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Review Article

Computed Tomography and Other Imaging Modalities in Pediatric Congenital Heart Disease

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ABSTRACT

Congenital heart defects (CHD) are the most common congenital disabilities. Early and accurate diagnosis of coronary heart disease is very important for patients to get timely and effective treatment. In recent years, the accuracy of coronary heart disease diagnosis has been greatly improved with the development of medical imaging equipment and technology. At present, the clinical application of echocardiogram (echo), cardiovascular magnetic resonance (CMR) and computed tomography angiography (CTA) in coronary heart disease anatomy and function has increased significantly, which plays an important role in preoperative diagnosis, intraoperative monitoring, and postoperative recovery evaluation. However, each imaging technique has its indications. Providing the best examination plan for patients requires clinicians and radiologists' close cooperation. Therefore, this study reviewed the imaging techniques for diagnosing coronary heart disease.

Keywords: Cardiovascular magnetic resonance, computed tomography, congenital heart defects, echocardiography, imaging diagnosis, radiation dose

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INTRODUCTION

Congenital heart defect (CHD) is a structural anomaly of the cardiovascular system which occurs during fetal development. It can be classified as cyanosis or acyanosis (left-to-right shunts or obstructive lesions), and the

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presence or absence of cyanosis depends on the direction of blood flow to the heart and the great arteries. The most common is Atrial Septal Defect (ASD) (Figure 1), Tetralogy of Fallot (TOF) (Figure 2), Ventricular Septal Defect (VSD) (Figure 2), Patent Ductus Arteriosus (PDA), Pulmonary Stenosis, and Aortic Stenosis et al. For example, in TOF, since the blood from the right heart is shunted to the left through the defect, the arterial blood is mixed with venous blood, and cyanosis occurs when the reduced hemoglobin level in the bloodstream is elevated above 5%. On the other hand, in the case of simple pulmonary stenosis, ASD, or VSD, blood from the left heart flows back to the right heart, and there are no venous and arterial blood mixes, so cyanosis is not present. There are many types of CHD, and several defects may occur in combination, also known as compound malformations.

According to the global burden of disease study (GBD) 2017, congenital heart disease (CHD) causes 261247 deaths worldwide, of which 180624 are infants under one year old (Zimmerman et al., 2020). The mortality rate of CHD in different countries and regions is quite different. Among them, the incidence rate of coronary heart disease is highest in sub-Saharan Africa, central and eastern China, Central Asia and Southeast Asia, and some inland provinces in China and India (Zimmerman et al., 2020). Coronary heart disease accounts for about 1% of the total number of newborns or nearly 40000 cases in the United States annually (Hoffman & Kaplan, 2002). In 2016, circulation published a study that estimated that about 1 million children in the United States had congenital heart defects in 2010 (Gilboa et al., 2016). The incidence rate of China's coronary heart disease is about 2.4–10.4 per thousand, according to a 2019 report on cardiovascular health and disease in China. It is a major congenital malformation in China (Hu, 2020). According to the health indicators of statistics in Malaysia in 2007, nearly 1/100 infants (nearly 1 or 5000 infants) in Malaysia suffered from coronary heart disease every year (MOH, 2007; MOH, 2008a; MOH, 2008b).

CHDs are a high incidence of congenital disabilities, the main cause of neonatal and infant deaths. Therefore, it is very important to diagnose CHD early and accurately so that patients can get timely and effective treatment. With

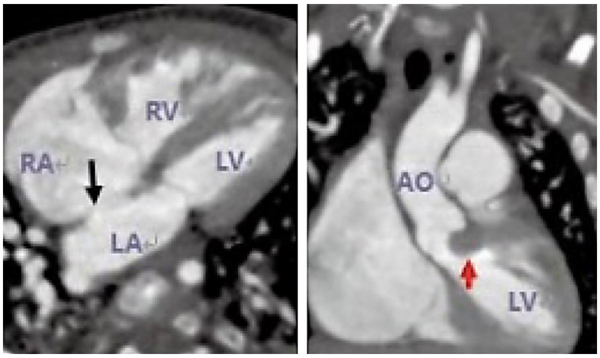
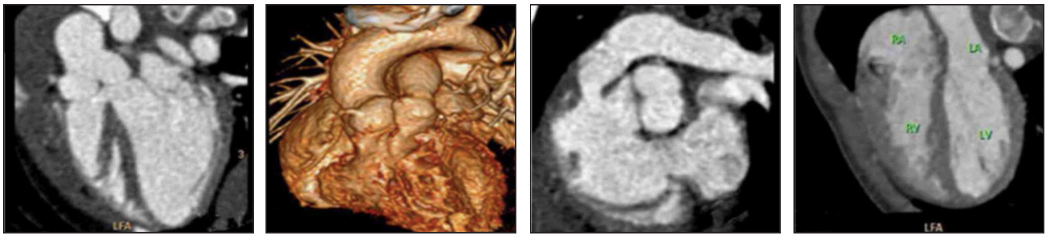


Figure 1. A 4-month-old girl with ASD. The diagram shows subaortic stenosis, ventricular septal projection on one side, left ventricular outflow tract (red arrow), and ASD (black arrow). RV = right ventricle, LV = left ventricle, RA = right atrium, LA = left atrium, AO = aorta. (Source: Miao et al., 2016)



(a) (b) (c) (d)

Figure 2. A 13-month-old girl with TOF: (a) The degree of aortic override was 50%; (b) Aortic root directly above the septal defect; (c) Narrowing of the right ventricle outflow tract, which was indicative of VSD.; and (d) Atrium and ventricle were a normal connection. (Source: D. Chen et al., 2017)

the development of medical imaging equipment and technology, there are more options for diagnosing CHD, and the accuracy has been greatly improved. At present, there are many diagnostic imaging methods, including Echocardiography (Echo), Cardiovascular Magnetic Resonance (CMR) and computed tomography angiography (CTA), which play an important role in the preoperative diagnosis, intraoperative monitoring, and postoperative recovery efficacy evaluation of CHD, and provide comprehensive and reliable information on cardiovascular anatomical structure and function of CHD.

CT scan can evaluate both anatomy and function of CHD morphologically. With the development of scanning and post-processing methods, the application of CTA in cardiovascular diseases is becoming more and more mature. However, due to the possibility of radiation damage in CT, different CT vendors have developed various techniques and systems to reduce the radiation dose to the patients.

The following problems exist in the imaging examination of CHD: (1) A single examination often cannot obtain all the lesion details and diagnostic information of CHD. (2) Traditional two-dimensional imaging is not ideal for treating CHD because the image display is incomplete. (3) Some examination methods are invasive and risky to patients. (4) Repeated imaging examination is a common phenomenon at present.

This review evaluates the role of imaging in treating patients with CHD; in particular, the recent advances in diagnosing CHD are described in detail. As much as possible, we will use published research evidence to support our discussion, while those lacking sufficient research evidence will adopt the expert consensus.

DIAGNOSTIC IMAGING OF CHD

Plain Chest X-Ray and Fluoroscopy

The advantage of a chest X-ray is that it cannot only show the outline and size of the heart but also fully reflect the outline of the lung, which is irreplaceable by any other imaging methods (Somerville & Grech, 2009). However, an X-ray cannot clearly show the structure of the heart due to the projections of the heart and the overlapping vessels. Therefore, it is necessary to combine different projection positions to show the edges of the various atria and the vessels and to judge the change in heart size. On the other hand, chest fluoroscopy has the characteristics of an X-ray, and it is dynamic, can arbitrarily change position, direction and angle, and can observe patients when inspiratory and suffocating in the organ change. However, the disadvantage of chest fluoroscopy is that it cannot save the image and can only be observed in real-time. Besides, patients are exposed to higher doses of radiation for longer periods.

Echocardiography (Echo)

An Echo is a simple, rapid, real-time dynamic observation of the cardiac structure and ventricular myocardial wall movement. It can visualize intracardiac malformations, especially for observing the morphology and function of valves and real-time hemodynamic measurements. Therefore, it is the non-invasive medical imaging technique preferred for diagnosing CHD (X. F. Chen et al., 2017). Transesophageal echocardiography (TEE) and real-time three-dimensional echocardiography (RT3DE) have expanded the clinical application of echocardiography in terms of exploration approaches and imaging modes, respectively. Echo has a non-invasive, no ionizing radiation and no radiation hazard (Lai et al., 2006). In patients with CHD, the ultrasound enhancing agent (UEA) improves the visualization of segmental wall motion of the left and right ventricles, allowing for better quantification of ventricular function at rest and during physiological or drug load. The use of UEA-enhanced Doppler signals is beneficial for quantification of right ventricular (RV) systolic blood pressure in patients with CHD, allowing simultaneous measurement of RV and left ventricular (LV) myocardial perfusion while analyzing ventricular wall motion (Kutty et al., 2016; Porter et al., 2018). The echo can be carried out near the bed and repeatedly detected (Marin et al., 2012). Moreover, the price is relatively lower than other imaging examinations.

