the safety profile is far more favorable than for iodinated contrast; however, it is not presently FDA approved for use in the heart.

Myocardial perfusion CMR follows the effect of a first pass of a bolus of intravenous gadolinium through multiple planes of the myocardium. Coronary MRI requires high spatial resolution. To characterize regional myocardial contraction, non-invasive “tagging” of the myocardium with a grid at end-diastole and subsequent cine acquisition to observe tag deformation allows for calculation of myocardial strain. Finally, velocity mapping is a sequence used to measure velocity and flow in blood vessels or within the heart (somewhat analogous to Doppler echocardiography) in which each pixel in the image displays the signal phase, which is encoded. Flow is calculated from the product of mean velocity, and the vessel area is measured throughout the cardiac cycle.

**CMR safety.** The CMR method is very safe for the cardiovascular patient, and no short- or long-term ill-effects have been demonstrated at current field strengths (less than 3-T). Claustrophobia is problematic in over 2% of patients (25). A very important safety issue for CMR is the prevention of ferromagnetic objects from entering the scanner area as these will become projectiles (attractive force accelerates as they approach the scanner). Common practice is to specifically check and verify that each medical device present in patients is MR safe. Metallic implants such as hip prostheses, mechanical heart valves, coronary stents, and sternal sutures present no hazard since the materials used are not ferromagnetic (although a local image artifact will result). Care is required in patients with cerebrovascular clips; however, specialist advice is needed for such patients. Patients with most pacemakers (implanted cardioverter-defibrillators [ICDs]) retained permanent transvenous pacemaker leads, and some other electronic implants (infusion or monitoring devices) should not be scanned, although some reports of success do exist in non-pacemaker-dependent patients who are carefully monitored during the procedure and have device interrogation before and after CMR (25,26).

**Biological and clinical effects of CMR exposure.** The biological effects of CMR exposure will be considered under the headings of attractive forces, heating, and stimulation. The presence of a large magnetic field will impart forces on all ferromagnetic materials. The RF field, which is used for excitation, can induce heating of tissue and implanted devices (particularly pacemaker leads or related devices). The RF power deposition (also known as specific absorption rate [SAR]) is actively monitored in accordance with FDA

standards. Finally, it is possible to stimulate sensitive tissues such as peripheral nerves owing to the rapidly changing gradient magnetic fields used to generate images. Myocardial stimulation has not been described with current hardware. Clinical CMR hardware has reached the limit for stimulation of peripheral nerves, and clinical imaging approaches are designed to avoid such stimulation.

### **CMR Laboratory Requirements**

**General considerations.** Defining the specific requirements for a valid CMR laboratory is beyond the scope of this document, which is concerned about accreditation for physicians. However, some general aspects of the appropriate MRI environment can be considered.

A continuous QC program must be established for all CMR units with the assistance of a qualified medical physicist and a Level 3-trained physician coordinator (levels of training are described in the following text). The scanners must be staffed by CMR technologists with appropriate background and/or training in CMR. A qualified medical physicist should periodically check equipment calibration (signal-to-noise ratio levels and image quality factors). A safety program should be active, and should include controlled access to the CMR equipment and training programs in CMR safety for all personnel. In addition, patient safety should be assured through a well documented screening and evaluation program for implanted devices, administered by the CMR medical director with ongoing documentation, training, and evaluation by nursing personnel performing screening procedures.

**MONITORING AND ANCILLARY HARDWARE.** The scanner should have appropriate monitoring hardware for ECG rhythm, non-invasive blood pressure measurement, and pulse oximetry determination during CMR procedures. If stress cardiac studies are performed using high-dose dobutamine, real-time image reconstruction and display or an on-the-fly display of cine images allowing rapid assessment of global and regional function to monitor the signs of myocardial ischemia should be available. For stress myocardial perfusion studies, CMR-compatible infusion pumps are necessary for the infusion of adenosine and possibly dipyridamole (if administered in the CMR imaging room), and an appropriate patient monitoring system is required. Nursing and physician personnel should be trained in the administration, monitoring, and side effects of the pharmacologic stress agents used by the center. Some patients benefit from supplemental oxygen using low flow nasal prongs during the study. A CMR-compatible power injector is necessary for gadolinium contrast-enhanced myocardial perfusion studies and preferred for contrast-enhanced MRA procedures. The CMR personnel should be trained in the recognition and management of reactions to CMR contrast media, to sedatives, and to other drugs administered as part of the CMR procedure.

**POST-PROCESSING AND DATA ANALYSIS.** The CMR laboratory should have the capabilities for post-processing CMR data, including LV and RV function determination, analysis of myocardial perfusion images, cine review of myocardial function studies, and a full 3D processing and display system for MRA studies.

**Clinical indications for CMR.** A comprehensive review of the clinical indications for CMR is beyond the scope of this report. Interested readers are referred elsewhere (24). A brief overview of broad clinical indications is presented in the text. These are intended to serve as a general guide for CMR training to include a broad spectrum of pathologic cases inclusive of these indications.

