Diagnostic Value of Prospective Electrocardiogram-triggered Dual-source Computed Tomography Angiography for Infants and Children with Interrupted Aortic Arch

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Abstract

Background: Accurate assessment of intra- as well as extra-cardiac malformations and radiation dosage concerns are especially crucial to infants and children with interrupted aortic arch (IAA). The purpose of this study is to investigate the value of prospective electrocardiogram (ECG)-triggered dual-source computed tomography (DSCT) angiography with low-dosage techniques in the diagnosis of IAA.

Methods: Thirteen patients with suspected IAA underwent prospective ECG-triggered DSCT scan and transthoracic echocardiography (TTE). Surgery was performed on all the patients. A five-point scale was used to assess image quality. The diagnostic accuracy of DSCT angiography and TTE was compared with the surgical findings as the reference standard. A nonparametric Chi-square test was used for comparative analysis. $P < 0.05$ was considered as a significant difference. The mean effective radiation dose (ED) was calculated.

Results: Diagnostic DSCT images were obtained for all the patients. Thirteen IAA cases with 60 separate cardiovascular anomalies were confirmed by surgical findings. The diagnostic accuracy of TTE and DSCT for total cardiovascular malformations was 93.7% and 97.9% ($P > 0.05$), and that for extra-cardiac vascular malformations was 92.3% and 99.0% ($P < 0.05$), respectively. The mean score of image quality was 3.77 ± 0.83. The mean ED was 0.30 ± 0.04 mSv (range from 0.23 mSv to 0.39 mSv).

Conclusions: In infants and children with IAA, prospective ECG-triggered DSCT with low radiation exposure and high diagnostic efficiency has higher accuracy compared to TTE in detection of extra-cardiac vascular anomalies.

Key words: Dual-source Computed Tomography; Image Quality; Interrupted Aortic Arch; Prospective ECG-triggered; Radiation Dose

INTRODUCTION

Radiation exposure is the primary concern for computed tomography (CT) examinations in infants and children. Children exposed to significant cumulative dosage could result in radiation-induced chromosomal DNA damage.[1] For cardiac CT angiography (CTA), the tube current output was turned on during the predefined phase of cardiac circle in prospective electrocardiogram (ECG)-triggered mode. Exposure time and radiation dosage were significantly reduced in comparison to conventional retrospective ECG-gating mode. This is important to interrupted aortic arch (IAA) patients characterized by early onset during infancy. There were only a few reports of the diagnosis of IAA by CT.[2-6] To the best of our

knowledge, this was the first study conducted for the purpose of evaluating the diagnostic value of prospective ECG-triggered dual-source CT (DSCT) angiography in comparison with transthoracic echocardiography (TTE), using surgical results as the reference standard.

METHODS

Ethics statement

The local ethics board gave prior approval to the study. Adverse effects of contrast medium injection and radiation exposure were explained to the guardians of all patients, and written informed consent was obtained from each of them.

Patients

From 2012 to 2014, 15 patients with suspected IAA were enrolled in this prospective study. The principal clinical symptoms of these patients included shortness

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of breath ($n = 14$), recurrent respiratory infection ($n = 8$), intolerance to feed ($n = 8$) and cyanosis ($n = 5$). Physical examination discovered 10 patients to have higher blood pressure of the arms than that of the legs and 2 patients with a higher blood pressure of the right arm than that of the left arm and the legs. Exclusion criteria were hypersensitive to contrast media ($n = 2$) or nephropathy ($n = 0$). Prospective ECG-triggered DSCT were performed on 13 patients after routine TTE examinations, and the interval between these two examinations was <7 days. Surgery was performed on all patients.

Dual-source CT protocol

Examinations were performed using a DSCT scanner (Somatom Definition, Siemens Healthcare, Forchheim, Germany). Sedation was achieved by oral administration of chloral hydrate under the supervision of a pediatrician. All patients were free-breathing during the exam.