However, in practical application, since most of the heart and the great vessels are covered by bone and lung tissue, the location and direction of the exploration are still limited, and the whole course of the vessels cannot be tracked. Besides, the spatial resolution is low, and the field of vision is small, so the anatomical observation of some parts is limited to some extent, such as the development of the middle and distal segments of the left and right pulmonary arteries, as well as the determination of the origin and location of the great vessels. At the same time, ultrasound images are all body layer images, which need multi-level observation to construct stereo images, so the accuracy of examination is related to the theoretical basis and experience of the sonographer.

Therefore, according to the American Society of Echocardiography (ASE), each pediatric cardiac sonographer must obtain a certificate of qualification within a certain period by passing the relevant examination prescribed by an industry-recognized qualification body. Must have passed a formal course of education in the specialty of ultrasound recognized by a professional association or authority and in accordance with the requirements of a qualifying body. Must be able to perform various echocardiographic examinations and write echocardiographic reports. The skill level must be maintained through participation in appropriate continuing medical education courses (Lai et al., 2006).

Transthoracic Echocardiography (TTE). TTE is the most common type of Echo. It is non-invasive and takes place entirely outside the patient's body. The probe is placed on the left, or right edge of the sternum, the apex of the heart, the supra sternal fovea or the subxiphoid region of the ribs for observation of the aortic valve, left ventricular outflow tract and descending aorta. Compared with CMR, TTE has the advantages of low cost and high availability (Koestenberger et al., 2012).

Transesophageal Echocardiography (TEE). TEE is another echo type in which the probe is placed inside the esophagus or stomach, then scans the heart and vessels from the rear and below. TEE provides regular observations of cardiac valve function, cardiovascular structural development, and ventricular function (Sluysmans & Colan, 2005; Gutgesell & Rembold, 1990). At present, micro-TEE can be widely used in children with CHD (Pavithran et al., 2014). However, this technique is limited in the assessment of complex CHD and extracardiac vascular malformations (Lian et al., 2018).

Real-Time Three-Dimensional Echocardiography (RT3DE). RT3DE has a promising clinical application in CHD; compared with the traditional two-dimensional echocardiography (2DE), which can only display the flat picture of the heart structure, RT3DE expands the vision of scanning the heart and blood vessels from the spatial dimension and the time dimension. Studies have shown that RT3DE can more accurately describe atrial septal defects (ASD) and various congenital valve damage, the fetal heart can be analyzed locally, and the degree of aortic dilatation in Marfan's syndrome can be studied quantitatively (Acar et al., 2004). The new high-resolution RT3DE probe and ultra-high-speed real-time ultrasound image processing platform can real-time, quickly collect images and can timely synchronous display the three-dimensional (3D) image of the heart. RT3DE can observe the cardiac valve structure, pathological property, and abnormal function. It is possible to accurately observe and quantitatively evaluate the heart valves, thus more accurately guiding interventional or surgical treatment of various heart valve diseases. RT3DE images can be obtained in less than 5 minutes, and the use of sedation by the examiner is never required. In 2012, the European and the American societies of echocardiography jointly issued the three-dimensional echocardiography (3DE) operating guidelines (Lang et al., 2012).

However, at present, the spatial resolution of RT3DE in quantitative valve imaging still needs to be improved. Furthermore, the temporal and spatial resolution needs to be improved to obtain the best image quality, and wide-angle acquisition is needed to realize distance visualization (Kleijn & Kamp, 2009). These limitations may cause measurement errors and variations in the results.

The Characteristic of the Echo. Compared with MR and CT, echocardiography has the following advantages: (1) Availability. The echo can be found in almost all hospitals and clinics. However, cardiac examination operators need to undergo a long period of training and evaluation. (2) Portability. Due to the development of portable ultrasound machines, the echo can be taken to the patient's bedside (Rehman et al., 2021). (3) Cost. The initial and operational costs of echocardiography are significantly lower than those of CMR and CT. (4) No radiation. Echo uses high-frequency sound waves to get the image of the heart.

Cardiovascular Magnetic Resonance (CMR)

With the development of Magnetic Resonance Imaging (MRI), CMR has been widely accepted in clinical practice because of its safety and accuracy in assessing myocardial function and showing the overall anatomy of the heart in the diagnosis of CHD, especially CHD with abnormal external great vessels, complex CHD, and postoperative CHD. Compared with Echo, CMR is more accurate in quantifying the shape and function of the heart, allowing the image can be observed repeatedly, and there are no strict requirements for the operator's experience and skill level. In addition, CMR can produce high-resolution images to describe the anatomical structures, such as the size of the heart, valve shape and chamber size, and also provide dynamic information such as angiography, myocardial perfusion, shunt, and abnormal morphological manifestations (Glockner et al., 2003). CMR has the additional advantage that it does not involve radiation. Therefore, CMR and Contrast-enhanced MR Angiography (CE MRA) are valuable tools for assessing associated vascular abnormalities and blood flow patterns (Sreedhar et al., 2005).

However, CMR of CHD generally takes more time to perform than other imaging methods, around 30–60 mins. The presence of implants or other metal objects can sometimes make it difficult to get a clear image, but movement during imaging can have the same effect. MRI can be very intimidating for children because it is noisy; to obtain high-quality images, pediatric patients need to lie completely still in an enclosed space and follow the breath-holding instructions while recording the image. In addition, imaging may be difficult to perform if patients are anxious or confused. Some children may be unable to stay still for the MRI scan, so young children (ages 1 to 6) often need sedatives to help them relax or fall asleep during the exam (Barkovich et al., 2018; Arlachov & Ganatra, 2012).

The Preparation of CMR. (1) Introduce the CMR to parents in detail and ask them to tell the child in advance in a way that the child can understand to ensure that the examination is performed successfully. (2) Before entering the examination room, the doctor checks the patient's medical history and checks if the patient has a metal device implanted or wearing a metal object to avoid damage or artifacts. (3) Anesthesia or sedation is often used in younger children because the examination is long, and the patient needs to remain stationary during the examination to avoid movement artifacts. (4) The contrast agent is given intravenously. (5) Patients need to wear a hearing protection device. (6) The temperature of the pediatric patient should be monitored, and a blanket should be added to keep the patient warm if necessary. (7) Patients need to wear a vital signs monitor. (8) By positioning the image to determine the appropriate coil placement and scanning range (Fratz et al., 2013).

Spin Echo Sequence (SE). The most common variant of SE is the Fast spin echo sequence (Siemens, TSE; GE, FSE; Philips, TSE; Toshiba, Fast SE) and Ultrafast spin echo sequence (Ultrafast SE) (Siemens, HASTE; GE, SSFSE; Philips, SSTSE; Toshiba, Fast-DIET). Ultrafast SE has a fast-scanning speed, collects one layer of cross-sectional images in one cardiac cycle, and is insensitive to breathing and motion artifacts so that it can collect images in free breathing (Lu & Zhao, 2010). First, since the sequence is black blood, axial and sagittal zero interval tomography images can roughly understand the relationship between atrioventricular and ventricle aorta, the development of ventricle and aorta, and atrioventricular valve development. Second, it can be positioned for other sequential scans. For example, two-chamber, four-chamber, and ventricular effluent tract films are all based on HASTE location scans in Siemens. However, the black blood sequence cannot provide optimal cine information. Compared with ultrafast gradient echo sequence (Ultrafast GRE), SE has a lower signal-to-noise ratio (SNR) (Ginat et al., 2011).

Gradient Echo Sequence (GRE). The GRE may use the Spoiled gradient echo sequence, Ultrafast GRE, and the Steady-state gradient echo sequence. GRE is an alternative technique to SE, which can identify the abnormal function of the heart wall and evaluate the bilateral ventricular function. The Cine sequence is characterized by high temporal resolution and high sensitivity to flow changes. This sequence is commonly used for preoperative diagnosis and postoperative follow-up of complex CHD, such as double outlet right ventricle (Yao et al., 2016).