**CMR in ischemic heart disease: regional and global function, perfusion, viability, and coronary angiography.** Because of its inherent 3D capabilities, high spatial and temporal resolution, and high contrast resolution, CMR is widely recognized as the "reference standard" for the quantitative assessment of RV and LV volumes, EF, mass, and regional ventricular function. The CMR tagging techniques are unique among all modalities for determination of myocardial strain.

Use of CMR is a highly accurate and reproducible noninvasive method for measuring EF, LV volumes, and LV mass, and also to assess LV structure and function (27). Usually bright blood gradient echo sequences, with 15 s of breath-hold, are used to cover the entire LV with short-axis views from the mitral plane. Also, the sample size needed to detect LV parameter changes in a clinical trial is far less than other imaging modalities; this markedly reduces the time and cost of patient care and pharmaceutical trials (28). Regional LV function can be measured as in echocardiography using visual assessment of endocardial motion but more frequently systolic wall thickening. Beek et al. (29) demonstrated the relationship between functional recovery and transmural necrosis using visual assessment of systolic endocardial motion and wall thickening. Previous studies used similar methods to document similar relationships both in the acute (30) and chronic (31) myocardial infarction (MI) settings.

Although physical exercise within the confines of the magnet is technically difficult, there have been extensive studies of pharmacologic CMR stress. Both beta-agonist (e.g., dobutamine) stress examinations for inducible wall motion abnormalities and stress vasodilator (e.g., adenosine) in combination with first passage of a small dose of gadolinium-DTPA for assessment of myocardial perfusion have been shown to be accurate for detecting CAD. As the ST-segment is distorted/uninterpretable in the CMR environment, close clinical patient monitoring is required. Recent progress in the diagnosis and treatment of CAD has intensified the need to differentiate viable from non-viable myocardium with accuracy and high spatial resolution. Use of CMR has been demonstrated to be an effective technique to assess myocardial viability (32). The development of inversion recovery gradient echo imaging techniques pro-

vided the ability to temporally distinguish perfusion abnormalities created by microvascular obstruction from myocardial hyper-enhancement secondary to myocardial necrosis (33,34). The prognostic value of contrast-enhanced MRI in patients with acute MI is well established (35). However, recent work on the specific utilization of this technique for the purpose of predicting local functional recovery after acute MI (29,30,36) has further expanded its potential utilization.

Acute and chronic MI can be detected with high accuracy and sensitivity using delayed enhancement CMR with an inversion recovery sequence. The inversion time is chosen to null/suppress normal myocardial signal with resultant bright signal in areas of fibrosis where gadolinium-DTPA will concentrate. Both the delayed-enhancement technique and low-dose dobutamine have been shown to have great utility for the assessment of myocardial viability among patients being considered for revascularization.

The application of CMR coronary angiography for the assessment of the course of anomalous coronary arteries and coronary artery bypass graft (CABG) patency is well established. The use of CMR coronary angiography for native vessel integrity has been shown to be feasible, especially for the proximal and mid-portions of the major coronary vessels, but it remains technically demanding in the branch vessels owing to their smaller size, tortuosity, complex 3D anatomy, and cardiac and respiratory motion artifacts (9,37,38). Using current 3D acquisitions and optimized sequences, good results for the exclusion of multivessel disease have been shown. Currently available intracoronary stents appear to be CMR “safe,” but they can result in a localized signal artifact. Each new stent material requires evaluation for CMR safety.

**CMR in non-ischemic cardiomyopathies.** The non-ischemic cardiomyopathies include a variety of disorders in which the primary pathology directly involves the myocardium. Use of CMR is proving increasingly valuable in the identification and management of these conditions—including delineation of hypertrophy and fibrosis for hypertrophic cardiomyopathy, iron deposition in hemochromatosis, fatty or fibrous replacement in arrhythmogenic RV dysplasia, and myocarditis. The CMR technique is very effective for monitoring the severity of LV hypertrophy in hypertrophic cardiomyopathy and for the monitoring of ventricular volumes in dilated cardiomyopathy.

**CMR in pericardial disease.** Both CMR and CCT accurately define pericardial thickening and circumferential and loculated pericardial effusions. Although CCT has the advantage of pericardial calcium identification, CMR has the advantage of being able to depict and quantify the functional abnormalities, which may be associated with pericardial disease, and for demonstrating physiologic signs of ventricular interdependence with calcified pericardium.

**CMR in valvular heart disease.** Although echocardiography remains the preferred imaging modality for the routine determination of valve morphology and flow abnormalities,

CMR is starting to be utilized in the care of patients with regurgitant lesions. Valvular regurgitation is usually recognized as a signal void on cine CMR. A quantitative assessment of single-valve lesions can be obtained by calculating the regurgitant volume from the difference of RV and LV stroke volumes or the use of phase-velocity data from the ascending aorta and main pulmonary artery to calculate regurgitant volumes. Also, CMR has been shown to provide data for the estimation of gradients and areas in mitral and aortic stenosis.

**CMR for CHD patients.** The CMR technique is a very important resource for the evaluation of known or suspected CHD in children and adults. Assessment of CHD was one of the first clinical indications for the performance of CMR, and its utility in the assessment of CHD has grown with the development of CMR technology. Although echocardiography is often the initial imaging modality used in the assessment of CHD, CMR can provide accurate 3D assessment of cardiac structure and blood flow, especially valuable for patients with suboptimal acoustic windows. In addition, especially in adults, CMR may be a better method for assessing the great vessels and complex CHD.

