Published in final edited form as:

Pediatr Radiol. 2018 January ; 48(1): 5–20. doi:10.1007/s00247-017-3991-x.

Radiation Dose Management for Pediatric Cardiac Computed Tomography: A Report from the Image Gently “Have-A-Heart” Campaign

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Abstract

Children with congenital and acquired heart disease (CAHD) may be exposed to relatively high lifetime cumulative doses of ionizing radiation from necessary medical imaging procedures including radiography, fluoroscopic procedures including diagnostic and interventional cardiac catheterizations, electrophysiology examinations, cardiac computed tomography (CT) studies, and nuclear cardiology examinations. Despite the clinical necessity of these imaging studies, the related ionizing radiation exposure could pose an increased lifetime attributable cancer risk. The Image Gently “Have-A-Heart” Campaign is promoting the appropriate use of medical imaging studies in children with CAHD while minimizing radiation exposure. The focus of this manuscript is to provide a comprehensive review of radiation dose management and CT performance in children with CAHD.

Keywords

congenital heart disease; cardiac computed tomography; pediatrics; radiation safety

Introduction

Diagnostic imaging and image-guided interventions are essential in the care of children with known or suspected congenital or acquired heart disease (CAHD). Many imaging modalities, including radiography, fluoroscopy/angiography, computed tomography (CT), and nuclear imaging depend on ionizing radiation for image formation. Ionizing radiation in high doses can have biological effects, including carcinogenesis [1]. However, the amount of radiation delivered for diagnostic imaging is typically low-level. Evidence of DNA damage has been shown to occur with ionizing radiation doses in the medical imaging range [2, 3], but how this relates to the risk of cancer is not known [1]. There have been reports of excess cancer risk in patients exposed to CT as children [4, 5], but the challenges to the methodologies of these studies, including the possibility of reverse causation, highlight the complexities of studying excess cancer risk in populations [6–9]. Children are especially vulnerable to the harmful effects of ionizing radiation due to the greater sensitivity of growing tissue and a longer anticipated lifetime to manifest radiation induced damage as compared to adults [10]. Moreover, due to reduced tissue attenuation, similar exposures in smaller children result in greater doses to organs and tissues than in larger children (i.e., teenagers) and adults.

The scientific and medical communities are engaged in a dialogue regarding the relationship of radiation from modalities such as CT and cancer risk. Opinions range from a perspective that small amounts of radiation may reduce cancer risk (hormesis), to positions that risk is effectively zero, linearly related to dose, or that risk is greater than linear [4, 5, 11–16]. The majority of the expert communities, reflected by reports from the International Commission on Radiological Protections, the United States National Academies and the National Council on Radiation Protection and Measurements [10, 17–20], subscribe to the position that the

risk associated with low dose ionizing radiation exposure is uncertain, with a linear relationship between dose and risk reasonably fitting the limited available data. This perspective is reflected in the principle of ALARA and incorporates both justification and optimization. Justification indicates that imaging is appropriately indicated and that the expected benefits are sufficiently greater than the risks. Optimization entails performing the study so that there is due consideration given to both image quality and radiation exposure, using only as much radiation as is necessary to address the clinical questions. A scientific statement of expert consensus recommendations for multimodality optimization of medical imaging procedures commonly performed in children with CAHD was written as part of the Image Gently “Have-A-Heart” Campaign [21]. This Image Gently report will focus on radiation dose management and cardiac CT performance in children with CAHD.

Several factors guide the discussion of CT radiation and risk in children CAHD: 1) increasing value and use of this modality even in the youngest children [22–24], 2) relatively high radiation dose of CT compared with radiography, 3) longer anticipated survival of children relative to adults, with the potential for larger cumulative doses, and 4) less familiarity with the proper performance of pediatric CT for CAHD among those who care for these patients relatively infrequently [23, 25–29]. Healthcare providers as well as patients, parents, other caregivers and the public have a limited and sometimes inaccurate understanding of which imaging examinations use radiation, the potential and effective radiation doses of these exams, and the attendant risks [30–39]. For these reasons, we will review key aspects of cardiac CT performance in children with CAHD as a reference with respect to radiation dose management for those involved in the care of these children including primary providers, pediatric radiologists, cardiologists, and surgeons, and physicists, technologists, and nurses. Topics include radiation dose metrics, reported cardiac CT dose ranges, considerations for selecting cardiac CT as an imaging modality, techniques for optimum performance of cardiac CT, risk communication with patients and caregivers, and implementation of institutional CT dose monitoring.

Radiation dose metrics

Effective dose is a calculated whole body metric reported in the SI unit of Sievert (Sv). Effective dose reflects the relative risk of detrimental biological effects from exposure to ionizing radiation and accounts for the absorbed dose to all cancer-susceptible organs of the body, the relative harm level of the type of ionizing radiation, and the organ radiation sensitivities with respect to cancer susceptibility from ionizing radiation exposure. As a whole body metric, effective dose is useful for comparing doses across different imaging modalities that employ ionizing radiation (e.g., radiographs, fluoroscopy, CT, nuclear medicine) [40, 41].

CT dose reports

Current CT scanners provide a DICOM structured dose report containing the volumetric CT dose index (CTDI_{vol}) and dose-length product (DLP) (Figure 1) [42]. CTDI_{vol} is a measurement of radiation output of a CT scanner that is calculated by irradiating a cylindrical acrylic phantom with either a diameter of 32 cm (models the adult body) or 16

cm (models the adult head) using standard conditions and methods [43, 44]. Air kerma (in mR) measurements at the edge and center of the phantom using an ionization chamber are consolidated with a weighted average then scaled by the pitch of the helical scan to calculate the $CTDI_{vol}$. $CTDI_{vol}$ is useful for comparing the overall effects of dose modification efforts on a single scanner, and for comparing the difference in radiation output for a specific exam between different CT scanners. The radiation output of a CT scanner may be based on patient-specific information, such as the use of the patient localizer images for tube current modulation based on tissue attenuation [45]. DLP is calculated from the product of $CTDI_{vol}$ and irradiated scan length (z-axis), and is reported in units of mGy-cm. Neither $CTDI_{vol}$ nor DLP are patient-specific as both are measurements of radiation output and not of patient dose [46]. DLP will not differentiate dose between a child and an adult cardiac CT scan using the same parameters and z-axis scan length. However, $CTDI_{vol}$ and DLP are widely used dose metrics because these values are automatically generated by the CT scanner both before and after each exam.

Unlike CT scanner radiation output measurements of $CTDI_{vol}$ and DLP, effective dose estimation for CT is not standard and continues to evolve [47]. Effective dose estimation methodologies include physical phantom based measurements, calculated estimates from the product of DLP and a conversion or *k*-factor based on the region of the body scanned (estimated effective dose in mSv = $k \times DLP$), and Monte Carlo simulations [41]. These methods have varying degrees of calculated effective dose agreement [40, 48, 49]. As a result, estimates of effective dose for a CT study performed on one patient may differ substantially because of effective dose calculation methodology alone [47, 49]. Additionally, and unlike many other body CT applications, there is no consensus on a standard calculation method for cardiac CT effective dose [50]. There are published conversion factors for the head, neck, chest, and abdomen and pelvis CT examinations. Chest conversion factors have been used to calculate effective dose for cardiac CT examinations, but the irradiated z-axis scan length for a chest CT examination is generally greater than for a cardiac CT study. Additionally, the ECG-synchronization used for cardiac CT is not accounted for by the chest conversion factors. Pediatric cardiac CT specific conversion factors have been published, but there are no currently available cardiac conversion factors for children of all sizes, all scanner types or all cardiac CT scan protocols [50–52]. However, pediatric cardiothoracic CT conversion factors representing the calculated average of multiple published pediatric cardiac and chest CT conversion factors have approval of the American Association of Physicists in Medicine and represent a useful alternative to the not yet universally available cardiac specific CT conversion factors [21]. Lastly, the generic weighting of radiosensitive organs is included in the effective dose calculation; however, individual patient metrics (such as variation in organ size and location, or age related sensitivities) are not reflected in this calculation. Steps towards describing the radiation absorbed by the imaged patient have been proposed that include the size-specific dose estimate (SSDE), a metric that involves the anteroposterior and lateral patient dimensions (effective diameter) or patient attenuation metrics (water equivalent diameter) in adjustments for $CTDI_{vol}$ [53, 54]. Patient dimensions can be measured from the CT localizer radiographs, from axial images, or can be directly measured on the patient using calipers. Water equivalent diameter can be calculated from the

CT localizer radiographs or axial CT images. SSDE has not been widely adopted for cardiac CT dose estimation [55, 56].

Radiation Effects

Ionizing radiation is associated with tissue reactions (formerly known as non-stochastic or deterministic effects) and stochastic effects. Tissue reactions such as skin ulceration and hair loss only occur when absorbed radiation doses exceed a threshold value [1]. Tissue reactions may result from cumulative absorbed dose within a short period of time (on the order of days). Tissue reactions are rarely seen in children because reasonable image quality is obtained with relatively low radiation output. In contrast, stochastic effects such as tumorigenesis are probabilistic (i.e., "all-or-nothing"), meaning that it is difficult to predict when or if an effect will occur and there is no known threshold below which no risk of occurrence can be assumed. The linear-no-threshold (LNT) model assumes that the risk of cancer induction is linearly proportional to organ dose and that there is no amount of incremental radiation exposure that is without risk. The LNT model was determined by extrapolation from epidemiological studies conducted for populations exposed to radiation doses ranging from 5 to 100 mSv [10]. Although the LNT model is contested, it has been generally accepted based upon the existing epidemiological and radiobiological evidence of the risk of cancer induction in a population from low dose ionizing radiation [10, 57].

The carcinogenic risk to the population as a result of a diagnostic imaging procedure can be estimated from the absorbed organ doses, for example using the BEIR VII risk models or the NIH Radiation Risk Assessment Tool (RadRAT) [10, 58]. While these estimates are useful for epidemiological studies, they cannot be used effectively for individual patient risk assessment [59].