Steady-state gradient echo sequence (Siemens, True-FISP; GE, FIESTA; Philips, balance-FFE; Toshiba, True SSFP) can be used to comprehensively observe the anatomical connection and function of the heart and the great vessels, which is conducive to the display of intracardiac malformations. It is characterized by fast scanning speed and high SNR. Among them, Time-adaptive sensitivity encoding (TSENSE) technology is not sensitive to breathing and mild motion artifacts, so it is very suitable for arrhythmia patients and infants who cannot cooperate with breath-holding (Jing et al., 2017; Lu & Zhao, 2010)

Contrast Enhanced MR Angiography (CE MRA). CE MRA is mainly used to display vascular malformation, including PDA and artery malformation (Lv et al., 2010). However, MRI contrast agents are associated with nephrogenic systemic fibrosis and should be used with caution in patients with renal insufficiency (Zeng et al., 2014; Elmholdt et al., 2011; Davison & Mead, 2010).

Computed Tomography (CT)

CT has good spatial resolution and can provide a three-dimensional reconstruction of the heart. It can clearly and objectively show the heart structure, the great vessels, the relationship between each atrioventricular valve and ventriculoarterial valve, intracardiac shunt, left and right ventricular function, and the volume of the heart chamber. With the development of technology, the CT scanning time is shortened while maintaining high image quality (Larson et al., 2011). Since the introduction of 64-slice CT, multi-slice spiral CT (MSCT) has been widely recognized as a non-invasive examination for the diagnosis of CHD (Crean, 2007; Ropers et al., 2006). In addition, most hospitals have CT equipment, which is usually cheaper than MRI (Fisher & Sawyers, 2020; Davis & Cunha, 2019). Therefore, CT has developed from the original single-slice to 64-slice, 256-slice, 320-slice spiral CT, and even more advanced dual-source CT (DSCT) (Siegel, 2003). A conventional chest CT scan can show the vessels of the heart, and the adjacent relationship between the mediastinal organs and tissues, so it is helpful to display pericardial effusion, thickening and calcification.

The main characteristic of CT is its excellent spatial resolution, which is better than MRI and Echo, adequate temporal resolution, and relatively poor contrast resolution. Compared with MSCT, flat volume CT have excellent spatial resolution and wider coverage, but the contrast resolution is less than MSCT. The high temporal resolution of cardiac CT is mainly achieved by rapid frame rotation time and partial scan reconstruction (Lin & Alessio, 2009).

The consequent disadvantage to obtaining a clear image is that the radiation dose is increased, and the scanning time is prolonged. In addition, infants and children are in the stage of physical development, and their tissues and organs are richer in water than adults. As a result, infants and children are at a significantly higher risk of radiation injury or damage than adults. Therefore, more attention should be paid to the radiation dose received by infants and children during CT examinations (Brenner & Hall, 2007). There are multiple data acquisition and scanning parameters in CT, non-gated acquisition mode, retrospective electrocardiogram (ECG)-gated spiral acquisition mode, and prospective ECG-triggered sequential acquisition mode.

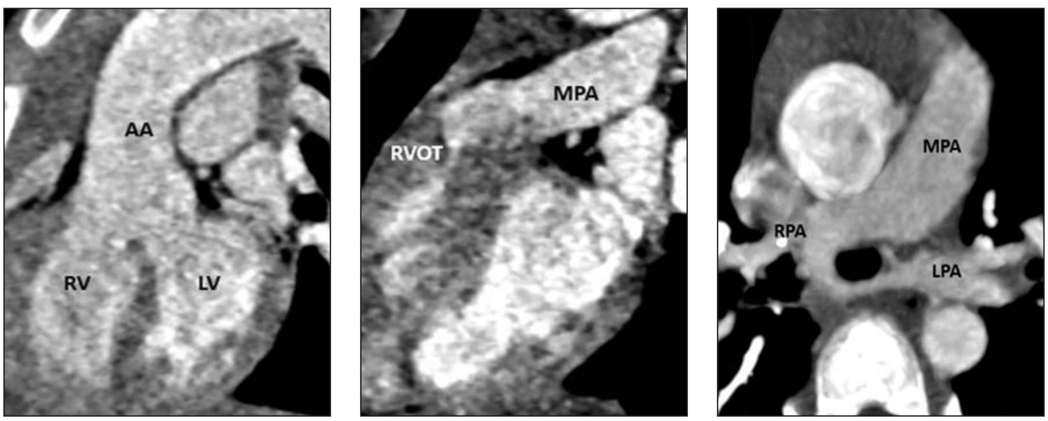
The Technical Characteristics of MSCT. Due to the high spatial resolution and good image quality, MSCT can display the details of cardiac deformities, especially the deformities in the connection of the great blood vessels, collateral circulation, progression and development of coronary arteries, and development of other organs related to the heart (Feng & Xing, 2012; Liu & Wang, 2017). It has high temporal resolution and reduces the inspection time. Continuous-level tomography avoids image overlap, and a variety of post-processing methods, such as volume reconstruction, surface reconstruction, multi-plane reconstruction, and maximum density projection, ensure the accurate expression of lesions. However, MSCT does not provide enough information about the cardiovascular function and hemodynamics (Enaba et al., 2017, Zhang et al., 2012).

The Preparation of MSCT. (1) The iodine contrast agent allergy test negative due to the poor expression ability of infants, respiratory, heart rate, blood pressure and skin mucosal changes should be closely monitored. (2) Establishment of injection route: superficial venous injection through the lower extremities was preferred to minimize the effect of contrast artifact. Secondly, the contrast agent should be injected through the superficial vein of the right upper limb to prevent the left innominate vein from interfering with the observation of the aortic arch. If an abnormal return of the left superior vena cava is suspected, it can be injected through the left upper limb superficial vein. If an abnormal return of the inferior vena cava is suspected, it should be injected through the superficial veins of both legs. The high concentration of contrast agent injected through the upper limb will affect the imaging of the brachiocephalic trunk. (3) Connecting electrocardiogram (ECG): to prevent metal artifacts caused by the electrode, it should be noted that the electrode should be placed far away from the scanning area. Usually, two upper limbs and an abdomen should be selected for young children. (4) Breath-holding training: for children who can cooperate with the examination, breath-holding training should be carried out. (5) Anesthesia is carried out by a professional anesthetic doctor for children who cannot cooperate with the examination. (6) ECG, respiration, and peripheral oxygen saturation should be monitored.

The Contraindications of MSCT. (1) Allergic to the iodine contrast agent. (2) Patients with acute or chronic renal failure. (3) Patients with severe cardiac insufficiency or corrected heart failure. (4) Patients with severe arrhythmias.

The Various Post-processing Technologies. (1) Volume Rendering (VR). VR can display the spatial position relationship and movement of the heart and large blood vessels. However, due to the need to combine with the image processing method of partial cutting, the operation is more complex and experienced operators are needed. (2)

Maximum Intensity Projection (MIP). MIP can display the anatomical structure of the heart and the large blood vessels from multiple directions and angles, and the thickness can be changed arbitrarily, with high measurement accuracy. However, the dense tissue blocks angiography. (3) Curved Planar Reconstruction (CPR). CPR can better show the calcification and distorted and stented vascular lumen. However, due to the high dependence on the accuracy of the probe, a single curve cannot adequately show eccentric lesions. In addition, hyperperfused vessels are difficult to show, so CPR is used relatively infrequently. (4) Multiplanar reconstruction (MPR) (Figure 3). The data obtained from the axial plane are converted into coronal, sagittal, or sloped non-axial planes. However, the reconstruction time is longer, and there is more data to review and archive each case.



(a) (b) (c)

Figure 3. A 5-year girl with VSD (Prospective ECG-triggering DSCT angiography). (a) Oblique coronal MPR image, (b) Oblique sagittal MPR image, (c) axial thin-section MIP image. AA= ascending aorta, MPA = main pulmonary artery, RPA = right pulmonary artery, SVC = superior vena cava. (Source: Nie et al., 2014)

Retrospective ECG-Gated Spiral Acquisition. The retrospective ECG-gated spiral acquisition mode adopts the small-pitch spiral scanning. This model is a whole cardiac cycle scan. The retrospective ECG-gated acquisition is similar to cameras, which can take continuous pictures by pressing the shutter at one time, taking numerous exposures and pictures, whether clear or useful, to select the best or several images in retrospect. ECG data is collected synchronously during CT scan, and the best data is selected for reconstruction according to the time phase of ECG data in retrospect. Therefore, continuous radiation exposure is performed in multiple consecutive heartbeat cycles to obtain clear images, leading to a higher radiation dose in retrospective ECG-gated spiral acquisition compared with that in prospective ECG-triggered sequential acquisition. The advantage of the retrospective ECG-gated protocol is that the image quality of the retrospective ECG-gated spiral mode was better than that of the prospective ECG-triggered sequential mode (Wang et al., 2017).

In addition, the retrospective ECG-gated spiral mode is not limited by heart rate and is applicable to patients with irregular heart rate, premature beat and fast heart rate (>70 beats per minute, bpm) (Stolzmann et al., 2011; Nakagawa et al., 2016).