A graduate of an ACGME-approved fellowship in cardiovascular diseases or residency in nuclear medicine or radiology should be able to determine the appropriate indications for CMR in CHD assessment, knowing whether to refer to CMR or another imaging modality. This is especially true in the assessment of pediatric CHD patients for whom echocardiography is not sufficient. The benefits of CMR in children must be balanced against the occasional requirement of deep sedation or general anesthesia.

### *Acquired Vascular Disease*

Use of CMR is particularly helpful for vascular lumen imaging because of its ability to generate projectional MRA. These can be generated either without contrast (time-of-flight technique) or contrast-enhanced with intravenous gadolinium. Consequently, it is well suited for use in patients with contraindications to X-ray contrast due to allergy or renal insufficiency. In addition to angiography, the wide variety of soft tissue contrast available on CMR (proton density, T1, T2, lipid-saturation) can be applied to vascular imaging to assess features of vessel wall such as hematoma/thrombus, inflammation, and atherosclerotic plaque. In addition to morphologic imaging of blood vessels, phase-contrast imaging (velocity mapping) can be used to quantify blood flow. Vascular CMR is beyond the scope of this document.

**Technical aspects of the CMR examination.** A CMR physician must be skilled in all technical aspects of performance of the CMR examination. This includes a thorough knowledge of available pulse sequences and the indications for their use. Sequences the CMR physician must be familiar with include:



1. Spin echo and cine sequences (segmented K-space gradient echo, steady-state free precession) for assessment of function and anatomy.
2. Fast, spin echo and half Fourier spin echo, black-blood sequences, for assessment of anatomy.
3. Phase contrast sequences for calculation of blood flow, shunt ratios, valve regurgitant fraction, and gradient assessment.
4. Contrast-enhanced MRA techniques for assessment of great vessels.
5. Delayed hyperenhancement imaging, dobutamine wall motion stress, and vasodilator stress perfusion imaging, tagging, and post-processing.

The CMR physicians should be familiar with the various types of coils available for cardiac imaging, and how they can be used in their patient populations (pediatric vs. adult), as well as K-space acquisition (symmetric, asymmetric, centric), and methods of ECG gating. The latter is especially important as the placement of leads may vary from the norm in patients with CHD.

In addition, the CMR physician must be familiar with the use of gadolinium-based MRI contrast agents including their indications and adverse reactions. The CMR physician should also be well versed in the treatment of the contrast reactions, including hives, wheezing, hemodynamic responses, and anaphylaxis, although rare. A thorough knowledge of appropriate doses of treatment medication, depending upon one's patient population (adult vs. pediatric), is crucial.

#### ***Minimal Knowledge and Skills Required for CMR Expertise***

The CMR training recommendations have been published by three societies: ACR, ACC, and SCMR (1-3). The ACC and SCMR recommendations directly address the goals of general training and are outlined by Task Force 12 of the COCATS-2 (1). The purpose of general training is to provide the practicing physician or resident/fellow in training with the working knowledge of CMR methods in order to facilitate patient care and management. It is recommended that all trainees in cardiovascular diseases and radiology have CMR exposure for at least one month or its equivalent when integrated with other activities during the practice of cardiovascular medicine or radiology. From a practical perspective, many clinicians in practice may not have access to CMR-enabled equipment or qualified (Level 2 or Level 3) mentors. It is recommended that candidates take this opportunity to supplement their education through lecture material, didactic reading, and journal or electronic media review. The committee reviewed guidelines set forth for other imaging modalities (for example, echocardiography, COCATS2) (1), and the caseload required reflects the need for increased time to learn the interpretation skills necessary but decreased physical training (for example, transducer time).

During general training in cardiovascular diseases and radiology, physicians should obtain a basic understanding of MR physics, which include the principles of image construction, T1 and T2 relaxation, measurements of blood flow, determinations of anatomy, image contrast, function, viability, myocardial perfusion, CMR contrast agents, and metabolism. Review of the indications and side effects of CMR contrast materials should occur along with exposure to proper receiver coil selection, methods of cardiac gating and triggering (e.g., ECG and peripheral pulse), respiratory motion suppression (e.g., breath-hold and navigators), and sources of image artifacts (e.g., motion, arrhythmias, and metal objects). Also, understanding of the contraindications to CMR, and the safety of devices within the MR environment, should be reviewed. Recognition of the sensitivity, specificity, diagnostic accuracy, costs, indications, and prognostic capability is to be accomplished in general training as this information is important for understanding the proper clinical use of CMR.

All cardiovascular and radiology trainees should actively participate in CMR interpretation under the supervision of a qualified (preferably Level 3) physician-mentor. Some supervision by an expert non-CMR physician can suffice for some of the basics of CMR, including workstation exposure, tomographic imaging training, and so on. Correlative sessions should be performed with other imaging modalities (echocardiography, nuclear cardiology, CCT, and invasive X-ray) as well as historical, physical examination, and laboratory and hemodynamic data. The types of procedures reviewed should include those directed toward assessments of the cardiovascular system, incorporating measures of structure, tissue characterization, function, myocardial perfusion, delayed hyperenhancement imaging, blood flow, plaque characterization, and angiography of the thoracic aorta and bypass grafts incorporating vessels within these territories. Procedures involving the use of intravenous contrast material should be included. A minimum of 50 such cases should be performed. This might include review and interpretation from an established teaching file of previous CMR cases or those administered from electronic media. Hands-on experience is not necessary for general training.