Pediatric cardiac CT dose ranges

Table 1 provides a broad overview of selected published effective dose ranges for pediatric cardiac CT studies. Notably the data in this table reflect inconsistencies in the way that effective dose is calculated for cardiac CT studies. Examinations are performed in patients of different ages using different scanner manufacturers with varying ECG-synchronization schemes and tube potentials. Dose calculation methodology and weighting factors between studies also vary. However, general trends are present [24, 28, 40, 50–52, 56, 60–72]. Most exams are performed at 80 kV, with the tube current reflecting age or weight-based adjustments. The effective doses generally increase with age and range from 0.2 to 9.6 mSv for children under 1 year, with larger ranges for children between 1 and 10 years of 0.5 to 28 mSv, and from 0.4 to 10.3 mSv for older children. Prospectively ECG-triggered exams have overall lower effective doses (0.05 to 5.8 mSv) than retrospectively ECG-gated exams (0.5 to 28 mSv).

Modality choices in pediatric cardiovascular imaging

Echocardiography remains the primary imaging modality in patients with CAHD for most clinical questions, with excellent diagnostic accuracy [73, 74]. Catheter-based angiography and cardiac magnetic resonance imaging (MRI) have been used as adjunct imaging

modalities when echocardiography yields an incomplete examination. With recent advances in CT technology, cardiac CT has been increasingly used for evaluation of CAHD [23, 75]. Each of these imaging modalities has benefits and limitations, so careful consideration should be given to choosing the optimal imaging modality for a given clinical question while minimizing risks (Table 2) [76].

Echocardiography is widely available, portable, has no known biologic effects, and has excellent ability to delineate intracardiac anatomy and function [77–79]. Imaging thoracic vascular anatomy, such as systemic and pulmonary venous return, distal branch pulmonary arteries, and some aortic arch anomalies, however, can be more difficult, particularly as patients age and their acoustic windows become more limited [80]. Echocardiography also has limited ability to quantify right ventricular function (whether in the sub-pulmonary or systemic position) and valvular regurgitation [81].

When echocardiography is insufficient, cardiac MRI is often utilized [79]. Cardiac MRI provides excellent visualization of both intracardiac and extracardiac vascular anatomy, assessment of valvular regurgitation and intracardiac shunting with phase contrast imaging, and is considered the gold standard for quantifying ventricular volumes and function [82, 83]. Cardiac MRI provides myocardial characterization data and can be used to assess myocardial perfusion at rest or with stress [84–86]. However, cardiac MRI has limitations (Table 3). The cost of cardiac MRI studies tends to be higher than either echocardiography or cardiac CT, although not as high as invasive procedures such as cardiac catheterization. Most comprehensive cardiac MRI examinations in patients with CAHD take 30–60 minutes to complete [87]. Patient cooperation is paramount to achieve a high quality study, so children less than 8 years of age and those with developmental delays may require sedation or anesthesia for the study, which entails several potential short- and long-term risks [87, 88]. Recent studies suggesting potential neurotoxicity of anesthetic agents on neurologic, cognitive and social development of neonates and young children remain inconclusive but motivate the desire to minimize anesthetic exposure [89, 90]. Gadolinium-based contrast agents are often used for detailed vascular definition or myocardial characterization [91, 92]. Gadolinium use has been linked to nephrogenic systemic fibrosis in patients with pre-existing kidney disease [93]. Recent studies have shown brain deposition of linear gadolinium chelates in the dentate nucleus and globus pallidus with an unknown clinical significance of this finding [94]. Increasingly, post-procedural patients with CAHD have metallic implants that can cause artifacts on cardiac MRI or, as with some implanted devices, preclude cardiac MRI entirely. While cardiac MRI can be performed with newer pacemakers or defibrillators, artifacts from the leads may significantly impair exam quality [95].

Cardiac catheterization provides excellent spatial resolution for delineation of vascular structures and allows direct measurement of saturation and pressure data. Thus it provides unique hemodynamic insights not currently possible with non-invasive imaging modalities. However, catheterization is invasive, involves ionizing radiation, and for many patients requires general anesthesia. Currently, catheterization is reserved primarily for interventional procedures and cases where direct hemodynamic measurements are needed for clinical decision making rather than solely for diagnostic imaging purposes [96].

Cardiac CT has a number of advantages compared to other imaging modalities for evaluating patients with CAHD. CT has excellent spatial resolution, though less than the spatial resolution of catheter angiography [76]. CT scanners are fast and can provide complete pediatric cardiovascular datasets in less than one second or in a single heart-beat, so many scans can be performed without the need for sedation or breath holding [24, 97]. In addition to cardiovascular information, cardiac CT also provides excellent visualization of the airways, pulmonary parenchyma, bones, and soft tissues.

Despite these advantages, cardiac CT does have risks and limitations. As previously discussed, the ionizing radiation required for CT in children has been arguably linked to a potential small increase in risk of malignancy [4, 5, 12–15]. Although functional and volumetric data can be obtained, the temporal resolution of CT is less than either echocardiography or cardiac MRI, which can impact ventricular functional analysis [98]. For nearly all cardiac CT scans, injection of iodinated contrast material is required for vessel opacification, but the risks of adverse reactions to iodinated contrast are low, especially in children, and in patients with normal kidney function [99].

Imaging scenarios where cardiac CT may be useful

In light of the risks and benefits and strengths and weaknesses associated with each of the anatomic imaging modalities, cardiac CT is the current optimal study for several indications [26]. Due to the small caliber of coronary arteries in young children, cardiac CT has particular advantages over cardiac MRI and echocardiography for coronary imaging. It is possible with relatively low radiation exposure to visualize coronary artery origins, proximal through distal courses including evidence of anomalous origins, acute origin angulations, or intramural segments in congenital or acquired anomalies, and in infants with complex anomalies [100–102]. Patients with repaired or palliated congenital heart disease have a higher incidence of coronary artery abnormalities. Current recommendations include imaging of coronary arteries “at least once in adulthood” for anyone who has undergone coronary artery manipulation (e.g., as part of the Ross procedure or arterial switch operation) [103]. In patients with acquired coronary disease, such as Kawasaki disease, cardiac CT can identify areas of coronary artery dilation or stenosis [104, 105]. The coronary luminal caliber can be assessed for evidence of vasculopathy, as seen in patients with transplant coronary artery disease, or those with concerns for atherosclerotic plaque, such as in children with familial hypercholesterolemia or older adults with CAHD [103, 106, 107]. Beyond coronary artery evaluation, cardiac CT is an excellent imaging modality in patients with suspected thoracic arterial abnormalities or thromboembolism [108]. Cardiac CT provides clear imaging of vascular rings, in which airway evaluation is also a key clinical question, as well as other aortic arch anomalies, branch pulmonary artery and pulmonary vein assessment, and evaluation for aortopulmonary collaterals [109–112].

Another common indication for cardiac CT arises in critically ill pediatric patients or those who are at high risk for anesthetic complications, including patients with single ventricle physiology, severe outflow tract obstruction and Williams syndrome [113]. As cardiac CT scans can now be typically performed in less than one second, cardiac CT provides a rapid diagnostic option for critically ill patients compared to cardiac MRI and invasive

angiography. Cardiac CT can be successfully performed without sedation in infants and young children making this an attractive alternative to cardiac MRI in this age group [114]. Finally, it may be advantageous to image patients with intrathoracic metal, including but not limited to pacemakers and defibrillators, by cardiac CT rather than cardiac MRI [115].

Pediatric Cardiac CT Technique Optimization

Recent technological advances and growing indications have increased the utility of cardiovascular CT and drive the need to optimize image quality [23, 26, 27, 116]. Consultation between cardiovascular imager and the referring provider is critical to clearly establish the goals of the cardiac CT study. Scan protocols targeted to clinical indication and patient size should be designed, implemented and audited with the combined input of medical physicists, cardiovascular imagers, technologists, and application specialists to optimize scanner performance in order to obtain the highest quality diagnostic images while minimizing radiation exposure. An experienced cardiovascular imaging physician should be at the scanner when needed to optimize the scan protocol for the particulars of the patient and clinical question.

Evaluation of extracardiac thoracic vasculature including the aorta, pulmonary arteries, pulmonary and systemic veins can generally be performed without ECG-synchronization [117–120]. If evaluating the aortic or pulmonary roots, ECG-synchronization is needed to eliminate pulsation artifacts [121]. ECG-synchronization is necessary for evaluation of ventricular function, volumetry, detailed coronary artery analysis, and dedicated evaluation of intracardiac anatomy [117]. If ECG-synchronization is used, the lowest radiation doses can generally be delivered to a patient with a slow and steady heart rate. Consequently, administration of heart rate lowering medication such as a beta-blocker alone or with the addition of phenylephrine as an adjunct to support blood pressure should be contemplated [122–125]. The use of calcium channel blockers for heart rate lowering may be useful if there are contraindications to beta-blocker administration [126]. Sublingual nitroglycerin to achieve coronary vasodilatation has been used to improve coronary CT quality in adults. Although not universally adopted for coronary CT in children, this approach could be considered if evaluating for coronary artery stenosis or distal coronary detail [25, 105, 127, 128].

Patients with pacemakers should be evaluated prior to an ECG-synchronized examination to determine if pacemaker rate or mode adjustment is needed to avoid heart rate irregularity which can result in scan artifacts [129]. ECG-synchronization can be either prospectively or retrospectively performed. The optimal phase of the cardiac cycle to freeze cardiac motion during image acquisition should be targeted and is generally at end-systole for heart rates above 80 bpm and at mid-diastole for lower heart rates [125, 130–132]. Prospective ECG-triggering can either be performed using an axial “step-and-shoot” method, high pitch helical scanning, or with volumetric scanning. For one vendor, axial “step-and-shoot” imaging is not available but rather prospective ECG-triggering is generally performed with low pitch helical scanning. For prospectively triggered acquisitions, the scanner predicts the time of the R wave and then triggers the scan acquisition at the time during the cardiac cycle designated by the operator [133]. This technique allows for dose modulation with radiation

delivered in only a predefined narrow window of the cardiac cycle and can lead to a dose reduction of 40–69% as compared to retrospective ECG-gating (Figure 2) [52, 71, 134–137]. If there is heart rate variability, image degradation may be seen with prospective ECG-triggering, so retrospective ECG-gating or prospective ECG-triggering with added temporal padding should be utilized. Retrospective ECG-gating may also diminish the effects of respiratory or patient motion. Retrospective ECG-gating involves backward-looking measurement of R wave timing with the x-ray beam turned on during the entire cardiac cycle. To decrease dose, beam intensity is modulated with the optimal phase of the cardiac cycle to freeze cardiac motion targeted during the relatively greater radiation dose with a significantly reduced radiation dose delivered during the remainder of the cardiac cycle [133] (Figure 2). Retrospective-ECG gating should also generally be used when performing volumetric or functional analysis. The narrowest acquisition window suitable for the diagnostic scenario and patient characteristics should be used; a wider acquisition window of relatively greater dose may be needed for patients with irregular heart rates.