However, the image quality of DSCT is similar to prospective and retrospective ECG-gated techniques, which can significantly reduce the effective dose of patients, and has important clinical value for subjects who cannot receive a high radiation dose and whose heart rate is lower than 67 bpm (Liu & Wang, 2017; Wang et al., 2017; Pache et al., 2011; Xu et al., 2010; Ünal et al., 2015).

Prospective ECG-Triggered Sequential Acquisition. Prospective ECG-triggered sequential acquisition mode is not a spiral scanning. The mechanism of the prospective ECG-triggered protocol is that the X-ray tube is selectively turned on only when triggered by the ECG signal, and the scan is triggered only when the heart is in diastole for the data collection. The main advantage of the prospective ECG-triggered sequential acquisition mode is that the X-ray exposure time is short. Therefore, the radiation dose is lower than that of the retrospective ECG-gated spiral acquisition mode.

However, as data collection is only carried out at a specific stage of a cardiac cycle and the machine rotation speed is limited, there are higher requirements for heart rate control and stability, so the function of cardiac valve or ventricular wall movement cannot be evaluated (Husmann et al., 2008; Stolzmann et al., 2008). The mode can set the scanning window in the R-R interval, which is very demanding for heart rate, rhythm, and breath hold. It is applicable to patients with a steady heart rate below 70 bpm or 65 bpm, so patients should not have a significant arrhythmia; otherwise, some data may be distorted and affect the accuracy of diagnosis (Roberts et al., 2008; Earls et al., 2008; Gopal et al., 2009).

Non-ECG-Gated Acquisition. Non-ECG-gated scanning is a spiral scan, a simple and feasible technique for CT in patients with CHD. It scans fast and is not limited by the heart rate of examinees. Since the introduction of MSCT, the greatest advantage of DSCT lies in cardiac imaging, where the dose of radiation in cardiac scanning is only 50% of that of conventional CT (Li et al., 2009), so cardiac CT with this scanning protocol has been widely used. In addition, this scanning protocol can be performed during breath-holding or free-breathing (Goo, 2010).

Furthermore, it can display the structure and malformations of the extracardiac vessels, particularly the origin and proximal segment of the coronary artery (Goo et al., 2005). In non-ECG-gated synchronous spiral CT scanning, the large pitch scanning mode is usually adopted for chest scanning, and the coronary arteries can be displayed. It is because the larger the pitch used, the faster the scanning speed and the shorter the scanning time under the same condition. Compared with retrospective ECG-gated imaging, non-ECG-gated synchronous imaging had a shorter time to obtain the images. However, retrospective ECG-gated protocols generated fewer cardiac motion artifacts in the aortic root (Horehledova et al., 2020).

Dual-Source CT for Cardiac Scanning. Prospective ECG-triggered sequential acquisition in DSCT freely set the width of the acquisition window between 200ms and 380ms during R-R data collection. Retrospective ECG-gated spiral acquisition in DSCT is the whole R-R interval collection. Under the advance guarantee of a full dose acquisition window of > 83ms, the ray dose of other periods in the R-R period can be set arbitrarily from 4% to 100% (Li et al., 2016; X. F. Chen et al., 2017).

320-Slice CT for Cardiac Scanning. The 320-slice CT has a detector of 16cm, which can cover the whole heart for children. One rotation only takes 0.35s, avoiding the influence of heartbeat, breathing and other factors on the image quality. The scan time is short, and the children are not easily wake up during the examination. The operability is better than Echo and MRI, and it is easier to accept by the children's families. Various abnormal shunts of the heart can be identified by dynamic volume scanning. The 320-slice CT eliminates the overlap of spiral CT scans and the redundant data needed for interpolation reconstruction algorithms, and the single cardiac scan dose is 3 to 4 mSv. However, it does not reflect the pressure and oxygen of the degree of pulmonary hypertension, which is a disadvantage of all non-invasive imaging of the heart (Sreedher et al., 2021).

To sum up, imaging diagnosis of CHD has entered a new era of how to apply correctly and efficiently different non-invasive examination methods such as Echo, CMR and CT, which requires closer collaboration between clinicians and radiologists and continuously optimize these methods to make the most of them. In Asian countries, pediatric cardiac CT is more commonly used than pediatric cardiac CMR (Tsai & Goo, 2013). However, compared with CMR and Echo, CT has radiation, and the risk of radiation exposure cannot be ignored. Therefore, the clinicians and technicians must minimize the radiation dose while maintaining adequate spatial, contrast and temporal resolution. The five imaging modalities for diagnosing children were tabulated in Table 1.

RADIATION AWARENESS

Radiation exposure is a method of measuring air ionization due to ionizing radiation of photons, defined as the charge of electricity released by such radiation in a particular air volume divided by the air's mass. All objects in nature emit radiation if the temperature is above zero absolute temperature, and most of the radiation is produced by natural minerals. Even the muscles, bones and tissues of the human body contain naturally occurring radioactive elements. Humans are exposed to natural radiation from the earth and beyond,

Table 1
Strengths and weaknesses of plain chest X-ray, fluoroscopy, CT, CMR, echo in children with CHD

Modality	Plain chest X-ray	Fluoroscopy	CT	CMR	Echo
Cost	+	+	++	+++	++
Examination time	+	+	++	+++	+++
Portability	+++	−	−	−	+++
Monitor*	+++	+++	++	+	+++
Sedative requirement	−	−	+	+++	−
Imaging data save	+	+	+++	+++	++
Need contrast media	−	−	+++	++	+
Limits of image reconstruction	+++	+++	−	−	+++
Contrast resolution	−	−	+	+++	+
Spatial resolution	−	−	+++	+	++
Temporal resolution	−	−	+	++	+++
Radiation dose	+	+	++	−	−

− = not available; + = low; ++ = moderate; +++ = high
*Monitor is for ease of monitoring the patient during the examination.

and radiation obtained from outer space is called cosmic radiation. In addition, other sources of radiation may be artificial, such as X-rays used to diagnose disease and treat cancer. For example, CT scans have higher radiation doses than traditional x-ray imaging procedures, and the ionizing radiation cause side effects (Slovis, 2003; ICRP, 2007).

According to Volume II of the UNSCEAR (2013) Report: Effects of radiation exposure on children, DNA molecules are prime targets for ionizing radiation, which kills cells and causes them to transform. Epidemiological studies have demonstrated that moderate to high doses of ionizing radiation can cause and promote cellular changes that lead to cancer, meaning that individuals who receive a dose of radiation are at risk for cancer (UNSCEAR, 2006). Children grow and metabolize faster than adults, meaning the side effects of radiation doses are more damaging to children. Children with CHD have more opportunities and time to be exposed to radiation, which increases the risk of other diseases. CT scans emit a high degree of ionizing radiation: About 11% of CT scans are pediatric (Mazrani et al., 2007). Studies found that every 500 children under 15 died from cancer caused by abdominal CT scans. Ionizing radiation is associated with brain tumors, and 1 in 1,500 children under 15 died from cancer caused by brain CT radiation (Shrimpton et al., 2005). In 2012, A retrospective cohort study published online by the Lancet medical journal revealed that CT scanning in children with a cumulative dose of about 50mGy might mostly triple the risk of leukemia, and the cumulative dose of around 60mGy were three times more likely to develop brain tumors. Therefore, it is recommended that children should adopt lower scanning conditions (Pearce et al., 2012). With the rapid increase and advancement of CT examination techniques in medicine, the correct use of radiological examination has become very important.

As a principle of dose control, the ALARA (as low as reasonably achievable) concept (the use of the lowest dose of radiation to obtain the appropriate image quality for accurate diagnosis) is generally accepted in the radiation field. However, blindly reducing the radiation dose will lead to the deterioration of image quality, resulting in misdiagnosis or rescan (Seibert, 2004); therefore, from the perspective of radiological protection, the reasons for radiological examination must be clarified before CT examination. In addition, clinically necessary to provide patient information and suspected diagnosis derived from symptoms and physical examination. This way, protection is optimized to ensure that patients and personnel are not exposed to excessive radiation.