**Formal training to achieve competence in CMR.** The recommendations for all levels of training below represent a cumulative experience, and it is expected that for many practicing clinicians the training will not be continuous. Time spent at didactic CME courses that specifically target CMR can also contribute to the total time. Due to the advancement in the sophistication and widespread availability of electronic training medias, the committee felt that some training can now be obtained outside the laboratory setting. However, for all Level 2 and Level 3 requirements, minimum time in a laboratory supervised by a Level 2 or Level 3 CMR physician is half of the time listed, with the other half garnered by supervised time, CME and other courses, case studies, CD/DVD training, and time spent at

major medical meetings devoted to performance of CMR, to cite just a few examples. The caseload recommendations might include studies from an established teaching file, previous CMR cases or electronic/on-line CME. Although this is less “in-laboratory” time than that listed in both the COCATS and the SCMR published recommendations (1,3), these other documents also include training time for peripheral imaging.

For all levels of competence, it is expected that the candidate will attend lectures on the basic concepts of CMR and include parallel self-study reading material. A basic understanding of CMR should be achieved, including the physics of MRI in general and of CMR in particular. The content should include the basics of CMR scan performance, CMR safety issues, and basics of CMR interpretation as compared with other cardiovascular imaging modalities including echocardiography, nuclear medicine, CCT, and invasive cardiac X-ray angiography.

**LEVEL 1 TRAINING.** Level 1 is defined as the minimal introductory training for familiarity with CMR, but this exposure is not sufficient for independent interpretation of CMR images. The individual should have intensive exposure to the methods and the multiple applications of CMR for a period of at least four weeks. This should provide a basic background in CMR for the practice of adult cardiology or for general radiology.

During this cumulative four-week experience, individuals should have been actively involved in CMR interpretation under the direction of a qualified (Level 2- or Level 3-trained) physician-mentor. For all studies in which other cardiovascular imaging methods are also available, correlation with CMR findings and interpretation should be included. Studies should consist as much as possible within the range of pathologies outlined in the previous text. Independent performance of CMR is not required for Level 1 training, and the mentored interpretive experience of 50 cases may include studies from an established teaching file or previous CMR cases.

**LEVEL 2 TRAINING.** Level 2 training is defined as the minimum recommended instruction for a physician to independently perform and interpret CMR. This is an extension of Level 1 training and is intended for individuals who wish to practice or actively be involved with CMR performance and interpretation. The minimum requirement is three months of cumulative experience, with a minimum time in a program supervised by a Level 2 or Level 3 CMR physician over a period of six weeks, with the other six weeks garnered by supervised time, CME and other courses, case studies, CD/DVD training, time spent at major medical meetings devoted to performance of CMR, and so forth. In-lab training time is defined as a minimum of 35 h/week.

Didactic instruction as well as tested self-study should be administered in MR physics, MR applications and indications, and clinical interpretation. Didactic studies should

consist of more advanced lectures and reading materials as well as formal case presentations and should include the following:

1. Physics—trainees should receive didactic lectures from a CMR-trained physician and/or physicist on the basic physics of MR. Topics should include:
  - a. Image formation, including K-space (implications of symmetric and asymmetric, spiral, radial K-space sampling) gradient echo imaging, spin echo imaging, echo planar imaging, fast spin echo imaging, and 2D and 3D imaging.
  - b. Physics implicating patient safety, including energy deposition, specific absorption rate (SAR) limits and possible neurological effects, and heating and motion of metallic implants.
  - c. Specialized imaging sequences, including flow and motion, phase imaging, time-of-flight, respiratory gating, contrast agents, and MR tagging.
  - d. Hardware components, including basic elements of gradient coil design, receiver coils, and digital sampling.
2. Applications and Indications—didactic activities should include discussion of the sensitivity, specificity, accuracy, utility, costs, and disadvantages of all CMR techniques and applications. The following techniques should be covered in the didactic program:
  - a. ECG and peripheral pulse gating and triggering, including timing of image acquisition within the R-R interval, motion artifacts and their effects upon image interpretation, velocity calculation, and other physiological quantifications.
  - b. Respiratory motion suppression, including its uses and effects upon image interpretation.
  - c. Stress pharmacologic agents and their application to CMR, including adequate monitoring under CMR performance and reversal of stress conditions.
  - d. Imaging of structure and tissue characterization (T1, T2, spin echo imaging), tissue (inversion recovery, saturation recovery methods) and fat suppression.
  - e. Imaging of ventricular function (cine and tagged cine MRI).
  - f. Flow imaging (velocity-encoded techniques).
  - g. First-pass perfusion and delayed contrast-enhancement imaging (gadolinium-enhanced techniques).
  - h. Image processing for creating of angiographic images, velocity and flow calculation, function parameters (EF, myocardial mass, and so on)
  - i. Clinical instruction—a Level 3 CMR mentor must be able to provide the trainee with instruction in adequate image interpretation. Topics addressed should include those listed above.