The high-concentration contrast material (CM, Iohexol Injection, 350 mgI/ml, Beijing Beilu Pharmaceuticals, Beijing, China) was injected via peripheral veins in the elbow or back of the hand, using a dual-head power injector (Stellant; Medrad, Indianola, PA, USA). The volume of CM was 2 ml/kg of body weight, followed by a normal saline (NS) chaser injection of 1 ml/kg of body weight. The saline chaser was injected to reduce artifacts caused by undiluted intra-vascular CM. Total injection time of CM and NS was 20 s. For example, 20 ml CM and 10 ml NS would be injected to a patient with the weight of 10 kg, with an injection rate of 1.5 ml/s.

Dual-source CT parameters were set as follows: Collimation of 64×0.6 mm; slice acquisition, 128×0.6 mm by means of a z-flying focal spot; and gantry rotation time, 0.33 s. The tube voltage and tube current were adjusted based on body-weight: <3 kg, 80 kV, 60 mAs; 3.1–6 kg, 80 kV, 80 mAs; 6.1–10 kg, 80 kV, 100 mAs; 10.1–15 kg, 80 kV, 120 mAs; >15 kg, 100 kV, 120 mAs [Table 1]. Prospective ECG-triggered DSCT scan mode was applied with full dose exposure between 38% and 42% of R-R interval.[7] The scan range was from the level of the thoracic inlet to 3–4 cm below cardiac apex. Bolus tracking technique was used to synchronize the contrast medium injection and the CT scan. A four-chamber view was chosen to monitoring its even enhancement, and the scan was triggered manually.

Dual-source CT data postprocessing

The acquired data were reconstructed with a slice thickness of 0.75 mm and an interval of 0.5 mm with a medium smooth-tissue convolution kernel (B26f). Reconstructed images were transferred to a multi-modality workplace (Siemens Healthcare, Forchheim, Germany). Multiple planar reformation (MPR), maximum intensity projection (MIP) and volume rendering (VR) were used for image interpretation. Anatomic classification based on the location of the interruption of aortic arch[3] was used for IAA diagnosis: Type A, at the distal to the subclavian artery; Type B, between the second carotid artery and the ipsilateral subclavian artery; Type C, between two carotid arteries.

Image quality assessment

Subjective image quality was evaluated using a five-grade scoring system:[8]

Grade 1: No useful information obtained.

Grade 2: Poor image quality or lack of anatomical detail; incomplete demonstration of anatomical structures

Grade 3: Fair anatomical clarity; the clinically required anatomical structures could be defined with confidence

Grade 4: Good anatomical clarity; all structures were clearly interpretable

Grade 5: Excellent anatomical clarity; excellent image quality obtained

Image scores equal to or above graded 3 were considered sufficient for diagnostic purpose.[9] All evaluations were conducted by two radiologists, each having more than 2 years of cardiovascular diagnostic experiences, and both were blinded to the results of TTE and surgical findings. Consensus agreement was achieved with regard to any disagreement between the two observers. Both diagnostic efficiency and image quality score were calculated.

Radiation dosage

The parameter of radiation dose length product (DLP) was taken from the scan protocol generated by CT system. The effective radiation dose (ED) delivered from CT examination was calculated according to the age-dependent conversion factor (ED = $k \times$ DLP, $k = 0.039$ for patients of 0–4 months, $k = 0.026$ for 4 months to 1 year, $k = 0.018$ for 1–6 years).[10]

Statistical analysis

SPSS Statistics version 17.0 (SPSS, Chicago, IL, USA) was used for statistical analysis. With surgical findings as the gold standard, the sensitivity (Se), specificity (Sp), positive predictive value (PPV) and negative predictive value (NPV) of DSCT and TTE for IAA along with its accompanied malformations were evaluated separately. Inter-observer agreement for image quality scores was assessed by kappa statistics ($\kappa > 0.81$, excellent agreement; $\kappa = 0.61$–0.80, good agreement). Nonparametric Chi-square test was used for comparative analysis of diagnostic efficiency between DSCT angiography and TTE, and $P < 0.05$ was considered to be a significant difference.

Table 1: Body weight-based scanning parameters and radiation dose

Weight (kg)	Tube voltage (kV)	Tube current (mAs)	Cases (n)	DLP (mGy·cm)	ED (mSv)
<3.0	80	60	2	7	0.27
3.1−6.0	80	80	9	10.4	0.31
6.1−10.0	80	100	1	15	0.39
10.1−15.0	80	120	1	13	0.23
>15.0	100	120	0	-	-

DLP: Dose length product; ED: Effective radiation dose.