GUIDELINE

Children's imaging examination should follow the principles of non-invasive before invasive, simple before complex, economical before expensive. During the inspection and optimization, measures should be taken according to local conditions, starting from the actual situation of the local area and the children themselves. For example, due to the high cost and lack of availability of MRI, CT is generally more suitable to evaluate pediatric CHD than MRI in Asian countries (Tsai & Goo, 2013). In China, MRI examinations are made by appointment due to the long MRI examinations and the large population base, which is not as convenient and fast as CT. The premise of a successful CT examination of CHD in children and infants is to check and record patient information carefully. The correct positioning of the patient position on the CT gantry and the use of laser beam positioning is to avoid the incorrect position and excessive scanning range, which will lead to the deterioration of image quality and excessive radiation exposure (Booij et al., 2016). In infants and children, prolonged or repeated use of sedatives can lead to neurodevelopmental disorders, particularly in children with CHD, with a higher risk of adverse side effects (Char et al., 2016). Children who do not cooperate may be tested with mild sedation, as the time required for CT examination of CHD is shorter than that for MRI. If sedatives are used after the CT scan, pediatric patients should be monitored and observed until awakened.

It is generally recommended that patients hold their breath during the scan to avoid breathing movement artifacts. Breath-holding scanning can improve image quality (Goo, 2010), but for young children and infants, breathing cannot be controlled; for them, use free breathing during the scan. First, injecting the contrast agent through the superficial vein of the lower extremities is preferable to minimize the influence of the contrast agent's artifacts. Secondly, the contrast agent should be injected through the superficial vein of the right upper limb to prevent the left innominate vein from interfering with the observation of the aortic arch. If an abnormal return of the left superior vena cava is suspected, the injection can be made through the superficial vein of the left upper limb. If an abnormal return of the inferior vena cava is suspected, injections should be made through the superficial veins of the legs. The high-concentration contrast agent injected through the upper limbs will affect the imaging of the brachiocephalic trunk.

As mentioned above, CT has several scanning techniques that can be used to evaluate children with CHD, including non-ECG spiral scan, retrospective ECG-gated spiral acquisition, and that prospective ECG-triggered sequential acquisition. Different techniques depend on what needs to be observed. For example, the non-ECG spiral scan allows the evaluation of extrathoracic vessels. In addition, in free-breathing children with CHD, a high-pitch dual-source non-ECG spiral scan reduces cardiac and respiratory motion artifacts in thoracic CT (Sriharan et al., 2016).

Many adult studies have shown that prospective ECG-triggered sequential acquisition is recommended for use in patients with stable and low heart rates (≤70 bpm). However, this model has not been widely used in young children with a rapid heart rate and inability to control breathing; the main advantage of this pattern is the low radiation dose, and intracardiac structures and coronary arteries can be observed and functional assessments performed (Hausleiter et al., 2012; Earls et al., 2008; Roberts et al., 2008; Gopal et al., 2009). However, although the coronary artery and functional information can be obtained from prospective sequential gating, they are less optimal than retrospective gating.

A retrospective ECG-gated spiral scan provides excellent image quality (Goo, 2010), but its low pitch value results in a high radiation dose. In addition, the breath should be held during scanning to avoid breathing movement artifacts, which observes the intracardiac structure and coronary arteries and assess cardiac function (Jin et al., 2010).

The time has come to obtain good diagnostic images at the minimum cost of radiation exposure. Therefore, we list a guideline, which includes patient preparation, scanning parameters, scanning techniques, radiation dose reduction and optimization in Table 2.

PROBLEMS AND PROSPECTS

Cardiac imaging can provide valuable guidance for treating CHD in all stages. Furthermore, advances in the field of cardiac imaging have greatly improved the prognosis of these patients. Echo can be real-time, dynamic, multi-section two-dimensional imaging, combined with Doppler technology, which has great advantages in displaying CHD intracardiac malformations. However, it is affected by the acoustic window, the display of extracardiac malformations is not good, and the personal technical requirements of the sonographer are very high, so the diagnosis of complex CHD is limited (Lai et al., 2006).

Nowadays, low-dose CT has become a common focus in the medical imaging field. The management and supervision institutions of the medical and health industry constantly introduce relevant laws and regulations to guide manufacturers and scientific research

Table 2
Guidelines for CT scan of CHD in children

Radiologists Preparation
1. The examination is conducted under the guidance of an experienced radiologist. 2. Ensure the quality of diagnostic images.
Patient Preparation
1. Check the patient's name and inpatient/outpatient number. Record patient age, height, weight, body mass index (BMI), cooperation ability, and vital signs. 2. Using minimal or no sedatives in infants and children is recommended to avoid neurodevelopmental disorders. If sedatives were used, pediatric patients were monitored and observed until they were awake after a CT scan.
Scanning Parameters
1. Recommend holding breath during the scan to avoid breathing movement artifacts; for young children and infants, use free breathing while scanning. 2. Scanning range: pediatric cardiothoracic CT scans typically include the upper aortic arch and the diaphragm. The scanning range to assess the pulmonary veins is from supraclavicular to subphrenic.
Scanning Techniques
1. Set according to the patient's medical history and clinical requirements. 2. Non-ECG-gated acquisition (1) Using high-pitch dual-source scanning to observe the extracardiac and cardiac structures. (2) This pattern can be used in free-breathing children with CHD. (3) High-pitch dual-source non-ECG spiral scan reduces cardiac and respiratory motion artifacts in thoracic CT. 3. Retrospective ECG-gated spiral acquisition (1) Observe intracardiac structures and coronary arteries and perform a functional evaluation. (2) The radiation dose of this technique is higher than prospective ECG-triggered sequential acquisition. (3) This pattern provides excellent image quality (4) Breath should be held during scanning to avoid breathing movement artifacts. 4. Prospective ECG-triggered sequential acquisition. (1) Observe intracardiac structures and coronary arteries and perform a functional evaluation. (2) The radiation dose of this technique is lower than retrospective ECG-gated spiral acquisition.
Radiation Dose Reduction and Optimization
1. Follow the ALARA principle.
The Iodinated Contrast Medium
1. Recommend the tri-phasic injection protocol. 2. The appropriate injection method is selected according to the patient's condition and medical history. 3. The injection rate depends on the size of the vascular catheter and CT indications.

BMI = body mass index, ALARA = As Low As Reasonably Achievable

institutions to develop more advanced and effective innovative designs. At the same time, medical practitioners should be regulated to rationally use low doses in practical work, abide by the ALARA principle, and try to reduce patient doses to meet the requirements of clinical diagnosis.

MSCT, especially 64-slice CT, has been used to diagnose CHD in infants and young children, but its temporal resolution is low. The patient's heart rate must be less than 65 bpm to ensure the image quality of coronary artery imaging. The heart rate of newborns and infants is often 150 bpm, so it is difficult to show the origin and course of the coronary arteries clearly.

Compared with ordinary 64-slice CT scanning technology, DSCT has higher temporal resolution and relatively low heart rate and breath-holding requirements. In addition, there are more scanning modes to choose from: personalization of scanning. As the pitch increases, the scanning speeds up, and the radiation dose can be reduced.

320-slice CT has extremely high temporal and spatial resolution and powerful post-processing functions. It can clearly and intuitively display most intra- and extracardiac malformations of complex CHD. It is safe and non-invasive, and the scanning dose is low, so it is very suitable for the examination of newborns and infants. Compared with other imaging methods, its clinical application value is more reflected in the accurate display of the anatomical morphology and collateral circulation of the connection between the heart and the great blood vessels, the part of the extracardiac great blood vessels. The severity of the collateral circulation will determine whether the child can undergo surgery, the formulation of the surgical plan, and the prognosis after surgery. Showing the origin and course of the coronary arteries is of great significance for the preparation of a detailed surgical plan before surgery, thereby minimizing intraoperative risks (Sreedher et al., 2021).

MRI has no ionizing radiation, does not necessarily require intravenous contrast and can acquire images at multiple angles. However, the temporal and spatial resolution is relatively low, the scanning time is long, and the large noise during the scanning process makes it difficult to obtain better imaging results in newborns and infants.

In addition, for patients, the cost and cost-effectiveness of the test also need to be considered by the patient's family and the medical field.

CONCLUSION

In recent years, medical imaging equipment and technology have been developed and promoted, and various new equipment and technology that can be used in the pediatric cardiac examination and imaging diagnosis of CHD have entered a new era. While each method has its inherent advantages and disadvantages, radiologists, physicists, manufacturers and national supervisory institutions must work together to fully recognize the strong sensitivity of infants and children to radiation in order to ensure access to the lowest dose of diagnostic imaging and the rational use of low dose, achieve individualized exposure doses, and effectively coordinate multiple imaging methods to improve the diagnosis and treatment of heart disease in children and infants. For patients, avoid unnecessary inspection as much as possible and cooperate with doctors during the scan to reduce unnecessarily repeated scans.

In this review, we introduced several current cardiovascular imaging methods for CHD. Nowadays, the integration of various imaging technologies has been widely recognized and developed for the accuracy and clinical practicability of the diagnosis of CHD in children. Therefore, radiologists and sonographers perform MPR through workstations to obtain more and clearer images, broaden diagnostic thinking and reflect the complementary advantages of imaging technology. Therefore, it is conceivable that the combination of multiple imaging technologies will enter a new, exciting, and high potential stage in diagnosing and treating CHD.