During this training experience, each candidate should actively participate in CMR study interpretation under the direction of a qualified (preferably Level 3-trained) physician-mentor. The candidate should be involved with

interpretation of at least 150 CMR examinations in which at least 50 necessitated the candidate being physically present and involved in the acquisition and interpretation of the case. Cases should reflect the broad range of anticipated pathology.

Each physician should receive didactic lectures from a CMR mentor and/or physicist on the basic physics of MR in general and on CMR in particular. Lectures should include discussions of anatomy, contrast administration and kinetics, CMR safety, and the principles of 3D imaging and post-processing. Finally, the physician should be thoroughly acquainted with the many morphologic and pathophysiologic manifestations and artifacts demonstrated on CMR images.

**Table 6** provides a summary of the overall requirements for CMR Level 1 and Level 2 training.

**LEVEL 3 TRAINING.** Level 3 training represents the highest level of exposure/expertise that would enable an individual to serve as director of an academic CMR section or director of an independent CMR facility. This individual would be directly responsible for QC and training of technologists and to be a mentor to other physicians seeking such training. The minimum cumulative training period should be 12 months and include all the didactic requirements of Level 2 training as well as participation in CMR study interpretation under the direction of a qualified (Level 3-trained) physician-mentor. In-lab training time is defined as a minimum of 35 h/week. The candidate should be involved with interpretation of at least 300 CMR examinations in which at least 100 involved the candidate as the primary operator and interpreter. Cases should reflect the broad range of pathology expected in a CMR practice.

In addition to the recommendations for Level 1 and Level 2 training, Level 3 training should include active participation in an ongoing laboratory, clinical research, or teaching. This also requires continued and documented clinical and educational experiences. These requirements are listed in **Table 7**. Cooperation between radiology and cardiovascular disease colleagues is encouraged. Additionally, supervising CMR physicians should have appropriate knowledge of alternative imaging methods, including the use and indications for specialized procedures encompassing echocardiography and vascular ultrasound, CCT, and nuclear medicine/PET studies.

**Special training in CHD requirements.** A physician with Level 2 or Level 3 training in CMR should be capable of

recognizing simple CHD. However, as with echocardiography (39), few adult cardiology training programs have a sufficient case load and case mix of complex lesions to ensure an adequate level of training. Although those trained in CMR may be able to recognize the presence of a complex congenital lesion, many MRI programs are unable to provide enough experience to trainees to develop the special skills necessary to evaluate complex CHD, post-surgical appearance, and post-surgical complications. Competence in performing and/or interpreting CMR in pediatric and adult patients with complex CHD requires the basic knowledge of MRI physics, instrumentation, anatomy, physiology, and pathology for CMR interpretation. Practitioners who wish to perform CMR in patient populations with adult and pediatric CHD need special experience. A recommended case load (as part of the total number recommended for competence) for Level 2 is 25 cases, and Level 3 is 50 cases, with additional 20 cases annually to maintain competence. Of note, case mix is an important aspect of the training experience.

The CMR physician must also be well trained in the following:

For the pediatric CHD patient:

1. Cardiac structure and physiology during growth and development from infancy to adulthood.
2. Spectrum of acquired heart disease in the pediatric age group.
3. Spectrum of surgical palliation and surgical repair of CHD and its manifestations on CMR.
4. Spectrum of catheter-based interventions for CHD and its manifestations in the CMR examination.
5. Indications for performance of CMR in the pediatric patient, including the risks of general anesthesia and conscious sedation in relationship to the benefit of diagnostic information obtained for a given purpose.

For the adult CHD patient:

1. Anatomic and physiologic spectrum of CHD and its manifestations in the adult.
2. Spectrum of surgical palliation and repair for CHD and its manifestations on CMR.
3. Spectrum of catheter-based interventions for CHD and its manifestations in the adult CMR.
4. Sequelae of surgical palliation and repair and catheter-based interventions and their presence and manifestation in CMR.

**Table 6.** Requirements for CMR Study Performance and Interpretation to Achieve Level 1, 2, and 3 Training

	Cumulative Duration of Training	Minimum Total Number of Mentored Examinations Performed	Minimum Number of Mentored Examinations Interpreted
Level 1	1 month	—	50†
Level 2	3 months*	50	150†
Level 3	1 year*	100	300†

\*This represents cumulative time spent interpreting, performing, and learning about CMR, and need not be a consecutive block of time, but at least 50% of the time should represent supervised laboratory experience. This can include time spent at educational courses on the topic. Training time is defined as a minimum of 35 h/week. †The caseload recommendations may include studies from an established teaching file, previous CMR cases, and electronic/on-line CME.