RESULTS

Diagnostic DSCT angiographic images were obtained from all 13 patients (ages ranged from 23 days to 2 years). Thirteen patients were diagnosed IAA by surgical findings, and a total of 10 intra-cardiac anomalies and 50 extra-cardiac anomalies were confirmed by surgical findings.

Image quality assessment

The mean image quality score was 3.77 ± 0.83, and distributed as score 2 (1/13, 7.69%), score 3 (3/13, 23.08%), score 4 (7/13, 53.85%) and score 5 (2/13, 15.38%). Agreement on grades of overall image quality between the two observers was good (κ = 0.75).

Diagnostic performance

According to surgical findings, 5 patients were diagnosed with Type A IAA and 8 patients with Type B IAA. A total of 60 separate cardiovascular anomalies were proven by surgical results. For intra-cardiac malformations, atrial septal defect (ASD) [Figure 1] was identified in 2 patients, and ventricular septal defect (VSD) was identified in 8 patients. For extra-cardiac malformations, 12 patients were discovered to have pulmonary artery hypertension, 11 patients to have persistent ductus arteriosus [Figure 2], 6 patients to have bronchial artery dilation, 3 patients to have an aberrant right subclavian artery, 1 patient to have an isolated left subclavian artery [Figure 3], 1 patient to have aorta-pulmonary artery collateral circulation and 3 patients were identified having ascending aorta (AA)-descending aorta (DA) collateral circulation. One ASD and one pulmonary artery hypertension were missed, and one pulmonary artery hypertension was misdiagnosed on DSCT images. The TTE misdiagnosed one bronchial artery dilation, and missed one IAA, one ASD, one bronchial artery dilation, two aberrant right subclavian artery, one isolated left subclavian artery, one aorta-pulmoary artery collateral circulation and one AA-DA collateral circulation.

Interrupted aortic arch was taken as an extra-cardiac malformation, the Se, Sp, PPV and NPV for prospective ECG-triggered DSCT scan were 96.7%, 98.8%, 98.3% and 97.6%, respectively. And those for TTE were 86.7%, 98.8%, 98.1% and 91.9%, respectively [Table 2]. The diagnostic accuracies of TTE and DSCT were 93.7% and 97.9%, respectively. There was no significant difference in diagnostic accuracy between DSCT and TTE in IAA with regard to overall malformations ($P > 0.05$) and intra-cardiac malformations ($P > 0.05$). However, there was a difference between DSCT and TTE in the diagnostic accuracy of extra-cardiac malformation ($P < 0.05$).

Radiation dosage

There were 2 patients with the body weight of <3 kg, 9 patients with a body weight of 3.1–6 kg, 1 patient with the body weight of 6.1–10 kg and 1 patient with the body weight of 10.1–15 kg [Table 1]. The mean ED of 13 patients was 0.30 ± 0.04 mSv (ranging from 0.23 mSv to 0.39 mSv).

DISCUSSION

Interrupted aortic arch is defined as a complete luminal and anatomic discontinuity between the the ascending and descending aorta, which accounts for 1% of congenital heart disease (CHD).[11] The anatomic classification of IAA used in this study was based on the locations of the interruption, each of which has a different embryological origin: The aortic sac, the fourth arch and the junction of the fourth and sixth arches.[3] In our study, Type B is the most common (8/13, 61.5%), followed by Type A (5/13, 38.5%), which was in line with Celoria and Patton.[12]