Evaluation of extracardiac vasculature and coronary artery origins using high pitch dual source or wide detector scanners can generally be performed in a freely breathing child [56, 61]. Scan acquisition with breath holding or under anesthesia for suspended respiration is ideal for detailed distal coronary or intracardiac evaluation [138].

Tube potential (in units of kV) and tube current-time product (in units of mAs) should be built into protocols for each study based on clinical indication and body size as radiation dose and image quality need to be balanced. These parameters may need to be adjusted for individual cases to further optimize quality and radiation dose. The lowest tube potential that will yield adequate image quality for body size should be used. A lower tube potential provides the dual advantage of not only providing a higher contrast-to-noise ratio that accentuates iodinated cardiovascular contrast enhancement in CT, but can also be used to lower contrast amounts and radiation dose [139]. Generally 80 kV (or 70 kV if available) is adequate for scanning most infants and children through the first decade of life [140–142]. 100 kV may be needed for larger children or adolescents, especially if examining subtle details such as coronary artery stenosis. Automatic tube current modulation should be employed to decrease radiation dose while maintaining constant image noise and preserving image quality. For adequate performance of automatic tube current modulation, the patient should be centered in the gantry [143–145]. Applying iterative reconstruction techniques will prospectively allow a lower radiation dose to be delivered relative to standard protocols and will also decrease image noise thus improving image quality [146–150]. The z-axis scan range should be minimized to cover only the anatomy of interest. There is generally no need to scan the entire chest.

Homogenous vascular opacification of the structure(s) of interest is paramount to cardiac CT. The iodinated contrast injection rate is determined by the size of the intravenous cannula and total allowable volume of contrast and can be in the range of 0.5 – 6 mL/sec with a contrast dose of 1–3 mL/kg up to a maximum contrast amount of approximately 125 mL in an adult-sized patient [108, 151]. Power injection is the most reproducible method of intravenous contrast administration. Optimum scan acquisition delay can be evaluated with bolus tracking using a region of interest with automatic scan triggering when a

predetermined Hounsfield unit threshold is met, a timing bolus, or a manual scan trigger when opacification of the structure(s) of interest is visualized during dynamic evaluation. If a timing bolus is used, an empiric 2–3 second diagnostic delay is added to the time of peak test bolus opacification of the structure of interest for neonates and up to 8 seconds for older children/adolescents [152]. An empiric scan delay without bolus tracking may also be used, but may not be as reliable. A single scan acquisition should be timed so that all necessary structures are simultaneously opacified without additional pre-contrast or delayed post-contrast images whenever possible [117]. Contrast administration may either be biphasic, typically consisting first of full strength contrast or a contrast/normal saline mix followed by a normal saline flush or triphasic, typically consisting first of full strength contrast followed by a contrast/normal saline mix, then a normal saline flush. The normal saline flush helps to clear the intravenous catheter tubing and central systemic veins of dense contrast material that may cause streak artifact in young children as smaller total amounts of contrast are administered in these patients. Care should be taken to avoid any air in the intravenous line during contrast administration in children with right-to-left shunts. Also, in children with intracardiac shunts, there is generally rapid and near simultaneous opacification of all cardiac chambers, which needs to be considered when planning the timing of the diagnostic scan.

Special consideration should be taken when imaging the patient with the Fontan circulation and total cavopulmonary connection. The specific Fontan anatomy must be well understood, with the plan to opacity the superior and inferior vena cava and the pulmonary arteries to avoid the pitfall of unopacified blood mimicking thrombus in the Fontan pathway. This can be achieved with simultaneous dual injection of contrast in an upper and a lower extremity vein and early phase imaging performed to assess for thrombus in the pulmonary arteries and Fontan baffle [153]. Delayed imaging may be performed as needed to assess for thrombus in the inferior vena cava and Fontan baffle if not optimally opacified on the initial study. Alternatively, contrast may be injected into an upper extremity vein with a single delayed scan acquisition timed to the equilibrium phase of contrast enhancement at least 70 seconds following the initiation of contrast injection when the pulmonary arteries, the superior and inferior vena cava are all opacified [108, 151].

Familiarity with scan technology and attention to contributions of parameters to radiation dose and image appearance can provide both dose conscious and high quality cardiac CT studies over a wide variety of indications and sizes in children (Figures 3 and 4).

Informing Patients and Families about Pediatric Cardiac CT

Optimal informed decision-making for pediatric cardiac CT is a collaborative family-centered process that must acknowledge both the unique patient characteristics and the wide range of public knowledge and perceptions regarding the risks of exposure to ionizing radiation [16, 33, 36, 154]. There is evidence that families prefer to be informed of risks related to medical imaging procedures, though this may not be applicable to all settings [155]. Accordingly, discussion of the risk/benefit profile of a cardiac CT exam is a multi-disciplinary responsibility that can extend across the entire congenital heart center enterprise [29]. The many opportunities for an effective dialogue are shared by referring physicians,

interpreting cardiologists and radiologists, imaging technologists, medical physicists, nurses, and, in some cases, the anesthesiologists and intensivists providing supportive care. Discussion of the use of ionizing radiation for cardiac CT should be a shared responsibility of the primary cardiologist, cardiac surgeon or caregiver and cardiovascular imager, with the imaging team best prepared to address specific concerns relating to radiation dose [156]. For an uncomplicated exam, written or web-based materials should be adequate and the technologist or imaging nurse will play a large role in the dialogue with the patient and family [29, 157, 158]. Cardiac CT exams that may require a larger ionizing radiation dose (e.g., dynamic or functional imaging or dual phase acquisitions), administration of heart rate lowering medications, anesthesia, studies obtained in critically ill children, or patients who will undergo contrast exposure in the setting of kidney disease or iodinated contrast allergy may warrant more extensive dialogue. Such discussions should incorporate input from the referring cardiology, intensive care or cardiothoracic surgery services [89, 123, 124]. Nonetheless, pediatric specific standardized dose thresholds for triggering formal discussions, or even written consent, have not been reached by expert consensus [159]. Many team members may contribute to the collective process, individualizing the conversation to a specific patient and the related exam indications, protocol, risks or other imaging alternatives.

Implementing a CT Dose Management Program

Enterprise radiation dose management must incorporate both CT protocol development and optimization to be compliant with hospital accrediting standards and should include a regular audit of protocol compliance [160]. This audit should assess how well CT protocols are meeting expectations related to dose and quality with review of designated outliers or areas of practice outside of established standards. While there are numerous ways to conduct these reviews, the current trend is to adopt software solutions that collect, archive and analyze CT radiation dose related data that affords monitoring of both the individual patient and practice population performance. Knowing what data to monitor (amidst an increasingly large amount of available data), establishing what is practice beyond standards, and what follow-through to initiate in response to outlier data are some of the challenges for a dose management program. Other challenges include frequency of review, accountable parties, inclusion of all services that use these modalities, how to incorporate impact of evolving dose management strategies (e.g., iterative reconstruction on the CT dose profile for the practice), evolving dose metrics (e.g., the move away from effective dose and towards organ dose), and lack of available US national benchmarks for dose ranges in children [161].

Dose management analytics may be institution specific, but certain data elements and variability should be uniformly captured, in order to ensure adherence to standardized protocols and enable cross-institutional analysis. These data elements include 1) appropriate CT utilization analysis [162], 2) evaluation of size-specific protocol use, 3) assessment of correct CT technical performance (e.g., correctly functioning automatic dose modulation features), 4) monitoring of CT protocol dose consistency across the scanners and operators in the enterprise, and 6) comparison of delivered radiation doses with established standards with variation from established standards adequately assessed and addressed.

While these principles are generally applicable to all CT radiation dose management, they are particularly important in pediatric cardiac CT. Imaging children introduces variability in patient size that should be reflected in the cardiac CT protocols and the configuration of equipment. However, the default settings provided by the manufacturers may not be optimally designed for pediatrics and can return suboptimal image quality or higher radiation exposures than may be necessary [163]. An additional layer of complexity is introduced in pediatric cardiac imaging as the complex balance between image quality, contrast timing, and cardiac/respiratory gating can affect radiation dose. Anatomic variability can lead to substantial variation in dose or quality for the same CT protocol. For this reason, constant vigilance in reviewing radiation exposure data is needed to ensure that quality and dose are optimal in pediatric cardiac CT.

Conclusion

Children with CAHD may require lifelong imaging surveillance. Advances in technology have made pediatric cardiac CT the best imaging modality choice in certain scenarios as detailed images can be obtained quickly and often without sedation. Discussion among caregivers regarding the relative risks and benefits of cardiac CT versus other imaging modalities should lead to the most appropriate imaging study being performed. Understanding cardiac CT technical parameters and how to apply them to children of various sizes and heart rates is necessary to optimize image quality at the lowest radiation dose. Instituting a dose management program will help ensure regulatory compliance and should aim to achieve consistently high quality images with appropriate radiation exposure.