**Table 7.** Requirements for Level 2 and Level 3 CMR Training Clinical Competence

	Level 2	Level 3
Initial experience	<ul style="list-style-type: none"> <li>● Board certification or eligibility, valid medical license, and completion of a 3-month (cumulative) specialty residency or fellowship in CMR, AND</li> <li>● 150 CMR examinations in which 50 where the candidate is physically present, involved in the acquisition and interpretation of the case, AND</li> <li>● Completion of 30 h of courses related to MR in general and/or CMR in particular</li> </ul>	<ul style="list-style-type: none"> <li>● Board certification or eligibility, valid medical license, and completion of a 12-month (cumulative) specialty residency or fellowship in CMR, AND</li> <li>● 300 CMR examinations in which 100 where the candidate is physically present, involved in the acquisition and interpretation of the case, AND</li> <li>● Completion of 60 h of courses related to MR in general and/or CMR in particular</li> </ul>
Continuing education	30 h of coursework every 36 months in CMR	60 h of coursework every 36 months in CMR

5. Impact of acquired heart disease on the physiology of the underlying congenital lesion.

**PROOF OF TRAINING.** Documentation of training can be achieved by means of letters or certificates from the director of a fellowship training program or from individuals who are Level 2 or Level 3 qualified in hospital-based or independent imaging centers or clinics (Table 8). This documentation should state the dates of training and that the candidate had successfully achieved or surpassed each of the training elements (Levels 1, 2, and 3).

Practicing physicians can achieve appropriate training in CMR without enrolling in a full-time formal training program. However, the same prerequisite medical knowledge, medical training, and goals as previously outlined are required. Directly working with a mentor on an ad-hoc basis is acceptable, but formalized time of cumulative exposure for Levels 1 through 3 competence will be maintained. Currently, a practicing physician seeking this training should have completed an ACGME-approved cardiovascular diseases fellowship, nuclear medicine or general radiology residency, and hold a valid license to practice.

**Maintaining CMR expertise.** Individuals, even after a formal fellowship training period, are required to continue maintenance of expertise in CMR. Those who are currently at Level 1 or Level 2 training can advance to the next level by pursuing independent advanced studies either from an academic center or an independent center specializing in CMR. No formal mechanisms currently exist regarding assurance of maintaining competence. The field of CMR has expanded rapidly, and ongoing procedural and technical improvements are expected.

Maintenance of CMR expertise requires both ongoing continuing education and regular performance and interpretation of clinical and research CMR examinations. Physicians should periodically attend postgraduate courses and workshops that focus on clinical applications of CMR, especially those that emphasize new and evolving techniques and developments. In addition, physicians should seek to compare the quality, completeness, and results of their own examinations with those presented at scientific meetings and in professional publications. Level 2- and Level 3-trained individuals will be required to document category I CME in the area. Recommended CME for maintaining Level 2 training is 30 h devoted to CMR over a 3-year period. Recommended CME for maintaining Level 3 training is 60 h devoted to CMR over a 3-year period. It is also recommended that at least 50 CMR examinations each year be performed and interpreted for those at Level 2 and at least 100 CMR examinations for those maintaining Level 3 training.

**Prior experience to qualify for Levels 2 and 3 training for CMR.** It is expected that a substantial number of practitioners from radiology, cardiology, and nuclear medicine have been performing CMR studies for some time prior to the creation of these guidelines. These practitioners can qualify for completion of Level 2 or Level 3 training by having achieved the minimum criteria set forth below by July 1, 2008, as well as board certification and completion of an ACGME-approved radiology residency or cardiology fellowship, or at least six months' formal training in CMR.

Level 2 training: there should be substantive activities in

**Table 8.** Documentation and Maintenance of Clinical Competence in CMR

Documentation of Competence	Training Guidelines	Proof of Competence
Training completed after July 1, 2008	Level 2 training	Letter or certification from training supervisor OR letter attesting to competence from Level 2- or 3-trained physician
Training completed before July 1, 2008	Level 2 training OR interpretation of at least 150 studies (in which 50 where the candidate is physically present, involved in the acquisition and interpretation of the case) and attendance in at least 30 h of devoted CME Level 3 training OR interpretation of at least 300 studies (in which 100 where the candidate is physically present, involved in the acquisition and interpretation of the case) and attendance in at least 60 h of devoted CME, and acknowledged teacher of CMR	
Maintenance of competence	Performance and/or interpretation of 50 (Level 2) or 100 (Level 3) cases/yr	

CMR over the last three years, with documented involvement in the performance and interpretation of the last three years.

Level 3 training: activities in CMR should include running a CMR laboratory, with documented involvement in the performance and interpretation of at least 300 CMR studies; attendance in at least 60 h of CME devoted to CMR, and being an acknowledged CMR instructor as a faculty member teaching CME courses on the topic; or CMR teaching activities with at least three published studies in the area of CMR. Proof of competence can be obtained by a letter of attestation by a Level 3 physician who has overread the studies or a letter or certificate from one's training supervisor (Table 8).