Earlier studies showed that IAA was associated with a high mortality rate of > 90% at year of one and the survival time was approximately 4–10 days without treatment.[13,14] Low birth weight, immediate presentation, Type B IAA, and
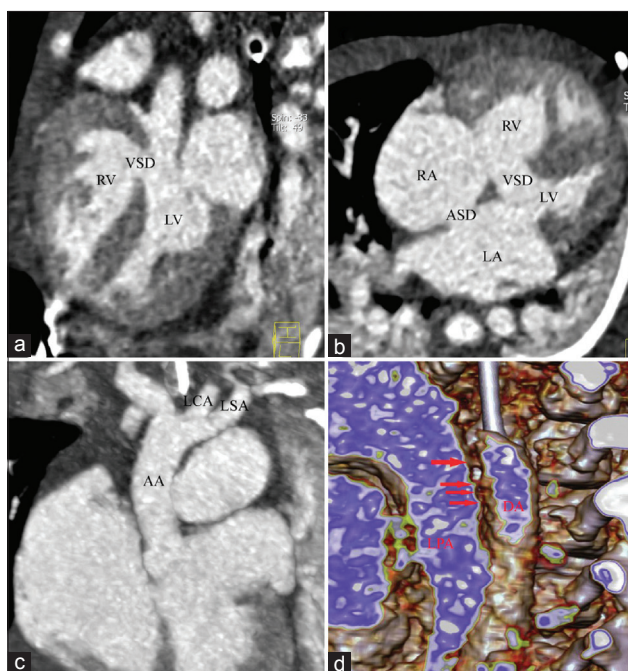

Figure 1: A 27-day-old girl, effective radiation dose: 0.27 mSv. (a) Thick section oblique sagittal multiple planar reformation (MPR) image; and (b) thick section oblique transverse MPR image showed ventricular septal defect and atrial septal defect; (c) Oblique sagittal maximum intensity projection image showed no interruption at the proximal to the subclavian artery; (d) Volume rendering image showed multiple Aorta-Pulmonary artery collateral circulations (red arrows).

Table 2: Diagnostic performances of DSCT and TTE

Cardiovascular imaging modality	TTE (%)			DSCT (%)		
	Intra-cardiac	Extra-cardiac	Total	Intra-cardiac	Extra-cardiac	Total
Sensitivity	90.0	86.0	86.7	90.0	98.0	96.7
Specificity	100.0	98.1	98.8	96.6	100.0	98.8
PPV	100.0	97.7	98.1	90.0	100.0	98.3
NPV	96.7	88.3	91.1	96.6	98.2	97.6
Diagnostic accuracy	97.4	92.3	93.7	94.9	99.0	97.9

In this table, IAA was taken as an extra-cardiac malformation. PPV: Positive predictive value; NPV: Negative predictive value; IAA: Interrupted aortic arch; DSCT: Dual-source computed tomography; TTE: Transthoracic echocardiography.
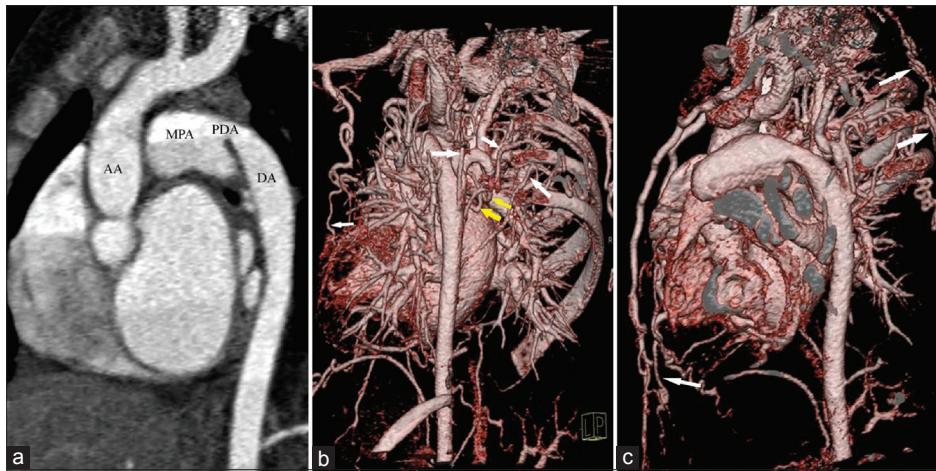
Figure 2: A 11-month-old boy, effective radiation dose: 0.34 mSv. (a) Thick section oblique sagittal multiple planar reformation image showed descending aorta (DA) arose from main pulmonary artery; (b and c) Volume rendering images showed bronchial artery dilation (yellow arrows) and ascending aorta-DA collateral circulation (white arrows).
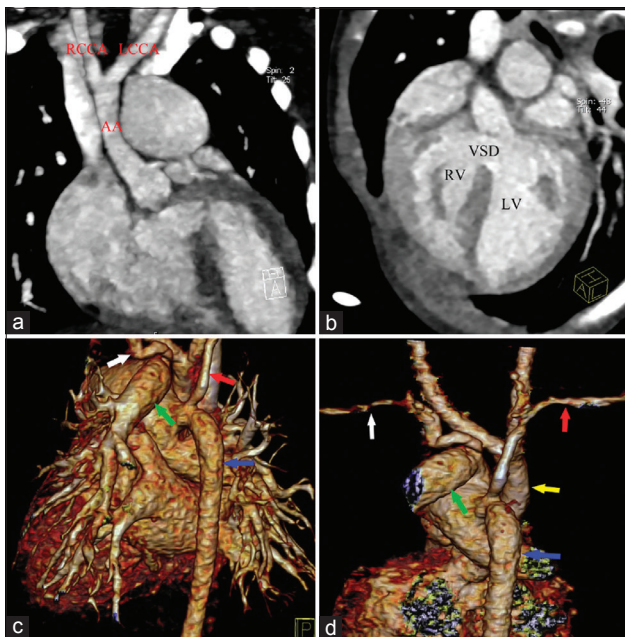