References

1. United Nations Scientific Committee on the Effects of Atomic Radiation (2013) Sources, Effects and Risks of Ionizing Radiation. UNSCEAR Report 2013 to the General Assembly with Scientific Annexes Volume II, Scientific Annex B: Effects of Radiation Exposure of Children. E.14.IX.2. Sources, Effects and Risks of Ionizing Radiation. United Nations.
2. Nguyen PK, Lee WH, Li YF, et al. (2015) Assessment of the Radiation Effects of Cardiac CT Angiography Using Protein and Genetic Biomarkers. *JACC Cardiovascular imaging* 8:873–884. [PubMed: 26210695]
3. Beels L, Bacher K, De Wolf D, et al. (2009) gamma-H2AX foci as a biomarker for patient X-ray exposure in pediatric cardiac catheterization: are we underestimating radiation risks? *Circulation* 120:1903–1909. [PubMed: 19858412]
4. Pearce MS, Salotti JA, Little MP, et al. (2012) Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. *Lancet* 380:499–505. [PubMed: 22681860]
5. Mathews JD, Forsythe AV, Brady Z, et al. (2013) Cancer risk in 680,000 people exposed to computed tomography scans in childhood or adolescence: data linkage study of 11 million Australians. *BMJ* 346:f2360. [PubMed: 23694687]
6. Gardavaud F, Luciani A, Rahmouni A (2012) CT scans in childhood and risk of leukaemia and brain tumours. *Lancet* 380:1735; author reply 1736–1737.
7. Deng J, Zhang Y, Nath R, et al. (2012) CT scans in childhood and risk of leukaemia and brain tumours. *Lancet* 380:1735; author reply 1736–1737.
8. Zopf DA, Green GE (2012) CT scans in childhood and risk of leukaemia and brain tumours. *Lancet* 380:1735–1736; author reply 1736–1737.
9. Hauptmann M, Meulepas JM (2012) CT scans in childhood and risk of leukaemia and brain tumours. *Lancet* 380:1736; author reply 1736–1737. [PubMed: 23158245]

10. National Research Council of the National Academies (2006) Health risks from exposure to low levels of ionizing radiation : BEIR VII, Phase 2 In: Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation BoRE, Research Division on Earth and Life Studies (ed). National Academy Press, Washington, DC.
11. Jolly D, Meyer J (2009) A brief review of radiation hormesis. *Australas Phys Eng Sci Med* 32:180–187. [PubMed: 20169836]
12. Huang WY, Muo CH, Lin CY, et al. (2014) Paediatric head CT scan and subsequent risk of malignancy and benign brain tumour: a nation-wide population-based cohort study. *Br J Cancer* 110:2354–2360. [PubMed: 24569470]
13. Krille L, Dreger S, Schindel R, et al. (2015) Risk of cancer incidence before the age of 15 years after exposure to ionising radiation from computed tomography: results from a German cohort study. *Radiat Environ Biophys* 54:1–12. [PubMed: 25567615]
14. Journy N, Rehel JL, Ducou Le Pointe H, et al. (2015) Are the studies on cancer risk from CT scans biased by indication? Elements of answer from a large-scale cohort study in France. *Br J Cancer* 112:185–193. [PubMed: 25314057]
15. Boice JD (2015) Radiation epidemiology and recent paediatric computed tomography studies. *Annals of the ICRP* 44:236–248. [PubMed: 25816281]
16. Cohen MD (2015) ALARA, image gently and CT-induced cancer. *Pediatric radiology* 45:465–470. [PubMed: 25680877]
17. ICRP (1999) 1999 Annual Report Of the International Commission on Radiological Protection. *Annals of the ICRP*.
18. ICRP (2005) Low-dose extrapolation of radiation-related cancer risk. ICRP publication 99. *Annals of the ICRP* 35.
19. NCRP (2001) National Council on Radiation Protection and Measurement, Report No. 135 - Liver cancer risk from internally-deposited radionuclides. Bethesda, MD.
20. NCRP (2001) National Council on Radiation Protection and Measurements , Report No 136 - Evaluation of the Linear-Nonthreshold Dose-Response Model for Ionizing Radiation National Committee on Radiation Protection (U.S.), National Committee on Radiation Protection and Measurements (U.S.), & National Council on Radiation Protection and Measurements, Wahsington, D.C.
21. Hill KD, Frush DP, Han BK, et al. (2017) Radiation Safety in Children with Congenital and Acquired Heart Disease: A Scientific Position Statement on Multimodality Dose Optimization from the Image Gently Alliance. *JACC Cardiovascular imaging*.
22. Gherardi GG, Iball GR, Darby MJ, et al. (2011) Cardiac computed tomography and conventional angiography in the diagnosis of congenital cardiac disease in children: recent trends and radiation doses. *Cardiology in the young* 21:616–622. [PubMed: 21733206]
23. Han BK, Lesser AM, Vezmar M, et al. (2013) Cardiovascular imaging trends in congenital heart disease: a single center experience. *Journal of cardiovascular computed tomography* 7:361–366. [PubMed: 24331931]
24. Han BK, Lindberg J, Grant K, et al. (2011) Accuracy and safety of high pitch computed tomography imaging in young children with complex congenital heart disease. *The American journal of cardiology* 107:1541–1546. [PubMed: 21539949]
25. Goo HW (2013) Current trends in cardiac CT in children. *Acta radiologica* 54:1055–1062. [PubMed: 23104372]
26. Han BK, Rigsby CK, Hlavacek A, et al. (2015) Computed Tomography Imaging in Patients with Congenital Heart Disease Part I: Rationale and Utility. An Expert Consensus Document of the Society of Cardiovascular Computed Tomography (SCCT): Endorsed by the Society of Pediatric Radiology (SPR) and the North American Society of Cardiac Imaging (NASCI). *Journal of cardiovascular computed tomography* 9:475–492. [PubMed: 26272851]
27. Meinel FG, Henzler T, Schoepf UJ, et al. (2015) ECG-synchronized CT angiography in 324 consecutive pediatric patients: spectrum of indications and trends in radiation dose. *Pediatric cardiology* 36:569–578. [PubMed: 25380963]

28. Yang JC, Lin MT, Jaw FS, et al. (2015) Trends in the utilization of computed tomography and cardiac catheterization among children with congenital heart disease. *J Formos Med Assoc* 114:1061–1068. [PubMed: 25241602]
29. Perez M. MD, Frush DP, Boyd M, Bushberg JT, Ebdon-Jackson S, Mikhail M, Murphy M, Prasopa-Plaizier N, Remedios D, Shannoun F, Shogren A (2016) World Health Organization: Communicating radiation risks in pediatric imaging to support risk-benefit dialogue.
30. Prabhu V, Rosenkrantz AB (2015) Imbalance of opinions expressed on Twitter relating to CT radiation risk: an opportunity for increased radiologist representation. *AJR American journal of roentgenology* 204:W48–51. [PubMed: 25539274]
31. Sadigh G, Khan R, Kassin MT, et al. (2014) Radiation safety knowledge and perceptions among residents: a potential improvement opportunity for graduate medical education in the United States. *Acad Radiol* 21:869–878. [PubMed: 24713540]
32. Rehani MM, Berris T (2012) International Atomic Energy Agency study with referring physicians on patient radiation exposure and its tracking: a prospective survey using a web-based questionnaire. *BMJ Open* 2.
33. Boutis K, Cogollo W, Fischer J, et al. (2013) Parental knowledge of potential cancer risks from exposure to computed tomography. *Pediatrics* 132:305–311. [PubMed: 23837174]
34. Puri S, Hu R, Quazi RR, et al. (2012) Physicians' and midlevel providers' awareness of lifetime radiation-attributable cancer risk associated with commonly performed CT studies: relationship to practice behavior. *AJR American journal of roentgenology* 199:1328–1336. [PubMed: 23169726]
35. Lam DL, Larson DB, Eisenberg JD, et al. (2015) Communicating Potential Radiation-Induced Cancer Risks From Medical Imaging Directly to Patients. *AJR American journal of roentgenology* 205:962–970. [PubMed: 26295534]
36. Hartwig HD, Clingenpeel J, Perkins AM, et al. (2013) Parental knowledge of radiation exposure in medical imaging used in the pediatric emergency department. *Pediatric emergency care* 29:705–709. [PubMed: 23714757]
37. Robey TE, Edwards K, Murphy MK (2014) Barriers to computed tomography radiation risk communication in the emergency department: a qualitative analysis of patient and physician perspectives. *Academic emergency medicine : official journal of the Society for Academic Emergency Medicine* 21:122–129. [PubMed: 24673667]
38. Ditkofsky N, Shekhani HN, Cloutier M, et al. (2016) Ionizing Radiation Knowledge Among Emergency Department Providers. *Journal of the American College of Radiology : JACR* 13:1044–1049 e1041. [PubMed: 27162040]
39. Steele JR, Jones AK, Clarke RK, et al. (2017) Use of an Online Education Platform to Enhance Patients' Knowledge About Radiation in Diagnostic Imaging. *Journal of the American College of Radiology*.
40. ICRP (2007) The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103. *Annals of the ICRP*, pp 1–332. [PubMed: 18082557]
41. Einstein AJ, Moser KW, Thompson RC, et al. (2007) Radiation dose to patients from cardiac diagnostic imaging. *Circulation* 116:1290–1305. [PubMed: 17846343]
42. McNitt-Gray MF (2002) AAPM/RSNA Physics Tutorial for Residents: Topics in CT. Radiation dose in CT. *Radiographics : a review publication of the Radiological Society of North America, Inc* 22:1541–1553.
43. Shope TB, Gagne RM, Johnson GC (1981) A method for describing the doses delivered by transmission x-ray computed tomography. *Medical physics* 8:488–495. [PubMed: 7322067]
44. Department of Health and Human Services Food and Drug Administration (1984) 21 CFR Part 1020: Diagnostic x-ray systems and their major components; amendments to performance standard–FDA. Final rule. *Federal register* 49:34698–34714. [PubMed: 10267667]
45. McCollough CH (2005) Automatic exposure control in CT: are we done yet? *Radiology* 237:755–756. [PubMed: 16304094]
46. McCollough CH, Leng S, Yu L, et al. (2011) CT dose index and patient dose: they are not the same thing. *Radiology* 259:311–316. [PubMed: 21502387]