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## REFERENCES

1. Pohost GM, Kim RJ, Kramer CM, Reichek N. Task Force 12: Training in Cardiovascular Magnetic Resonance. Available at: <http://www.acc.org/clinical/training/COCATS2.pdf>. Last update 2002.
2. Weinreb JC, Larson PA, Woodard PK, et al. American College of Radiology Clinical Practice Statement on noninvasive imaging. *Radiology* 2005;235:723-7.
3. Society for Cardiovascular Magnetic Resonance (SCMR) Clinical Practice Committee. Guidelines for credentialing in cardiovascular magnetic resonance (CMR). *J Cardiovasc Magn Reson* 2000;2:233-4.
4. Bell MR, Lerman LO, Rumberger JA. Validation of minimally invasive measurement of myocardial perfusion using electron beam computed tomography and application in human volunteers. *Heart* 1999;81:628-35.
5. Rumberger JA. Use of ultrafast (cine) X-ray computed tomography in cardiac and cardiovascular imaging. In: Giuliani ER, editor. *Mayo Clinic Practice of Cardiology*. St. Louis, MO: Mosby, 1996:303-24.
6. Arad Y, Spadaro LA, Goodman K, Newstein D, Guerci AD. Prediction of coronary events with electron beam computed tomography. *J Am Coll Cardiol* 2000;36:1253-60.
7. Kondos GT, Hoff JA, Sevrukov A, et al. Electron-beam tomography coronary artery calcium and cardiac events: a 37-month follow-up of 5,635 initially asymptomatic low- to intermediate-risk adults. *Circulation* 2003;107:2571-6.
8. Shaw LJ, Raggi P, Schisterman E, Berman DS, Callister TQ. Prognostic value of cardiac risk factors and coronary artery calcium screening for all-cause mortality. *Radiology* 2003;228:826-33.
9. Budoff MJ, Achenbach S, Duerinckx A. Clinical utility of computed tomography and magnetic resonance techniques for noninvasive coronary angiography. *J Am Coll Cardiol* 2003;42:1867-78.
10. Lu B, Shavelle DM, Mao S, et al. Improved accuracy of noninvasive electron beam coronary angiography. *Invest Radiol* 2004;39:73-9.
11. Ropers D, Baum U, Pohle K, et al. Detection of coronary artery stenoses with thin-slice multi-detector row spiral computed tomography and multiplanar reconstruction. *Circulation* 2003;107:664-6.
12. Hoffmann U, Moselewski F, Cury RC, et al. Predictive value of 16-slice multidetector spiral computed tomography to detect significant obstructive coronary artery disease in patients at high risk for coronary artery disease: patient-versus segment-based analysis. *Circulation* 2004;110:2638-43.
13. Leta R, Carreras F, Alomar X, et al. [Non-invasive coronary angiography with 16 multidetector-row spiral computed tomography: a comparative study with invasive coronary angiography]. *Rev Esp Cardiol* 2004; 7:217-24.
14. Nasir K, Budoff MJ, Post WS, et al. Electron beam CT versus helical CT scans for assessing coronary calcification: current utility and future directions. *Am Heart J* 2003;146:969-77.
15. Hunold P, Vogt FM, Schmermund A, et al. Radiation exposure during cardiac CT: effective doses at multi-detector row CT and electron-beam CT. *Radiology* 2003;226:145-52.
16. Morin RL, Gerber TC, McCollough CH. Radiation dose in computed tomography of the heart. *Circulation* 2003;107:917-22.
17. Jakobs TF, Becker CR, Ohnesorge B, et al. Multislice helical CT of the heart with retrospective ECG gating: reduction of radiation exposure by ECG-controlled tube current modulation. *Eur Radiol* 2002;12:1081-6.
18. Kuettner A, Beck T, Drosch T, et al. Diagnostic accuracy of noninvasive coronary imaging using 16-detector slice spiral computed tomography with 188 ms temporal resolution. *J Am Coll Cardiol* 2005;45:123-7.
19. Mollet NR, Cademartiri F, Krestin GP, et al. Improved diagnostic accuracy with 16-row multi-slice computed tomography coronary angiography. *J Am Coll Cardiol* 2005;45:128-32.
20. Cerqueira MD, Weissman NJ, Dilsizian V, et al. Standardized myocardial segmentation and nomenclature for tomographic imaging of the heart: a statement for healthcare professionals from the Cardiac Imaging Committee of the Council on Clinical Cardiology of the American Heart Association. *Circulation* 2002;105:539-42.
21. Baik HK, Budoff MJ, Lane KL, Bakhsheshi H, Brundage BH. Accurate measures of left ventricular ejection fraction using electron beam tomography: a comparison with radionuclide angiography, and cine angiography. *Int J Card Imaging* 2000;16:391-8.
22. Shavelle DM, Takasu J, Budoff MJ, Mao S, Zhao XQ, O'Brien KD. HMG CoA reductase inhibitor (statin) and aortic valve calcium. *Lancet* 2002;359:1125-6.
23. Benatar NA, Cronin BF, O'Doherty MJ. Radiation dose rates from patients undergoing PET: implications for technologists and waiting areas. *Eur J Nucl Med* 2000;27:583-9.
24. Pennell DJ, Sechtem UP, Higgins CB, et al. Clinical indications for cardiovascular magnetic resonance (CMR): Consensus Panel report. *Eur Heart J* 2004;25:1940-65.
25. Kuijpers D, Janssen CH, van Dijkman PR, Oudkerk M. Dobutamine stress MRI. Part I. Safety and feasibility of dobutamine cardiovascular magnetic resonance in patients suspected of myocardial ischemia. *Eur Radiol* 2004;14:1823-8.
26. Martin ET, Coman JA, Shellock FG, Pulling CC, Fair R, Jenkins K. Magnetic resonance imaging and cardiac pacemaker safety at 1.5-Tesla. *J Am Coll Cardiol* 2004;43:1315-24.
27. Task Force of the European Society of Cardiology, in collaboration with the Association of European Paediatric Cardiologists. The clinical role of magnetic resonance in cardiovascular disease. *Eur Heart J* 1998;19:19-39.
28. Semelka RC, Tomei E, Wagner S, et al. Normal left ventricular dimensions and function: interstudy reproducibility of measurements with cine MR imaging. *Radiology* 1990;174:763-8.
29. Beck AM, Kuhl HP, Bondarenko O, et al. Delayed contrast-enhanced magnetic resonance imaging for the prediction of regional functional improvement after acute myocardial infarction. *J Am Coll Cardiol* 2003;42:895-901.
30. Choi KM, Kim RJ, Gubernikoff G, Vargas JD, Parker M, Judd RM. Transmural extent of acute myocardial infarction predicts long-term improvement in contractile function. *Circulation* 2001; 104:1101-7.
31. Kim RJ, Wu E, Rafael A, et al. The use of contrast-enhanced magnetic resonance imaging to identify reversible myocardial dysfunction. *N Engl J Med* 2000;343:1445-53.
32. Goldman MR, Brady TJ, Pykett IL, et al. Quantification of experimental myocardial infarction using nuclear magnetic resonance imaging and paramagnetic ion contrast enhancement in excised canine hearts. *Circulation* 1982;66:1012-6.
33. Lima JA, Judd RM, Bazille A, Schulman SP, Atalar E, Zerhouni EA. Regional heterogeneity of human myocardial infarcts demonstrated by