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REFERENCES

Acar, P., Dulac, Y., Taktak, A., & Villacèque, M. (2004). Echocardiographie 3D temps réel des cardiopathies congénitales [Real time 3D echocardiography in congenital heart disease]. *Archives des maladies du coeur et des vaisseaux*, *97*(5), 472-478.

Arlachov, Y., & Ganatra, R. H. (2012). Sedation/anaesthesia in paediatric radiology. *The British Journal of Radiology*, *85*(1019), e1018-e1031. https://doi.org/10.1259/bjr/28871143

Barkovich, M. J., Xu, D., Desikan, R. S., Williams, C., & Barkovich, A. J. (2018). Pediatric neuro MRI: Tricks to minimize sedation. *Pediatric Radiology*, *48*(1), 50-55. https://doi.org/10.1007/s00247-017-3785-1

Booij, R., Dijkshoorn, M. L., van Straten, M., du Plessis, F. A., Budde, R. P. J., Moelker, A., Krestin, G. P., & Ouhlous, M. (2016). Cardiovascular imaging in pediatric patients using dual source CT. *Journal of Cardiovascular Computed Tomography*, *10*(1), 13-21. https://doi.org/10/1016/j.jcct.2015.10.003

Brenner, D. J., & Hall, E. J. (2007). Computed tomography - An increasing source of radiation exposure. *The New England Journal of Medicine*, *357*(22), 2277-2284. https://doi.org/10.1056/NEJMra072149

Char, D., Ramamoorthy, C., & Wise-Faberowski, L. (2016). Cognitive dysfunction in children with heart disease: The role of anesthesia and sedation. *Congenital Heart Disease*, *11*(3), 221-229. https://doi.org/10.1111/chd.12352

Chen, D., Zhong, H. B., Lin, D. X., Chen, W. R., & Xie, L. D. (2017). The predictive value of echocardiography combined with electrocardiogram in the diagnosis of pulmonary arterial hypertension associated with congenital heart disease. *Chinese Journal of Hypertension, 25(8), 767-772. https://doi.org/10.16439/j.cnki.1673-7245.2017.08.024*

Chen, X. F., Jiang, F., Li, L., Chen, Y., Chen, X., Jiang, Y. Y., Xiang, L., & Ma, X. J. (2017). Application of low-dose dual-source computed tomography angiography in children with complex congenital heart disease. *Experimental and Therapeutic Medicine*, *14*(2), 1177-1183. https://doi.org/10.3892/etm.2017.4591

Crean, A. (2007). Cardiovascular MR and CT in congenital heart. disease. *Heart (British Cardiac Society)*, *93*(12), 1637-1647. *https://doi.org/*10.1136/hrt.2006.104729

Davis, C. P., & Cunha, J. P. (2019). *CT scan vs. MRI differences between machines, costs, uses*. MedicineNet. https://www.medicinenet.com/ct_scan_vs_mri/article.htm

Davison, R., & Mead, P. (2010). Nephrogenic systemic fibrosis (NSF): The role of tamoxifen. *NDT Plus*, *3*(5), 505-512. https://doi.org/10.1093/ndtplus/sfq111

Earls, J. P., Berman, E. L., Urban, B. A., Curry, C. A., Lane, J. L., Jennings, R. S., McCulloch, C. C., Hsieh, J., & Londt, J. H. (2008). Prospectively gated transverse coronary CT angiography versus retrospectively gated helical technique: Improved image quality and reduced radiation dose. *Radiology*, *246*(3), 742-753. https://doi.org/10.1148/radiol.2463070989

Elmholdt, T. R., Pedersen, M., Jørgensen, B., Søndergaard, K., Jensen, J. D., Ramsing, M., & Olesen, A. B. (2011). Nephrogenic systemic fibrosis is found only among gadolinium-exposed patients with renal insufficiency: A case-control study from Denmark. *The British Journal of Dermatology*, *165*(4), 828-836. https://doi.org/10.1111/j.1365-2133.2011.10465.x

Enaba, M. M., Hasan, D. I., Alsowey, A. M., & Elsayed, H. (2017). Multidetector computed tomography (CT) in evaluation of congenital cyanotic heart diseases. *Polish Journal of Radiology*, *82*, 645-659. https://doi.org/10.12659/PJR.903222

Feng, C. Z., & Xing, F. Q. (2012). Diagnose of neonate with complex congenital heart disease on 64-detector CT. *Journal of Chengdu College, 7*(2), 7-14.

Fisher, J. K., & Sawyers, T. (2020). *CT scan vs. MRI*. Healthline. https://www.healthline.com/health/ct-scan-vs-mri

Fratz, S., Chung, T., Greil, G. F., Samyn, M. M., Taylor, A. M., Buechel, E. R. V., Yoo, S. J., & Powell, A. J. (2013). Guidelines and protocols for cardiovascular magnetic resonance in children and adults with congenital heart disease: SCMR expert consensus group on congenital heart disease. *Journal of Cardiovascular Magnetic Resonance*, *15*(1), Article 51. https://doi.org/10.1186/1532-429X-15-51

Gilboa, S. M., Devine, O. J., Kucik, J. E., Oster, M. E., Riehle-Colarusso, T., Nembhard, W. N., Xu, P., Correa, A., Jenkins, K., & Marelli, A. J. (2016). Congenital heart defects in the United States: Estimating the magnitude of the affected population in 2010. *Circulation*, *134*(2), 101-109. https://doi.org/10.1161/CIRCULATIONAHA.115.019307

Ginat, D. T., Fong, M. W., Tuttle, D. J., Hobbs, S. K., & Vyas, R. C. (2011). Cardiac imaging: Part 1, MR pulse sequences, imaging planes, and basic anatomy. *American Journal of Roentgenology*, *197*(4), 808-815. https://doi.org/10.2214/AJR.10.7231

Glockner, J. F., Johnston, D. L., & McGee, K. P. (2003). Evaluation of cardiac valvular disease with MR imaging: Qualitative and quantitative techniques. *Radiographics*, *23*(1), Article e9. https://doi.org/10.1148/rg.e9

Goo, H. W. (2010). State-of-the-art CT imaging techniques for congenital heart disease. *Korean Journal of Radiology*, *11*(1), 4-18. https://doi.org/10.3348/kjr.2010.11.1.4

Goo, H. W., Park, I. S., Ko, J. K., Kim, Y. H., Seo, D. M., Yun, T. J., & Park, J. J. (2005). Visibility of the origin and proximal course of coronary arteries on non-ECG-gated heart CT in patients with congenital heart disease. *Pediatric Radiology*, *35*(8), 792-798. https://doi.org/10.1007/s00247-005-1482-y

Gopal, A., Mao, S. S., Karlsberg, D., Young, E., Waggoner, J., Ahmadi, N., Pal, R. S., Leal, J., Karlsberg, R. P., & Budoff, M. J. (2009). Radiation reduction with prospective ECG-triggering acquisition using 64-multidetector computed tomographic angiography. *The International Journal of Cardiovascular Imaging*, *25*(4), 405-416. https://doi.org/10.1007/s10554-008-9396-z

Gutgesell, H. P., & Rembold, C. M. (1990). Growth of the human heart relative to body surface area. *The American Journal of Cardiology*, *65*(9), 662-668. https://doi.org/10.1016/0002-9149(90)91048-b

Hausleiter, J., Meyer, T. S., Martuscelli, E., Spagnolo, P., Yamamoto, H., Carrascosa, P., Anger, T., Lehmkuhl, L., Alkadhi, H., Martinoff, S., Hadamitzky, M., Hein, F., Bischoff, B., Kuse, M., Schömig, A., & Achenbach, S. (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*(5), 484-493. https://doi.org/10.1016/j.jcmg.2011.12.017

Hoffman, J., & Kaplan, S. (2002). The incidence of congenital heart disease. *Journal of the American College of Cardiology*, *39*(12), 1890-1900. https://doi.org/10.1016/s0735-1097(02)01886-7

Horehledova, B., Mihl, C., Boswijk, E., Crombag, G., Nijssen, E. C., Nelemans, P. J., Veenstra, L. F., Wildberger, J. E., & Das, M. (2020). Retrospectively ECG-gated helical vs. non-ECG-synchronized high-pitch CTA of the aortic root for TAVI planning. *PloS One*, *15*(5), Article e0232673. https://doi.org/10.1371/journal.pone.0232673

Hu, S. (2020). Report on cardiovascular health and diseases in China 2019: Updated summary. *Chinese Circulation Journal, 35*(9), 833-854.