47. Newman B, Ganguly A, Kim JE, et al. (2012) Comparison of different methods of calculating CT radiation effective dose in children. *AJR American journal of roentgenology* 199:W232–239. [PubMed: 22826426]
48. McCollough CH, Schueler BA (2000) Calculation of effective dose. *Medical physics* 27:828–837. [PubMed: 10841384]
49. Christner JA, Kofler JM, McCollough CH (2010) Estimating effective dose for CT using dose-length product compared with using organ doses: consequences of adopting International Commission on Radiological Protection publication 103 or dual-energy scanning. *AJR American journal of roentgenology* 194:881–889. [PubMed: 20308486]
50. Trattner S, Chelliah A, Prinsen P, et al. (2017) Estimating Effective Dose of Radiation From Pediatric Cardiac CT Angiography Using a 64-MDCT Scanner: New Conversion Factors Relating Dose-Length Product to Effective Dose. *AJR American journal of roentgenology* 208:585–594. [PubMed: 28095022]
51. Hollingsworth CL, Yoshizumi TT, Frush DP, et al. (2007) Pediatric cardiac-gated CT angiography: assessment of radiation dose. *AJR American journal of roentgenology* 189:12–18. [PubMed: 17579144]
52. Podberesky DJ, Angel E, Yoshizumi TT, et al. (2012) Radiation dose estimation for prospective and retrospective ECG-gated cardiac CT angiography in infants and small children using a 320-MDCT volume scanner. *AJR American journal of roentgenology* 199:1129–1135. [PubMed: 23096189]
53. American Association of Physicists in Medicine (2011) Size-specific dose estimates (SSDE) in pediatric and adult body CT examinations. AAPM Task Group 204, College Park, MD.
54. McCollough C, Bakalyar DM, Bostani M, et al. (2014) Use of Water Equivalent Diameter for Calculating Patient Size and Size-Specific Dose Estimates (SSDE) in CT: The Report of AAPM Task Group 220. AAPM report 2014:6–23. [PubMed: 27546949]
55. Kidoh M, Utsunomiya D, Oda S, et al. (2015) Validity of the size-specific dose estimate in adults undergoing coronary CT angiography: comparison with the volume CT dose index. *The international journal of cardiovascular imaging* 31 Suppl 2:205–211.
56. Westra SJ, Li X, Gulati K, et al. (2014) Entrance skin dosimetry and size-specific dose estimate from pediatric chest CTA. *Journal of cardiovascular computed tomography* 8:97–107. [PubMed: 24211194]
57. Siegel JA, Pennington CW, Sacks B (2017) Subjecting Radiologic Imaging to the Linear No-Threshold Hypothesis: A Non Sequitur of Non-Trivial Proportion. *Journal of nuclear medicine : official publication, Society of Nuclear Medicine* 58:1–6.
58. Berrington de Gonzalez A, Iulian Apostolaei A, Veiga LH, et al. (2012) RadRAT: a radiation risk assessment tool for lifetime cancer risk projection. *Journal of radiological protection : official journal of the Society for Radiological Protection* 32:205–222. [PubMed: 22810503]
59. Brenner DJ, Shuryak I, Einstein AJ (2011) Impact of reduced patient life expectancy on potential cancer risks from radiologic imaging. *Radiology* 261:193–198. [PubMed: 21771956]
60. Deak PD, Smal Y, Kalender WA (2010) Multisection CT protocols: sex- and age-specific conversion factors used to determine effective dose from dose-length product. *Radiology* 257:158–166. [PubMed: 20851940]
61. Ghoshhajra BB, Lee AM, Engel LC, et al. (2014) Radiation dose reduction in pediatric cardiac computed tomography: experience from a tertiary medical center. *Pediatric cardiology* 35:171–179. [PubMed: 23872908]
62. ICRP (1991) 1990 Recommendations of the International Commission on Radiological Protection. *Annals of the ICRP*, pp 1–201.
63. Thomas KE, Wang B (2008) Age-specific effective doses for pediatric MSCT examinations at a large children's hospital using DLP conversion coefficients: a simple estimation method. *Pediatric radiology* 38:645–656. [PubMed: 18392817]
64. Shrimpton P (2004) Assessment of patient dose in CT. National Radiological Protection Board.
65. Paul JF, Rohnean A, Elfassy E, et al. (2011) Radiation dose for thoracic and coronary step-and-shoot CT using a 128-slice dual-source machine in infants and small children with congenital heart disease. *Pediatric radiology* 41:244–249. [PubMed: 20821005]

66. Ben Saad M, Rohnean A, Sigal-Cinqualbre A, et al. (2009) Evaluation of image quality and radiation dose of thoracic and coronary dual-source CT in 110 infants with congenital heart disease. *Pediatric radiology* 39:668–676. [PubMed: 19319514]
67. Zankl M, Panzer W, Drexler G (1991) The calculation of dose from external photon exposures using reference human phantoms and Monte Carlo methods Pt 6. Germany, pp 126.
68. Goo HW, Yang DH (2010) Coronary artery visibility in free-breathing young children with congenital heart disease on cardiac 64-slice CT: dual-source ECG-triggered sequential scan vs. single-source non-ECG-synchronized spiral scan. *Pediatric radiology* 40:1670–1680. [PubMed: 20464385]
69. Kim JE, Newman B (2010) Evaluation of a radiation dose reduction strategy for pediatric chest CT. *AJR American journal of roentgenology* 194:1188–1193. [PubMed: 20410401]
70. Young C, Taylor AM, Owens CM (2011) Paediatric cardiac computed tomography: a review of imaging techniques and radiation dose consideration. *European radiology* 21:518–529. [PubMed: 21188593]
71. Cheng Z, Wang X, Duan Y, et al. (2010) Low-dose prospective ECG-triggering dual-source CT angiography in infants and children with complex congenital heart disease: first experience. *European radiology* 20:2503–2511. [PubMed: 20532783]
72. Huang B, Law MW, Mak HK, et al. (2009) Pediatric 64-MDCT coronary angiography with ECG-modulated tube current: radiation dose and cancer risk. *AJR American journal of roentgenology* 193:539–544. [PubMed: 19620454]
73. Cheitlin MD, Alpert JS, Armstrong WF, et al. (1997) ACC/AHA Guidelines for the Clinical Application of Echocardiography. A report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Committee on Clinical Application of Echocardiography). Developed in collaboration with the American Society of Echocardiography. *Circulation* 95:1686–1744. [PubMed: 9118558]
74. Lai WW, Geva T, Shirali GS, et al. (2006) Guidelines and standards for performance of a pediatric echocardiogram: a report from the Task Force of the Pediatric Council of the American Society of Echocardiography. *J Am Soc Echocardiogr* 19:1413–1430. [PubMed: 17138024]
75. Han BK, Lesser JR (2013) CT imaging in congenital heart disease: an approach to imaging and interpreting complex lesions after surgical intervention for tetralogy of Fallot, transposition of the great arteries, and single ventricle heart disease. *Journal of cardiovascular computed tomography* 7:338–353. [PubMed: 24331929]
76. Lin E, Alessio A (2009) What are the basic concepts of temporal, contrast, and spatial resolution in cardiac CT? *Journal of cardiovascular computed tomography* 3:403–408. [PubMed: 19717355]
77. Marino B, Corno A, Carotti A, et al. (1990) Pediatric cardiac surgery guided by echocardiography. Established indications and new trends. *Scand J Thorac Cardiovasc Surg* 24:197–201. [PubMed: 2293358]
78. Tworetzky W, McElhinney DB, Brook MM, et al. (1999) Echocardiographic diagnosis alone for the complete repair of major congenital heart defects. *Journal of the American College of Cardiology* 33:228–233. [PubMed: 9935035]
79. Prakash A, Powell AJ, Geva T (2010) Multimodality noninvasive imaging for assessment of congenital heart disease. *Circ Cardiovasc Imaging* 3:112–125. [PubMed: 20086225]
80. Stern KW, McElhinney DB, Gauvreau K, et al. (2011) Echocardiographic evaluation before bidirectional Glenn operation in functional single-ventricle heart disease: comparison to catheter angiography. *Circ Cardiovasc Imaging* 4:498–505. [PubMed: 21730025]
81. Margossian R, Schwartz ML, Prakash A, et al. (2009) Comparison of echocardiographic and cardiac magnetic resonance imaging measurements of functional single ventricular volumes, mass, and ejection fraction (from the Pediatric Heart Network Fontan Cross-Sectional Study). *The American journal of cardiology* 104:419–428. [PubMed: 19616678]
82. Mooij CF, de Wit CJ, Graham DA, et al. (2008) Reproducibility of MRI measurements of right ventricular size and function in patients with normal and dilated ventricles. *J Magn Reson Imaging* 28:67–73. [PubMed: 18581357]

83. Powell AJ, Maier SE, Chung T, et al. (2000) Phase-velocity cine magnetic resonance imaging measurement of pulsatile blood flow in children and young adults: in vitro and in vivo validation. *Pediatric cardiology* 21:104–110. [PubMed: 10754076]
84. Beroukhi RS, Prakash A, Buechel ER, et al. (2011) Characterization of cardiac tumors in children by cardiovascular magnetic resonance imaging: a multicenter experience. *Journal of the American College of Cardiology* 58:1044–1054. [PubMed: 21867841]
85. Babu-Narayan SV, Kilner PJ, Li W, et al. (2006) Ventricular fibrosis suggested by cardiovascular magnetic resonance in adults with repaired tetralogy of fallot and its relationship to adverse markers of clinical outcome. *Circulation* 113:405–413. [PubMed: 16432072]
86. Buechel ER, Balmer C, Bauersfeld U, et al. (2009) Feasibility of perfusion cardiovascular magnetic resonance in paediatric patients. *J Cardiovasc Magn Reson* 11:51. [PubMed: 19948020]
87. Taylor AM (2008) Cardiac imaging: MR or CT? Which to use when. *Pediatric radiology* 38 Suppl 3:S433–438. [PubMed: 18470452]
88. Rappaport BA, Suresh S, Hertz S, et al. (2015) Anesthetic neurotoxicity--clinical implications of animal models. *N Engl J Med* 372:796–797. [PubMed: 25714157]
89. Rappaport B, Mellon RD, Simone A, et al. (2011) Defining safe use of anesthesia in children. *N Engl J Med* 364:1387–1390. [PubMed: 21388302]
90. Andropoulos DB, Greene MF (2017) Anesthesia and Developing Brains - Implications of the FDA Warning. *N Engl J Med* 376:905–907. [PubMed: 28177852]
91. Tandon A, Hashemi S, Parks WJ, et al. (2016) Improved high-resolution pediatric vascular cardiovascular magnetic resonance with gadofosveset-enhanced 3D respiratory navigated, inversion recovery prepared gradient echo readout imaging compared to 3D balanced steady-state free precession readout imaging. *J Cardiovasc Magn Reson* 18:74. [PubMed: 27802802]
92. Kim RJ, Fieno DS, Parrish TB, et al. (1999) Relationship of MRI delayed contrast enhancement to irreversible injury, infarct age, and contractile function. *Circulation* 100:1992–2002. [PubMed: 10556226]
93. Grobner T (2006) Gadolinium--a specific trigger for the development of nephrogenic fibrosing dermopathy and nephrogenic systemic fibrosis? *Nephrol Dial Transplant* 21:1104–1108. [PubMed: 16431890]
94. Kanda T, Ishii K, Kawaguchi H, et al. (2014) High signal intensity in the dentate nucleus and globus pallidus on unenhanced T1-weighted MR images: relationship with increasing cumulative dose of a gadolinium-based contrast material. *Radiology* 270:834–841. [PubMed: 24475844]
95. Pulver AF, Puchalski MD, Bradley DJ, et al. (2009) Safety and imaging quality of MRI in pediatric and adult congenital heart disease patients with pacemakers. *Pacing Clin Electrophysiol* 32:450–456. [PubMed: 19335853]
96. Feltes TF, Bacha E, Beekman RH, 3rd, et al. (2011) Indications for cardiac catheterization and intervention in pediatric cardiac disease: a scientific statement from the American Heart Association. *Circulation* 123:2607–2652. [PubMed: 21536996]
97. Han BK, Overman DM, Grant K, et al. (2013) Non-sedated, free breathing cardiac CT for evaluation of complex congenital heart disease in neonates. *Journal of cardiovascular computed tomography* 7:354–360. [PubMed: 24331930]
98. Sayyed SH, Cassidy MM, Hadi MA (2009) Use of multidetector computed tomography for evaluation of global and regional left ventricular function. *Journal of cardiovascular computed tomography* 3:S23–34. [PubMed: 19138579]
99. Callahan MJ, Poznauskis L, Zurakowski D, et al. (2009) Nonionic iodinated intravenous contrast material-related reactions: incidence in large urban children's hospital--retrospective analysis of data in 12,494 patients. *Radiology* 250:674–681. [PubMed: 19244041]
100. Attili A, Hensley AK, Jones FD, et al. (2013) Echocardiography and coronary CT angiography imaging of variations in coronary anatomy and coronary abnormalities in athletic children: detection of coronary abnormalities that create a risk for sudden death. *Echocardiography* 30:225–233. [PubMed: 23167634]
101. Kaushal S, Backer CL, Popescu AR, et al. (2011) Intramural coronary length correlates with symptoms in patients with anomalous aortic origin of the coronary artery. *Ann Thorac Surg* 92:986–991; discussion 991–982. [PubMed: 21871287]