- contrast-enhanced MRI: potential mechanisms. *Circulation* 1995;92:1117–25.
34. Rochitte CE, Lima JA, Bluemke DA, et al. Magnitude and time course of microvascular obstruction and tissue injury after acute myocardial infarction. *Circulation* 1998;98:1006–14.
  35. Wu KC, Zerhouni EA, Judd RM, et al. Prognostic significance of microvascular obstruction by magnetic resonance imaging in patients with acute myocardial infarction. *Circulation* 1998;97:765–72.
  36. Gerber BL, Garot J, Bluemke DA, Wu KC, Lima JA. Accuracy of contrast-enhanced magnetic resonance imaging in predicting improvement of regional myocardial function in patients after acute myocardial infarction. *Circulation* 2002;106:1083–9.
  37. Woodard PK, Li D, Haacke EM, et al. Detection of coronary stenoses on source and projection images using three-dimensional MR angiography with retrospective respiratory gating: preliminary experience. *AJR Am J Roentgenol* 1998;170:883–8.
  38. Kim WY, Danias PG, Stuber M, et al. Coronary magnetic resonance angiography for the detection of coronary stenoses. *N Engl J Med* 2001;345:1863–9.
  39. Quinones MA, Douglas PS, Foster E, et al. ACC/AHA clinical competence statement on echocardiography: a report of the American College of Cardiology/American Heart Association/American College of Physicians-American Society of Internal Medicine Task Force on Clinical Competence. *J Am Coll Cardiol* 2003;41:687–708.

**Appendix.** ACCF/AHA Writing Committee to Develop a Clinical Competence Statement on Cardiac Imaging With Computed Tomography and Magnetic Resonance—Relationships With Industry

Name	Consultant	Research Grant	Scientific Advisory Board	Speaker's Bureau	Steering Committee	Stock Holder
Dr. Matthew J. Budoff	None	None	None	● General Electric	None	None
Dr. Mylan C. Cohen	None	None	None	None	None	None
Dr. Mario J. Garcia	None	● Philips Medical Systems ● Bristol Myers Squibb	None	● GE Healthcare ● Bristol Myers Squibb	None	None
Dr. John McB. Hodgson	● Volcano Therapeutics	● Bristol Myers Squibb	● Volcano Therapeutics	● Medicines ● Guilford ● Radi ● Volcano Therapeutics	None	None
Dr. W. Gregory Hundley	None	● Mallinckrodt ● Bracco Diagnostics	None	● Bracco Diagnostics ● Pfizer	None	None
Dr. Joao A.C. Lima	None	● Merck, Inc. ● Fujisawa Inc. ● Toshiba Inc.	● GEMS	● Toshiba Inc.	None	None
Dr. Warren J. Manning	● Amesham Health	● Philips Medical Systems	● Astra-Zeneca ● Bristol Myers Imaging	None	None	None
Dr. Gerald M. Pohost	● White Memorial Hospital	● GE Healthcare	None	● Takeda	None	None
Dr. Paolo M. Raggi	None	● Pfizer	None	None	None	None
Dr. George P. Rodgers	None	None	None	None	None	None
Dr. John A. Rumberger	None	None	None	● GE Healthcare	None	None
Dr. Allen J. Taylor	None	Kos	None	● Pfizer ● Kos ● Wyeth	None	None

This table represents the relationships of committee members with industry that were reported orally at the initial Writing Committee meeting and updated in conjunction with all meetings and conference calls of the Writing Committee during the document development process. It does not necessarily reflect relationships with industry at the time of publication.