Figure 3: A 23-day-old boy, effective radiation dose: 0.31 mSv. (a) Thick section coronary maximum intensity projection image showed right common carotid artery and left common carotid artery arose from ascending aorta; (b) Thick section oblique sagittal multiple planar reformation image showed ventricular septal defect; (c and d) Volume rendering images (posterior view) showed isolated left subclavian artery (white arrows), which arose from left pulmonary artery (green arrows) and aberrant right subclavian artery (red arrows), which arose from descending aorta (blue arrows).

anomalies primarily associated with cardiac structures, such as initial left ventricular outflow tract, were regarded as high-risk factors for death. In a recent study, 59% patients were reported to survive for 16 years after proper treatment in addition with the improvement of perioperative care, this survival rate was increased up to 70%.[15] The cardiovascular anomalies along with IAA may be more crucial for patient outcome than IAA itself.[16] Thus, an appropriate modality to identify both IAA and other cardiovascular anomalies appeared to be crucial indicators for effective clinical treatment.

Prospective ECG-triggered dual-source CT

Two X-ray tubes of DSCT could provide a high temporal resolution of 83 ms. Shorter scanning time could minimize the breath artifact. Thus, DSCT was helpful for neonates who cannot hold their breath. Besides, prospective ECG-triggered DSCT could permit advance prediction of R-wave. With a sequential prospective mode for data acquisition, full-exposure tube output could be initiated at selected phases, such as 38–42% in this study. Therefore, radiation dosage could be remarkably reduced. Meanwhile, the high performance of DSCT angiograph offered good image quality on heart and complex anatomy of cardiovascular malformation, which could be helpful in the development of more effective surgical plans.

Multiple planar reformation could provide the detail of malformations, and track vascular source and measurement parameters, which are important for clinical therapy (e.g., the distance of VSD, the diameter of AA and main pulmonary artery). MIP could give a holistic view of regions of interests such as the connection of different vessels and blood support of descending artery in one image. VR could visually display a full view of the entire heart and vessels, including for example, the location of the interruption of the aortic arch, and the growth of the aortic artery, pulmonary artery and collateral branches. However, the intra-cardiac structures could not be well displayed on VR images.

Advantages of prospective ECG-triggered dual-source CT

The retrospective ECG-gating with a relatively high radiation dosage might increase the risk of cancer. Brenner and Hall[17] stated that there was direct evidence from epidemiologic studies that organ doses corresponding to common CT study resulted in an increased risk of cancer. Therefore, the development of low-dose techniques was indicated.

Prospective ECG-triggered DSCT with a predicted R-R interval for data acquisition could significantly reduce radiation dosage. It was reported that the prospective ECG-gating technique could reduce the radiation burden by more than 80% while maintaining the image quality in comparison with retrospective ECG-gating in cardiac CTA examinations.[18-20] Our result showed that prospective ECG-triggered DSCT examination could achieve 0.30 mSv of ED while maintaining diagnostic image quality. We chose 38–42% phases of cardiac cycle as full dose exposure as against 75% phase in Earls's research,[21] because of the higher heart rate of patient cohorts enrolled (most were infants).