102. Jia Q, Zhuang J, Jiang J, et al. (2017) Image quality of ct angiography using model-based iterative reconstruction in infants with congenital heart disease: Comparison with filtered back projection and hybrid iterative reconstruction. *European journal of radiology* 86:190–197. [PubMed: 28027746]
103. Warnes CA, Williams RG, Bashore TM, et al. (2008) ACC/AHA 2008 Guidelines for the Management of Adults with Congenital Heart Disease: Executive Summary: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (writing committee to develop guidelines for the management of adults with congenital heart disease). *Circulation* 118:2395–2451. [PubMed: 18997168]
104. Chu WC, Mok GC, Lam WW, et al. (2006) Assessment of coronary artery aneurysms in paediatric patients with Kawasaki disease by multidetector row CT angiography: feasibility and comparison with 2D echocardiography. *Pediatric radiology* 36:1148–1153. [PubMed: 16912893]
105. Kim JW, Goo HW (2013) Coronary artery abnormalities in Kawasaki disease: comparison between CT and MR coronary angiography. *Acta radiologica* 54:156–163. [PubMed: 23482350]
106. Bae KT, Hong C, Takahashi N, et al. (2004) Multi-detector row computed tomographic angiography in pediatric heart transplant recipients: Initial observations. *Transplantation* 77:599–602. [PubMed: 15084942]
107. Wever-Pinzon O, Romero J, Kelesidis I, et al. (2014) Coronary computed tomography angiography for the detection of cardiac allograft vasculopathy: a meta-analysis of prospective trials. *Journal of the American College of Cardiology* 63:1992–2004. [PubMed: 24681148]
108. Ghadimi Mahani M, Agarwal PP, Rigsby CK, et al. (2016) CT for Assessment of Thrombosis and Pulmonary Embolism in Multiple Stages of Single-Ventricle Palliation: Challenges and Suggested Protocols. *Radiographics : a review publication of the Radiological Society of North America, Inc* 36:1273–1284.
109. Di Sessa TG, Di Sessa P, Gregory B, et al. (2009) The use of 3D contrast-enhanced CT reconstructions to project images of vascular rings and coarctation of the aorta. *Echocardiography* 26:76–81. [PubMed: 19125810]
110. Backer CL, Monge MC, Popescu AR, et al. (2016) Vascular rings. *Semin Pediatr Surg* 25:165–175. [PubMed: 27301603]
111. Meinel FG, Huda W, Schoepf UJ, et al. (2013) Diagnostic accuracy of CT angiography in infants with tetralogy of Fallot with pulmonary atresia and major aortopulmonary collateral arteries. *Journal of cardiovascular computed tomography* 7:367–375. [PubMed: 24331932]
112. Lee EY, Jenkins KJ, Muneeb M, et al. (2013) Proximal pulmonary vein stenosis detection in pediatric patients: value of multiplanar and 3-D VR imaging evaluation. *Pediatric radiology* 43:929–936. [PubMed: 23475282]
113. Han BK, Vezmar M, Lesser JR, et al. (2014) Selective use of cardiac computed tomography angiography: an alternative diagnostic modality before second-stage single ventricle palliation. *J Thorac Cardiovasc Surg* 148:1548–1554. [PubMed: 24930614]
114. Jadhav SP, Golriz F, Atweh LA, et al. (2015) CT angiography of neonates and infants: comparison of radiation dose and image quality of target mode prospectively ECG-gated 320-MDCT and ungated helical 64-MDCT. *AJR American journal of roentgenology* 204:W184–191. [PubMed: 25615779]
115. Friedman BA, Schoepf UJ, Bastarrika GA, et al. (2009) Computed tomographic angiography of infants with congenital heart disease receiving extracorporeal membrane oxygenation. *Pediatric cardiology* 30:1154–1156. [PubMed: 19636487]
116. Paul JF, Rohnean A, Sigal-Cinqualbre A (2010) Multidetector CT for congenital heart patients: what a paediatric radiologist should know. *Pediatric radiology* 40:869–875. [PubMed: 20432005]
117. Han BK, Rigsby CK, Leipsic J, et al. (2015) Computed Tomography Imaging in Patients with Congenital Heart Disease, Part 2: Technical Recommendations. An Expert Consensus Document of the Society of Cardiovascular Computed Tomography (SCCT): Endorsed by the Society of Pediatric Radiology (SPR) and the North American Society of Cardiac Imaging (NASCI). *Journal of cardiovascular computed tomography* 9:493–513. [PubMed: 26679548]
118. Shuman WP, Leipsic JA, Busey JM, et al. (2012) Prospectively ECG Gated CT pulmonary angiography versus helical ungated CT pulmonary angiography: Impact on cardiac related

- motion artifacts and patient radiation dose. *European Journal of Radiology* 81:2444–2449. [PubMed: 21703791]
119. Karlo C, Leschka S, Goetti RP, et al. (2011) High-pitch dual-source CT angiography of the aortic valve-aortic root complex without ECG-synchronization. *European Radiology* 21:205–212. [PubMed: 20677006]
 120. Lell MM, May M, Deak P, et al. (2011) High-pitch spiral computed tomography: effect on image quality and radiation dose in pediatric chest computed tomography. *Investigative radiology* 46:116–123. [PubMed: 20856124]
 121. Scherthaner RE, Stadler A, Beitzke D, et al. (2012) Dose modulated retrospective ECG-gated versus non-gated 64-row CT angiography of the aorta at the same radiation dose: comparison of motion artifacts, diagnostic confidence and signal-to-noise-ratios. *European journal of radiology* 81:e585–590. [PubMed: 21820829]
 122. Leschka S, Scheffel H, Husmann L, et al. (2008) Effect of decrease in heart rate variability on the diagnostic accuracy of 64-MDCT coronary angiography. *AJR American journal of roentgenology* 190:1583–1590. [PubMed: 18492910]
 123. Rigsby CK, deFreitas RA, Nicholas AC, et al. (2010) Safety and efficacy of a drug regimen to control heart rate during 64-slice ECG-gated coronary CTA in children. *Pediatric radiology* 40:1880–1889. [PubMed: 20499055]
 124. Chelliah A, Kubacki T, Julien HM, et al. (2016) Pediatric coronary CTA using phenylephrine to lower heart rate. *Journal of cardiovascular computed tomography* 10:339–340. [PubMed: 27363865]
 125. Achenbach S, Manolopoulos M, Schuhback A, et al. (2012) Influence of heart rate and phase of the cardiac cycle on the occurrence of motion artifact in dual-source CT angiography of the coronary arteries. *Journal of cardiovascular computed tomography* 6:91–98. [PubMed: 22381662]
 126. Maffei E, Palumbo AA, Martini C, et al. (2009) “In-house” pharmacological management for computed tomography coronary angiography: heart rate reduction, timing and safety of different drugs used during patient preparation. *European radiology* 19:2931–2940. [PubMed: 19597820]
 127. Takx RA, Sucha D, Park J, et al. (2015) Sublingual Nitroglycerin Administration in Coronary Computed Tomography Angiography: a Systematic Review. *European radiology* 25:3536–3542. [PubMed: 25994194]
 128. Sato K, Isobe S, Sugiura K, et al. (2009) Optimal starting time of acquisition and feasibility of complementary administration of nitroglycerin with intravenous beta-blocker in multislice computed tomography. *Journal of computer assisted tomography* 33:193–198. [PubMed: 19346844]
 129. Lesser JR, Flygenring BJ, Knickelbine T, et al. (2009) Practical approaches to overcoming artifacts in coronary CT angiography. *Journal of cardiovascular computed tomography* 3:4–15. [PubMed: 19201371]
 130. Bamberg F, Sommer WH, Schenzle JC, et al. (2010) Systolic acquisition of coronary dual-source computed tomography angiography: feasibility in an unselected patient population. *European radiology* 20:1331–1336. [PubMed: 20033181]
 131. Seifarth H, Wienbeck S, Pusken M, et al. (2007) Optimal systolic and diastolic reconstruction windows for coronary CT angiography using dual-source CT. *AJR American journal of roentgenology* 189:1317–1323. [PubMed: 18029865]
 132. Goo HW (2015) Coronary artery imaging in children. *Korean journal of radiology* 16:239–250. [PubMed: 25741188]
 133. Shuman WP, Branch KR, May JM, et al. (2008) Prospective versus retrospective ECG gating for 64-detector CT of the coronary arteries: comparison of image quality and patient radiation dose. *Radiology* 248:431–437. [PubMed: 18552312]
 134. Sun Z, Ng KH (2012) Prospective versus retrospective ECG-gated multislice CT coronary angiography: a systematic review of radiation dose and diagnostic accuracy. *European journal of radiology* 81:e94–100. [PubMed: 21316887]