Husmann, L., Valenta, I., Gaemperli, O., Adda, O., Treyer, V., Wyss, C. A., Veit-Haibach, P., Fuminari, T., Schulthess, G. K., & Kaufmann, P. A. (2008). Feasibility of low-dose coronary CT angiography: First experience with prospective ECG-gating. *European Heart Journal*, *29*(2), 191-197. https://doi.org/10.1093/eurheartj/ehm614

ICRP. (2007). 2007 Recommendations of the international commission on radiological protection. *Annals of the ICRP*, *37*(2-4), 1-94. https://doi.org/10.1016/j.icrp.2007.10.003

Jin, K. N., Park, E. A., Shin, C. I., Lee, W., Chung, J. W., & Park, J. H. (2010). Retrospective versus prospective ECG-gated dual-source CT in pediatric patients with congenital heart diseases: Comparison of image quality and radiation dose. *The International Journal of Cardiovascular Imaging*, *26*(1), 63-73. https://doi.org/10.1007/s10554-009-9579-2

Jing, L., Pulenthiran, A., Nevius, C. D., Mejia-Spiegeler, A., Suever, J. D., Wehner, G. J., Kirchner, H. L., Haggerty, C. M., & Fornwalt, B. K. (2017). Impaired right ventricular contractile function in childhood obesity and its association with right and left ventricular changes: A cine DENSE cardiac magnetic resonance study. *Journal of Cardiovascular Magnetic Resonance, 19*(1), Article 49. https://doi.org/10.1186/s12968-017-0363-5

Kleijn, S. A., & Kamp, O. (2009). Clinical application of three-dimensional echocardiography: Past, present and future. *Netherlands Heart Journal*, *17*(1), 18-24. https://doi.org/10.1007/BF03086210

Koestenberger, M., Friedberg, M. K., Ravekes, W., Nestaas, E., & Hansmann, G. (2012). Non-invasive imaging for congenital heart disease: Recent innovations in transthoracic echocardiography. *Journal of Clinical & Experimental Cardiology*, *S8*(002), 1-5. https://doi.org/10.4172/2155-9880.S8-002

Kutty, S., Xiao, Y., Olson, J., Xie, F., Danford, D. A., Erickson, C. C., & Porter, T. R. (2016). Safety and efficacy of cardiac ultrasound contrast in children and adolescents for resting and stress echocardiography. *Journal of the American Society of Echocardiography*, *29*(7), 655-662. https://doi.org/10.1016/j.echo.2016.02.019

Lai, W. W., Geva, T., Shirali, G. S., Frommelt, P. C., Humes, R. A., Brook, M. M., Pignatelli, R. H., & Rychik, J. (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. *Journal of the American Society of Echocardiography, 19*(12), 1413-1430. https://doi.org/10.1016/j.echo.2006.09.001

Lang, R. M., Badano, L. P., Tsang, W., Adams, D. H., Agricola, E., Buck, T., Faletra, F. F., Franke, A., Hung, J., de Isla, L. P., Kamp, O., Kasprzak, J. D., Lancellotti, P., Marwick, T. H., McCulloch, M. L., Monaghan, M. J., Nihoyannopoulos, P., Pandian, N. G., Pellikka, P. A., & Pepi, M. (2012). EAE/ASE recommendations for image acquisition and display using three-dimensional echocardiography. *Journal of the American Society of Echocardiography, 25*(1), 3-46. https://doi.org/10.1016/j.echo.2011.11.010

Larson, D. B., Johnson, L. W., Schnell, B. M., Goske, M. J., Salisbury, S. R., & Forman, H. P. (2011). Rising use of CT in child visits to the emergency department in the United States, 1995-2008. *Radiology*, *259*(3), 793-801. https://doi.org/10.1148/radiol.11101939

Li, F., Yang, G., & Zhu, Z.M. (2009). Investigation on technical principle and clinical application of dual-source CT. *Chinese Medical Equipment Journal, 30*(2), 112-113. https://doi.org/10.3969/j.issn.1003-8868.2009.02.050

Li, M., Gan, T., Shun, K., Song, X. R., & Wu, R. N. (2016). Diagnostic value for complex congenital heart disease: The comparative study of low doses of large pitch dual-source CT imaging and echocardiography. *Progress in Modern Biomedicine, 16*(2), 229-308.

Lian, J., Wang, X. Q., & Wang, P. F. (2018). Application value of transthoracic echocardiography and DSCT in preoperation of children with congenital heart disease. *Chinese Jounrnal of CT and MRI, 16*(1), 72-74. https://doi.org/10.3969/j.issn.1672-5131.2018.01.023

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*(6), 403-408. https://doi.org/10.1016/j.jcct.2009.07.003

Liu, N., & Wang, Q. Z. (2017). The diagnosis value of MSCT for complex congenital heart disease in children. *Chinese Journal of CT and MRI, 15*(9), 47-50. https://doi.org/10.3969/j.issn.1672-5131.2017.09.015

Lu, M. J., &, Zhao, S. H. (2010). Magnetic resonance imaging in complex congenital heart disease. *Advances in Cardiovascular Disease, 5*(3), 652-655.

Lv, J. H., Lu, M. J., Zhao, S. H., Jiang, S. L., Zhang, G. J., Zhang, Y., & Jin, L. X. (2010). “One-stop shop” examination of complicated and complex congenital heart diseases with MRI. *Chinese Journal of Medical Imaging Technology,* ***26***(10), 1864-1868.

Marin, J. R., Zuckerbraun, N. S., & Kahn, J. M. (2012). Use of emergency ultrasound in United States pediatric emergency medicine fellowship programs in 2011. *Journal of Ultrasound in Medicine, 31*(9), 1357-1363. https://doi.org/10.7863/jum.2012.31.9.1357

Mazrani, W., McHugh, K., & Marsden, P. J. (2007). The radiation burden of radiological investigations. *Archives of Disease in Childhood*, *92*(12), 1127-1131. https://doi.org/10.1136/adc.2006.101782

Miao, Y., Bing, J. W., & Bu, G. L. (2016). Application of prospectively electrocardiograph-gated 128-slcie sprial CT angiography in children with complex congenital heart disease. *Chinese Journal of CT and MRI, 14*(10), 51-53.

MOH. (2007). *Health indicators: Indicators for monitoring and evaluation of strategy health for all*. Ministry of Health. https://www.moh.gov.my/moh/images/gallery/publications/md/hi/hi_2007.pdf

MOH. (2008a). *Health facts 2007*. Ministry of Health. http://vlib.moh.gov.my/cms/documentstorage/com.tms.cms.document.Document_2e89ce05-a0188549-d5315d00-5bfa49a4/2007.pdf

MOH. (2008b). *Annual report 2007 (*pp.75-76). Ministry of Health. https://www.moh.gov.my/moh/images/gallery/publications/md/ar/2007-2.pdf

Nakagawa, M., Ozawa, Y., Nomura, N., Inukai, S., Tsubokura, S., Sakurai, K., Shimohira, M., Ogawa, M., & Shibamoto, Y. (2016). Utility of dual source CT with ECG-triggered high-pitch spiral acquisition (Flash Spiral Cardio mode) to evaluate morphological features of ventricles in children with complex congenital heart defects. *Japanese Journal of Radiology*, *34*(4), 284-291. https://doi.org/10.1007/s11604-016-0522-x

Nie, P., Yang, G., Wang, X., Duan, Y., Xu, W., Li, H., Cao, T., Liu, X., Ji, X., Cheng, Z., & Wang, A. (2014). Application of prospective ECG-gated high-pitch 128-slice dual-source CT angiography in the diagnosis of congenital extracardiac vascular anomalies in infants and children. *PloS One*, *9*(12), Article e115793. https://doi.org/10.1371/journal.pone.0115793

Pache, G., Grohmann, J., Bulla, S., Arnold, R., Stiller, B., Schlensak, C., Langer, M., & Blanke, P. (2011). Prospective electrocardiography-triggered CT angiography of the great thoracic vessels in infants and toddlers with congenital heart disease: Feasibility and image quality. *European Journal of Radiology*, *80*(3), e440-e445. https://doi.org/10.1016/j.ejrad.2011.01.032

Pavithran, S., Natarajan, K., Vishwambaran, B., Arke, A. D., & Sivakumar, K. (2014). Preliminary evaluation of a microtransesophageal probe in neonates and young infants undergoing surgery for congenital heart disease. *Annals of Pediatric Cardiology*, *7*(3), 173-179. https://doi.org/10.4103/0974-2069.140829

Pearce, M. S., Salotti, J. A., Little, M. P., McHugh, K., Lee, C., Kim, K. P., Howe, N. L., Ronckers, C. M., Rajaraman, P., Craft, A. W., Parker, L., & de González DPhil, A. B. (2012). Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: A retrospective cohort study. *The Lancet, 380*(9840), 499-505. https://doi.org/10.1016/S0140-6736(12)60815-0

Porter, T. R., Mulvagh, S. L., Abdelmoneim, S. S., Becher, H., Belcik, J. T., Bierig, M., Choy, J., Gaibazzi, N., Gillam, L. D., Janardhanan, R., Kutty, S., Leong-Poi, H., Linder, J. R., Main, M. L., Mathias Jr, W., Park, M. M., Senior, R., & Villanueva, F. (2018). Clinical applications of ultrasonic enhancing agents in echocardiography: 2018 American Society of echocardiography guidelines update. *Journal of the American Society of Echocardiography, 31*(3), 241-274. https://doi.org/10.1016/j.echo.2017.11.013

Rehman, R., Yelamanchili, V. S., & Makaryus, A. N. (2021). *Cardiac imaging*. StatPearls Publishing LLC.