Comparisons with other imaging modalities

In the past, cardiovascular specialists thought that TTE was the ultimate solution for CHD. It was inexpensive, noninvasive, accessible, and could provide both anatomical and functional information about the heart.[22,23] TTE also has an advantage in the diagnosis of intra-cardiac deformations. However, for IAA, the accompanied malformations of the aortic arch, pulmonary artery, subclavian artery and bronchial artery, etc. could not be detected well by TTE.[24] The limited spatial resolution of TTE could be resolved by prospective ECG-triggered DSCT. Meanwhile, the limitation of acoustic window for full-view observation of these structures will be overcome by DSCT angiography. This study demonstrated that DSCT held advantages in the diagnosis of extra-cardiac malformations along with IAA.

Magnetic resonance imaging (MRI) is an ionizing radiation-free imaging modality. Foran et al. reported that three-tesla cardiac MRI was feasible in preterm infants without sedation or breath holding.[25] A previous study demonstrated the obtainability of high-quality MR images for CHD,[26] whereas the relatively lower spatial resolution of MRI would be less likely to delineate small malformations such as those of collateral arteries. In contrast to MRI, the higher spatial resolution of DSCT could clearly display the coronary artery as well as collateral branches with diameters <1.0 mm. In addition, the inherent noisier environment, longer examination time, as well as nonavailability of MRI held back its application to infants and children.

Interventional cardiac catheterization (ICC) was regarded as the gold standard for cardiovascular diseases.[24] However, because of the invasive nature, it was far more widely used for treatment than for diagnosis.[27] In addition, the procedure-related mortality in neonatal diagnostic cardiac catheterization remained high, especially for premature and newborn infants.[27,28]

LIMITATIONS

First, in our study, only end-systolic phase datasets were acquired by prospective ECG-triggered DSCT scan mode. Therefore, the valvular function could not be evaluated. Second, only a small group of patients with IAA confirmed by surgery were included in this study. There might consequently be a certain sample-size bias in the results. A larger sample of patients should be investigated in further research. Third, TTE was used as a comparison, whereas MRI or ICC might be considered as appropriate comparisons in the future.

In infants and children with IAA, prospective ECG-triggered DSCT with low radiation exposure and high diagnostic efficiency has higher accuracy compared with TTE in detection of extra-cardiac vascular anomalies.