135. Qin J, Liu LY, Fang Y, et al. (2012) 320-detector CT coronary angiography with prospective and retrospective electrocardiogram gating in a single heartbeat: comparison of image quality and radiation dose. *The British journal of radiology* 85:945–951. [PubMed: 22745204]
136. Feng Q, Yin Y, Hua X, et al. (2010) Prospective ECG triggering versus low-dose retrospective ECG-gated 128-channel CT coronary angiography: comparison of image quality and radiation dose. *Clinical radiology* 65:809–814.
137. Hausleiter J, Meyer TS, Martuscelli E, et al. (2012) Image quality and radiation exposure with prospectively ECG-triggered axial scanning for coronary CT angiography: the multicenter, multivendor, randomized PROTECTION-III study. *JACC Cardiovascular imaging* 5:484–493. [PubMed: 22595156]
138. Chakravarthy M, Sunilkumar G, Pargaonkar S, et al. (2015) Induced apnea enhances image quality and visualization of cardiopulmonary anatomic during contrast-enhanced cardiac computerized tomographic angiography in children. *Annals of cardiac anaesthesia* 18:179–184. [PubMed: 25849686]
139. Lell MM, Jost G, Korporeal JG, et al. (2015) Optimizing contrast media injection protocols in state-of-the-art computed tomographic angiography. *Investigative radiology* 50:161–167. [PubMed: 25478743]
140. Lesser AM, Newell MC, Samara MA, et al. (2016) Radiation dose and image quality of 70 kVp functional cardiovascular computed tomography imaging in congenital heart disease. *Journal of cardiovascular computed tomography* 10:173–178. [PubMed: 26794867]
141. Kuettner A, Gehann B, Spolnik J, et al. (2009) Strategies for dose-optimized imaging in pediatric cardiac dual source CT. *RoFo : Fortschritte auf dem Gebiete der Röntgenstrahlen und der Nuklearmedizin* 181:339–348. [PubMed: 19291603]
142. Siegel MJ, Hildebolt C, Bradley D (2013) Effects of automated kilovoltage selection technology on contrast-enhanced pediatric CT and CT angiography. *Radiology* 268:538–547. [PubMed: 23564712]
143. Li J, Udayasankar UK, Toth TL, et al. (2007) Automatic patient centering for MDCT: effect on radiation dose. *AJR American journal of roentgenology* 188:547–552. [PubMed: 17242267]
144. Matsubara K, Koshida K, Ichikawa K, et al. (2009) Misoperation of CT automatic tube current modulation systems with inappropriate patient centering: phantom studies. *AJR American journal of roentgenology* 192:862–865. [PubMed: 19304687]
145. Cheng PM (2016) Patient Vertical Centering and Correlation with Radiation Output in Adult Abdominopelvic CT. *Journal of digital imaging* 29:428–437. [PubMed: 26810981]
146. Han BK, Grant KL, Garberich R, et al. (2012) Assessment of an iterative reconstruction algorithm (SAFIRE) on image quality in pediatric cardiac CT datasets. *Journal of cardiovascular computed tomography* 6:200–204. [PubMed: 22682262]
147. Mievil FA, Gudinchet F, Rizzo E, et al. (2011) Paediatric cardiac CT examinations: impact of the iterative reconstruction method ASIR on image quality--preliminary findings. *Pediatric radiology* 41:1154–1164. [PubMed: 21717165]
148. Nakagawa M, Ozawa Y, Sakurai K, et al. (2015) Image quality at low tube voltage (70 kV) and sinogram-affirmed iterative reconstruction for computed tomography in infants with congenital heart disease. *Pediatric radiology* 45:1472–1479. [PubMed: 26115723]
149. Nie P, Li H, Duan Y, et al. (2014) Impact of sinogram affirmed iterative reconstruction (SAFIRE) algorithm on image quality with 70 kVp-tube-voltage dual-source CT angiography in children with congenital heart disease. *PloS one* 9:e91123. [PubMed: 24614683]
150. Rempel O, Glockler M, Janka R, et al. (2016) Third-generation dual-source 70-kVp chest CT angiography with advanced iterative reconstruction in young children: image quality and radiation dose reduction. *Pediatric radiology* 46:462–472. [PubMed: 26739141]
151. Prabhu SP, Mahmood S, Sena L, et al. (2009) MDCT evaluation of pulmonary embolism in children and young adults following a lateral tunnel Fontan procedure: optimizing contrast-enhancement techniques. *Pediatric radiology* 39:938–944. [PubMed: 19471914]
152. Bae KT (2010) Intravenous contrast medium administration and scan timing at CT: considerations and approaches. *Radiology* 256:32–61. [PubMed: 20574084]

153. Greenberg SB, Bhutta ST (2008) A dual contrast injection technique for multidetector computed tomography angiography of Fontan procedures. *The international journal of cardiovascular imaging* 24:345–348. [PubMed: 17823851]
154. Westra SJ (2014) The communication of the radiation risk from CT in relation to its clinical benefit in the era of personalized medicine: part 1: the radiation risk from CT. *Pediatric radiology* 44 Suppl 3:515–518. [PubMed: 25304714]
155. Larson DB, Rader SB, Forman HP, et al. (2007) Informing parents about CT radiation exposure in children: it's OK to tell them. *AJR American journal of roentgenology* 189:271–275. [PubMed: 17646450]
156. Einstein AJ, Berman DS, Min JK, et al. (2014) Patient-centered imaging: shared decision making for cardiac imaging procedures with exposure to ionizing radiation. *Journal of the American College of Cardiology* 63:1480–1489. [PubMed: 24530677]
157. Broder JS, Frush DP (2014) Content and style of radiation risk communication for pediatric patients. *Journal of the American College of Radiology : JACR* 11:238–242. [PubMed: 24589396]
158. McCollough CH, Bushberg JT, Fletcher JG, et al. (2015) Answers to Common Questions About the Use and Safety of CT Scans. *Mayo Clinic proceedings* 90:1380–1392. [PubMed: 26434964]
159. Nievesstein RA, Frush DP (2012) Should we obtain informed consent for examinations that expose patients to radiation? *AJR American journal of roentgenology* 199:664–669. [PubMed: 22915409]
160. The Joint Commission (2016) Compliance Checklist for Diagnostic Imaging Joint Commission Resources, Chicago, IL.
161. Frush DP, Samei E (2016) CT Radiation Dose Monitoring: Current State and New Prospects CME, Medscape.
162. Mayo-Smith WW, Hara AK, Mahesh M, et al. (2014) How I do it: managing radiation dose in CT. *Radiology* 273:657–672. [PubMed: 25420167]
163. McCollough CH, Primak AN, Braun N, et al. (2009) Strategies for reducing radiation dose in CT. *Radiologic clinics of North America* 47:27–40. [PubMed: 19195532]

Total mAs 731		Total DLP 21 mGycm					
	Scan	kV	mAs / ref.	CTDI _{vol} * mGy	DLP mGycm	TI s	cSL mm
Patient Position F-SP							
Topogram	1	80	20 mA	0.02 L	0.4	2.0	0.6
Control Scan	2	80	182 / 540	2.64 L	1.3	0.28	5.0
Contrast							
TestBolus	3	80	20	2.84 L	2.8	0.28	10.0
Last scan no.	12						
Contrast							
FI_CorCTA	13D	80	221 / 398	1.03 L	16.2	0.28	0.6
*: L = 32cm, S = 16cm							

Figure 1.

CT dose report page from a cardiac CT examination in 2-year old male. Each scanned series is listed in the report page. kV, mAs/reference mAs for dose modulation purposes, CTDI_{vol}, DLP, rotation time in seconds (TI) and slice thickness (cSL) are listed for each scanned series. The 32 cm phantom diameter is indicated by the asterisk adjacent to the CTDI_{vol}. The control scan is a single slice localizer for the test bolus. The CTDI_{vol} for the control scan is less than the DLP because the slice thickness is 5.0 mm. The study was performed as an ECG-triggered high pitch cardiac CT examination with a DLP for the scan of 16.2 mGy·cm and a total DLP for all images of 21 mGy·cm.

Figure 2.

ECG tracings depicting prospective ECG-triggering and retrospective ECG-gating. The heart rate of 60 beats per minute was simulated by a cardiac trigger device incorporated into the scanner's cardiac monitor. A. Prospectively ECG-triggered tracing showing the x-ray beam on (dark blue bars) for only a targeted portion of the cardiac cycle centered at 65% of the R-R interval with temporal padding (light blue bars) to include 60-70% of the R-R interval. Prospective ECG-triggering allows for image reconstruction only during the portion of the cardiac cycle when the x-ray beam is on. B. With retrospective ECG-gating, the x-ray beam is on for the entire R-R interval, but the radiation dose is modulated up (dark blue bars) for a targeted portion of the cardiac cycle centered at 65% of the R-R interval with padding (light blue tall bars) to include 60-70% of the R-R interval. The dose during the remainder of the cardiac cycle is generally in the range of 20% of the full dose (light blue shorter baseline). Retrospective ECG-gating allows for reconstruction of images in any phase of the cardiac cycle, but image quality will be best at the targeted portion.

Figure 3.