Roberts, W. T., Bax, J. J., & Davies, L. C. (2008). Cardiac CT and CT coronary angiography: Technology and application. *Heart (British Cardiac Society)*, *94*(6), 781-792. https://doi.org/10.1136/hrt.2007.116392

Ropers, D., Rixe, J., Anders, K., Küttner, A., Baum, U., Bautz, W., Daniel, W. G., & Achenbach, S. (2006). Usefulness of multidetector row spiral computed tomography with 64- x 0.6-mm collimation and 330-ms rotation for the noninvasive detection of significant coronary artery stenoses. *The American Journal of Cardiology*, *97*(3), 343-348. https://doi.org/10.1016/j.amjcard.2005.08.050

Seibert, J. A. (2004). Tradeoffs between image quality and dose. *Pediatric Radiology*, *34*(3), S183-S195. https://doi.org/10.1007/s00247-004-1268-7

Shrimpton, P. C., Miller, H. C., Lewis, M. A., & Dunn, M. (2005). *Doses from computed tomography (CT) examinations in the UK-2003 review*. National Radiological Protection Board.

Siegel, M. J. (2003). Multiplanar and three-dimensional multi-detector row CT of thoracic vessels and airways in the pediatric population. *Radiology*, *229*(3), 641-650. https://doi.org/10.1148/radiol.2293020999

Slovis, T. L. (2003). Children, computed tomography radiation dose, and the as low as reasonably achievable (ALARA) concept. *Pediatrics*, *112*(4), 971-972. https://doi.org/10.1542/peds.112.4.971

Sluysmans, T., & Colan, S. D. (2005). Theoretical and empirical derivation of cardiovascular allometric relationships in children. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, *99*(2), 445-457. https://doi.org/10.1152/japplphysiol.01144.2004

Somerville, J., & Grech, V. (2009). The chest X-ray in congenital heart disease 1. Total anomalous pulmonary venous drainage and coarctation of the aorta. *Images in Paediatric Cardiology*, *11*(1), 7-9.

Sreedhar, C. M., Ram, M. S., Alam, A., & Indrajit, I. K. (2005). Cardiac MRI in congenital heart disease - Our experience. *Medical Journal, Armed Forces India*, *61*(1), 57-62. https://doi.org/10.1016/S0377-1237(05)80122-4

Sreedher, G., Bruckman, D., & Ganapathy, S. S. (2021). 320 slice CT in imaging of congenital heart diseases in infants: A single-center experience. *Cureus*, *13*(2), Article e13348. https://doi.org/10.7759/cureus.13348

Sriharan, M., Lazoura, O., Pavitt, C. W., Castellano, I., Owens, C. M., Rubens, M. B., Padley, S. P., & Nicol, E. D. (2016). Evaluation of high-pitch ungated pediatric cardiovascular computed tomography for the assessment of cardiac structures in neonates. *Journal of Thoracic Imaging*, *31*(3), 177-182. https://doi.org/10.1097/RTI.0000000000000201

Stolzmann, P., Goetti, R., Baumueller, S., Plass, A., Falk, V., Scheffel, H., Feuchtner, G., Marincek, B., Alkadhi, H., & Leschka, S. (2011). Prospective and retrospective ECG-gating for CT coronary angiography perform similarly accurate at low heart rates. *European Journal of Radiology*, *79*(1), 85-91. https://doi.org/10.1016/j.ejrad.2009.12.016

Stolzmann, P., Leschka, S., Scheffel, H., Krauss, T., Desbiolles, L., Plass, A., Genoni, M., Flohr, T. G., Wildermuth, S., Marincek, B., & Alkadhi, H. (2008). Dual-source CT in step-and-shoot mode: Noninvasive coronary angiography with low radiation dose. *Radiology*, *249*(1), 71-80. https://doi.org/10.1148/radiol.2483072032

Tsai, I. C., & Goo, H. W. (2013). Cardiac CT and MRI for congenital heart disease in Asian countries: Recent trends in publication based on a scientific database. *The International Journal of Cardiovascular Imaging*, *29*(1), 1-5. https://doi.org/10.1007/s10554-013-0184-z

Ünal, E., Yıldız, A. E., Güler, E., Karcaaltıncaba, M., Akata, D., Kılınçer, A., Atlı, E., Topçuoğlu, M., & Hazırolan, T. (2015). Comparison of image quality and radiation dose between prospectively ECG-triggered and retrospectively ECG-gated CT angiography: Establishing heart rate cut-off values in firstgeneration dual-source CT. *Anatolian Journal of Cardiology*, *15*(9), 759-764. https://doi.org/10.5152/akd.2014.5720

UNSCEAR. (2006). *Effects on ionizing radiation: United Nations scientific committee on the effects of atomic radiation* (Vol. 1). United Nations Scientific Committee on the Effects of Atomic Radiation. https://www.unscear.org/docs/publications/2006/UNSCEAR_2006_Report_Vol.I.pdf

UNSCEAR. (2013). *Effects of radiation exposure of children. Report to the general assembly with scientific annexes* (Vol. 1). United Nations Scientific Committee on the Effects of Atomic Radiation. https://www.unscear.org/unscear/uploads/documents/publications/UNSCEAR_2013_Annex-A-CORR.pdf

Wang, R., Xu, X. J., Huang, G., Zhou, X., Zhang, W. W., Ma, Y. Q., & Zuo, X. N. (2017). Comparison of image quality, diagnostic accuracy and radiation dose between flash model and retrospective ECG-triggered protocols in dual source computed tomography (DSCT) in congenital heart diseases. *Polish Journal of Radiology*, *82*, 114-119. https://doi.org/10.12659/PJR.899876

Xu, L., Yang, L., Zhang, Z., Li, Y., Fan, Z., Ma, X., Lv, B., & Yu, W. (2010). Low-dose adaptive sequential scan for dual-source CT coronary angiography in patients with high heart rate: Comparison with retrospective ECG gating. *European Journal of Radiology*, *76*(2), 183-187. https://doi.org/10.1016/j.ejrad.2009.06.003

Yao, Q., Hu, X. H., Shen, Q. L., Qiao, Z. W., Pa, M. E., Qian, B., Yan, W, L., & Huang, G. Y. (2016). Differential effect of the ratio of right ventricular volume to left ventricular volume in children with repaired tetralogy of Fallot. *Cardiology*, *133*(3), 135-140. https://doi.org/10.1159/000441291

Zeng, Q. B., Guo, Q. N, Luo, Q., Wu, G. Y., & Zhou, X. (2014). Manganese-based contrast agents for MRI. *Chinese Journal of Magnetic Resonance Imaging, 5*(4), 315-320.

Zhang, Y., Zou, C. J., & Xu, Y. Q. (2012). The clinical value of MSCT in anomalous pulmonary venous connection of neonate. *Journal of Medical Imaging, 22(11),1876-1878.*

Zimmerman, M. S., Smith, A. G. C., Sable, C. A., Echko, M. M., Wilner, L. B., Olsen, H. E., Atalay, H. T., Awasthi, A., Bhutta, Z. A., Boucher, J. L., Castro, F., Cortesi, P. A., Dubey, M., Fischer, F., Hamidi, S., Hay, S. I., Hoang, C. L., Hugo-Hamman, C., Jenkins, K. J., … & Kassebaum, N. J. (2020). Global, regional, and national burden of congenital heart disease, 1990–2017: A systematic analysis for the Global Burden of Disease Study 2017. *The Lancet Child & Adolescent Health, 4*(3), 185-200. https://doi.org/10.1016/s2352-4642(19)30402-X