REFERENCES

1. Ait-Ali L, Andreassi MG, Foffa I, Spadoni I, Vano E, Picano E. Cumulative patient effective dose and acute radiation-induced chromosomal DNA damage in children with congenital heart disease. Heart 2010;96:269-74.
2. Barutçu Saygili O, Saygili A, Erek E, Sarioglu A, Sarioglu T. Interrupted aortic arch with intact ventricular septum: A multidetector CT angiography evaluation. Anadolu Kardiyol Derg 2011;11:E8-9.
3. Yang DH, Goo HW, Seo DM, Yun TJ, Park JJ, Park IS, et al. Multislice CT angiography of interrupted aortic arch. Pediatr Radiol 2008;38:89-100.
4. Morriss J, Moreland J, Burkhart H, Kao S. Pre-surgical evaluation of interrupted aortic arch with 3-dimensional reconstruction of CT images. Ann Thorac Surg 2007;84:299.
5. Lee HY, Lee W, Chung JW, Park JH, Yeon KM. Interrupted aortic arch with aberrant subclavian artery: A rare form of arch anomaly demonstrated with multidetector CT and 3D reconstruction. Pediatr Radiol 2006;36:272-3.
6. Cinar A, Haliloglu M, Karagoz T, Karcaaltincaba M, Celiker A, Tekinalp G. Interrupted aortic arch in a neonate: Multidetector CT diagnosis. Pediatr Radiol 2004;34:901-3.
7. Nie P, Wang X, Cheng Z, Duan Y, Ji X, Chen J, et al. The value of low-dose prospective ECG-gated dual-source CT angiography in the diagnosis of coarctation of the aorta in infants and children. Clin Radiol 2012;67:738-45.
8. Ben Saad M, Rohnean A, Sigal-Cinqualbre A, Adler G, Paul JF. Evaluation of image quality and radiation dose of thoracic and coronary dual-source CT in 110 infants with congenital heart disease. Pediatr Radiol 2009;39:668-76.
9. Huang MP, Liang CH, Zhao ZJ, Liu H, Li JL, Zhang JE, et al. Evaluation of image quality and radiation dose at prospective ECG-triggered axial 256-slice multi-detector CT in infants with congenital heart disease. Pediatr Radiol 2011;41:858-66.
10. Shrimmpton PC. Assessment of patient dose in CT. NRPB_PE/1/2004. National Radiological Protection Board, Chilton, United kingdom; 2004.
11. Loffredo CA, Ferencz C, Wilson PD, Lurie IW. Interrupted aortic arch: An epidemiologic study. Teratology 2000;61:368-75.
12. Celoria GC, Patton RB. Congenital absence of the aortic arch. Am Heart J 1959;58:407-13.
13. Gokcebay TM, Batillas J, Pinck RL. Complete interruption of the aorta at the arch. Am J Roentgenol Radium Ther Nucl Med 1972;114:362-70.
14. Van Praagh R, Bernhard WF, Rosenthal A, Parisi LF, Fyler DC. Interrupted aortic arch: Surgical treatment. Am J Cardiol 1971;27:200-11.
15. McCrindle BW, Tchervenkov CI, Konstantinov IE, Williams WG, Neirotti RA, Jacobs ML, et al. Risk factors associated with mortality and interventions in 472 neonates with interrupted aortic arch: A Congenital Heart Surgeons Society study. J Thorac Cardiovasc Surg 2005;129:343-50.
16. Li Z, Li B, Fan X, Su J, Zhang J, He Y, et al. Surgical treatment of interrupted aortic arch associated with ventricular septal defect and patent ductus arteriosus in patients over one year of age. Chin Med J 2014;127:1684-90.
17. Brenner DJ, Hall EJ. Computed tomography – An increasing source of radiation exposure. N Engl J Med 2007;357:2277-84.
18. Shuman WP, Branch KR, May JM, Mitsumori LM, Lockhart DW,

Dubinsky TJ, *et al.* Prospective versus retrospective ECG gating for 64-detector CT of the coronary arteries: Comparison of image quality and patient radiation dose. Radiology 2008;248:431-7.

19. Zhao L, Zhang Z, Fan Z, Yang L, Du J. Prospective versus retrospective ECG gating for dual source CT of the coronary stent: Comparison of image quality, accuracy, and radiation dose. Eur J Radiol 2011;77:436-42.

20. Freeman A, Learner R, Eggleton S, Lambros J, Friedman D. Marked reduction of effective radiation dose in patients undergoing CT coronary angiography using prospective ECG gating. Heart Lung Circ 2011;20:512-6.

21. Earls JP. How to use a prospective gated technique for cardiac CT. J Cardiovasc Comput Tomogr 2009;3:45-51.

22. Sharma S, Anand R, Kanter KR, Williams WH, Dooley KJ, Jones DW, *et al.* The usefulness of echocardiography in the surgical management of infants with congenital heart disease. Clin Cardiol 1992;15:891-7.

23. Teo LL, Hia CP. Advanced cardiovascular imaging in congenital heart disease. Int J Clin Pract Suppl 2011;171:17-29.

24. Tsai IC, Chen MC, Jan SL, Wang CC, Fu YC, Lin PC, *et al.* Neonatal cardiac multidetector row CT: Why and how we do it. Pediatr Radiol 2008;38:438-51.

25. Foran AM, Fitzpatrick JA, Allsop J, Schmitz S, Franklin J, Pamboucas C, *et al.* Three-tesla cardiac magnetic resonance imaging for preterm infants. Pediatrics 2007;120:78-83.

26. Kellenberger CJ, Yoo SJ, Büchel ER. Cardiovascular MR imaging in neonates and infants with congenital heart disease. Radiographics 2007;27:5-18.

27. Kobayashi D, Sallaam S, Aggarwal S, Singh HR, Turner DR, Forbes TJ, *et al.* Catheterization-based intervention in low birth weight infants less than 2.5 kg with acute and long-term outcome. Catheter Cardiovasc Interv 2013;82:802-10.

28. Simpson JM, Moore P, Teitel DF. Cardiac catheterization of low birth weight infants. Am J Cardiol 2001;87:1372-7.