Six-month-old, 8.7 kg female with congenitally-corrected (levo-) transposition of the great arteries, large ventricular septal defect, and pulmonary atresia, status post right Blalock-Taussig shunt and with ductus arteriosus left patent. Cardiac CT examination was requested to delineate intracardiac anatomic relationships and to generate 3D images prior to a biventricular repair (atrial switch with Rastelli procedure). A. Axial image showing the leftward and anterior moderately dilated ascending aorta (A) and rightward and posterior main pulmonary artery (P). There is mild focal narrowing (arrow) of the left pulmonary artery at the insertion site of the patent ductus arteriosus. R, Right pulmonary artery. B. Axial image showing mesocardia with an anteriorly directed apex. There is atrioventricular discordance with the right atrium connected to the rightward and anterior subpulmonary left

ventricle (LV) and the left atrium connected to the leftward and posterior hypertrophied systemic right ventricle (RV). Note the large VSD (V). C. Sagittal oblique reformation showing the aorta (A) arising from the hypertrophied systemic right ventricle (RV). The proximal aspect of the patent ductus arteriosus is seen (arrow).

The contrast-enhanced ECG-gated cardiac CT was performed on a GE Lightspeed VCT XTe scanner (GE Healthcare, Waukesha, WI) with suspended respiration and utilizing the following parameters: 80 kV, 120 mA, gantry rotation time of 0.35 sec, and with prospective systolic ECG-triggering using a “step and shoot” protocol with two 4 centimeter acquired slabs. Heart rate at the time of study was 124-125 bpm. “Smart Prep” bolus tracking was used to time the initiation of scan acquisition, with repetitive monitoring scans performed at the level of the proximal descending aorta that measured the contrast enhancement in Hounsfield units (HU) within a prescribed region of interest within the aortic lumen. When the contrast threshold exceeded 220 HU, the scan was manually initiated. A bolus of 22 ml (2.5 ml/kg) iodinated contrast (Iohexol, Omnipaque 350, GE Healthcare, Princeton, NJ) was administered via power injector through a 22-gauge right antecubital intravenous cannula at 4 mL/sec, followed by 20 ml of saline at the same rate. CTDI_{vol} (32 cm phantom) was 0.79 mGy and DLP was 8.3 mGy-cm. Images were reconstructed with iterative reconstruction (ASIR 70%).

Figure 4.

15 year-old male with no past medical history following successful cardiopulmonary resuscitation for a syncopal and unresponsive episode that occurred while running in gym class. Transthoracic echocardiography was suspicious for an anomalous left coronary artery from the right sinus of Valsalva. Cardiac CT was requested and confirmed this diagnosis. A. Axial two-dimensional and B. 3D reformatted images. The anomalous left coronary artery (A, arrowhead and B, arrow) arises from the leftward aspect of the right sinus of Valsalva near the sinotubular junction. The left main coronary artery origin is acutely angled relative to the aortic root (A) and the proximal course between the aorta and right ventricular outflow tract/main pulmonary artery (P) is anteroposteriorly narrowed. C, D. Endoluminal 3D rendered images. The left main coronary artery ostium (L in C) is small and elliptical relative to the right coronary artery ostium (R in D). Imaging findings suggest a proximal intramural left main coronary artery course. The anomalous left main coronary artery origin from the right sinus of Valsalva with a small orifice and proximal intramural course was

confirmed surgically. The patient underwent creation of a neo-ostium in the left sinus of Valsalva rather than left coronary artery unroofing to avoid damaging the adjacent right/left commissural post.

Fifty milligrams metoprolol (approximately 1 mg/kg) was administered orally for heart rate uniformity control approximately 2 hours prior to imaging. The contrast enhanced CT study was performed without sedation on a second generation Siemens SOMATOM Definition Flash dual source scanner (Siemens Healthineers, Malvern, PA) using the following parameters: 100 kVp, 70 mAs, automatic exposure control (CAREDose4D). The scan was prospectively ECG-triggered and timed to mid-diastole using a high pitch (3.2) single heart beat acquisition; heart rate at the time of the study was regular and 55 bpm. A test bolus of 10 mL iodinated contrast (Iohexol, Omnipaque 350, GE Healthcare, Princeton, NJ) was administered with imaging at the level of the carina performed every 2 seconds beginning 10 seconds after initiation of contrast injection until peak test bolus contrast was achieved in the ascending aorta at 20 seconds. 70 ml iodinated contrast was then injected through an 18-gauge right upper extremity intravenous cannula at a rate of 6 ml/sec using a triphasic injection of 60 mL full strength contrast, followed by 20 mL of a 50% contrast/50% normal saline mix, and then 20 mL normal saline with the diagnostic scan onset at 28 seconds following initiation of contrast injection. $CTDI_{vol}$ (32 cm phantom) was 3.93 mGy and DLP was 54.2mGy·cm. Images were reconstructed with a soft tissue kernel and iterative reconstruction (SAFIRE) strength 2. 3D images were rendered on a Vitrea workstation (Vital Images, Minnetonka, MN).

Table 1.

Selected published cardiac CT effective dose ranges

Patient Age	Number of patients	Exam Type	Scanner Type(s)	Tube Potential (kV)	Effective Dose (mSv)	Effective Dose MOSFET (mSv)	Weighting Factor	DLP (32 cm phantom) (mGy·cm)	Source
10.7 ± 6.2 yrs	50	RG CT	Siemens 64 slice MDCT 64 slice DSCT 128 slice DSCT	80, 100, 120	6.1 (2.5–10.6)		ICRP 103 [40] [60]	211.5 (64.0–648.0)	Ghoshhajra [61]
	15	PT CT			2.2 (0.9–3.4)			136.0 (43.3–188.0)	
	30	HPH CT			0.9 (0.6–1.8)			49.0 (18.0–82.0)	
0 - 6 yrs	25	RG CT, PT CT, HPH CT			2.3 (1.4–4.3)			53.0 (28.0–91.8)	
6 - 12 yrs	27				1.8 (0.6–4.7)			82.0 (23.8–205.5)	
12 - 18 yrs	43				2.9 (1.2–10.3)			193.0 (71.8–657.8)	
1.2 (0.02- 5.4) yrs	30	PT CT	Siemens 128 slice DSCT	80	0.26±0.16 (0.05-0.8)		ICRP 60 [62] [63] [64]	5.7±4.8 (1-22)	Paul [65]
0-3 yrs	10	PT & RG CT	Siemens 16 slice MDCT 64 slice MDCT 128 slice DSCT	80, 100, 120	2.2 (0.4-4.9)		ICRP 103 [40] [60]		Westra [56]
3-8 yrs	11				4.7 (0.8-14.4)				
8-15 yrs	10				2.5 (0.1-11.3)				
> 15 yrs	11				2.6 (0.4-7.9)				
132 (1-361) days	110	cCT	Siemens 64 slice DSCT	80	0.5±0.2 (0.2-0.9)		ICRP 60 [62] [63] [64]	8±6 (4-18)	Ben Saad [66]
	32	RG CT		80	1.3±0.6 (0.6-2.8)			21±9 (10-39)	
0.4 (0-6) yrs	108	PT CT	Siemens 64 slice DSCT	80	0.36±0.12		GSF 30/91 [67][28]		Goo [68]
	108	cCT		80	0.99±0.23				
< 2 yrs	29	cCT	Toshiba 64 slice MDCT	80	2.1 (1.1-10.6)		ICRP 60 [62] [69] [64]	66 (39-272)	Han [24]

Patient Age	Number of patients	Exam Type	Scanner Type(s)	Tube Potential (kV)	Effective Dose (mSv)	Effective Dose MOSFET (mSv)	Weighting Factor	DLP (32 cm phantom) (mGy·cm)	Source
0-4.5 yrs	32	HPH CT	Siemens 128 slice DSCT	80	0.29 (0.1-1.9)			7 (3-50)	
		RG CT	40 slice MDCT *	***	1.9±0.7 (0.8-8)		**	28±11 (10-52)	Young [70]
		PT CT	Not specified *	***	0.7±0.2 (0.3-1.3)		***	11±3.3 (3-16)	
		cCT		***	0.9±0.2 (0.54-1.4)		***	12±4 (6-22)	
1.3 (0.2-6) yrs	35	PT CT	Siemens 64 slice DSCT	80	0.38±0.09 (0.24-0.58)		ICRP 60 [62] [64]	19.86±6.27 (10-32)	Cheng [71]
1 yr	Phantom	RG CT (120 bpm)	Toshiba 320 MDCT	100	1.6	2.7 +/- 0.04	ICRP 103 [40] [60]	64.8	Podbersky [52]
		PT CT (120 bpm)			2.3	4.5 +/- 0.05		90.4	
		RG CT (60-120 bpm)			0.5	1.2 +/- 0.03		16.1	
		PT CT (60-120 bpm)			1.6	4.9 +/- 0.09		50.5	
5 yr	Phantom	RG CT	GE 16 slice MDCT	80, 120	8.7-28	7.4-25.7	ICRP 60 [62] [64]	411.88-1344.02	Hollingsworth [51]
5 yr	Phantom	RG CT (40 bpm)	GE 64 slice MDCT	100		16.45	ICRP 103 [40]		Huang [72]
	Phantom	(90 bpm)				11.81			
1 yr	Phantom	RG CT (90-150 bpm)	GE 64 slice MDCT	80		5.8-9.6	ICRP 103 [40]		Trattner [48]
1 yr	Phantom	PT CT (90-150 bpm)				2.9-5.8			

Mean +/- SD, (range from minimum to maximum value)

cCT, non-gated cardiac CT

RG CT, retrospective ECG-gated helical scan

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PT CT, prospective ECG-triggered axial scan
HPH CT, prospective ECG-triggered high-pitch helical scan
* Scanner manufacturer not reported

Parameter not reported

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Table 2:

Strengths and weaknesses of cardiac CT, cardiac MRI, echocardiography, and cardiac catheterization in children

Modality	Spatial Resolution	Temporal Resolution	Availability	Exam time	Invasiveness	Cost	Need for Contrast Media	Field-of-view limitation	Contra-indications	Porta-bility	Sedation	Ease of monitoring patients during exam
Cardiac CT	++	+	++	+	++	Intermediate	Yes	No	Yes	-	Occasionally	++
Cardiac MRI	+	++	+	++	++	Intermediate	Often	No	Yes	-	Typically below age 8	+
Echocardiography	++	+++	+++	++	+	Intermediate	Rarely	Yes	No	+++	Rarely	+++
Catheterization	+++	+++	++	+++	+++	High	Yes	No	Yes	-	Typically for all pediatric patients	+++

+ = low; ++ = moderate; +++ = high; - = not available