Journal of the Formosan Medical Association (2015) 114, 1061–1068

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.jfma-online.com

ORIGINAL ARTICLE

Trends in the utilization of computed tomography and cardiac catheterization among children with congenital heart disease

Justin Cheng-Ta Yang [a,b,c,d,e], Ming-Tai Lin [c,f], Fu-Shan Jaw [a], Shyh-Jye Chen [b,*], Jou-Kou Wang [c,f], Tiffany Ting-Fang Shih [b], Mei-Hwan Wu [c,f], Yiu-Wah Li [b]

[a] Institute of Biomedical Engineering, College of Engineering and College of Medicine, National Taiwan University, Taipei, Taiwan
[b] Department of Medical Imaging, National Taiwan University Hospital, Taipei, Taiwan
[c] College of Medicine, National Taiwan University, Taipei, Taiwan
[d] Department of Medical Imaging, National Taiwan University Hospital, Hsin-Chu Branch, Hsinchu, Taiwan
[e] Department of Radiology, National Taiwan University Hospital, Chu-Tung Branch, Hsinchu, Taiwan
[f] Department of Pediatrics, National Taiwan University Hospital, Taipei, Taiwan

Received 13 May 2014; received in revised form 29 July 2014; accepted 4 August 2014

KEYWORDS
cardiac catheterization;
children;
congenital heart disease;
multidetector computed tomography;
utilization

Background/Purpose: Pediatric cardiac computed tomography (CT) is a noninvasive imaging modality used to clearly demonstrate the anatomical detail of congenital heart diseases. We investigated the impact of cardiac CT on the utilization of cardiac catheterization among children with congenital heart disease.
Methods: The study sample consisted of 2648 cardiac CT and 3814 cardiac catheterization from 1999 to 2009 for congenital heart diseases. Diagnoses were categorized into 11 disease groups. The numbers of examination, according to the different modalities, were compared using temporal trend analyses. The estimated effective radiation doses (mSv) of CT and catheterization were calculated and compared.
Results: The number of CT scans and interventional catheterizations had a slight annual increase of 1.2% and 2.7%, respectively, whereas that of diagnostic catheterization decreased by 6.2% per year. Disease groups fell into two categories according to utilization trend differences between CT and diagnostic catheterization. The increased use of CT reduces the need for diagnostic catheterization in patients with atrioventricular connection disorder, coronary

Conflicts of interest: The authors have no conflicts of interest relevant to this article.

* Corresponding author. Department of Medical Imaging, National Taiwan University Hospital, Number 7, Chung Shan South Road, Taipei 100, Taiwan.
E-mail addresses: james_5586@hotmail.com, 003924@ntuh.gov.tw (S.-J. Chen).

http://dx.doi.org/10.1016/j.jfma.2014.08.004

arterial disorder, great vessel disorder, septal disorder, tetralogy of Fallot, and ventriculoarterial connection disorder. Clinicians choose either catheterization or CT, or both examinations, depending on clinical conditions, in patients with semilunar valvular disorder, heterotaxy, myocardial disorder, pericardial disorder, and pulmonary vein disorder. The radiation dose of CT was lower than that of diagnostic cardiac catheterization in all age groups.
Conclusion: The use of noninvasive CT in children with selected heart conditions might reduce the use of diagnostic cardiac catheterization. This may release time and facilities within the catheterization laboratory to meet the increasing demand for cardiac interventions.

Introduction

Echocardiography and cardiac catheterization are common cardiac imaging modalities. Both modalities have drawbacks. The limitations of echocardiography include operator dependence, limited acoustic shadows, a small field of view, and poor evaluation of pulmonary veins. The limitations of cardiac catheterization include the overlapping of great vessels, difficulty in demonstrating systemic and pulmonary vessels at the same time, catheter-related complications, and high doses of iodinated contrast material and ionizing radiation. Computed tomography (CT) can overcome these limitations,[1] and previous studies widely reported its use in the evaluation of pediatric congenital heart disease.[2–5]

However, there are long-term risks of developing lethal malignancy induced by radiation exposure of CT scan.[6,7] Children are at higher risk than adults because their tissues are more radiosensitive and they have longer life expectancies to develop a radiation-induced malignancy.[8]

Recent studies have reported CT utilization trends in pediatric patients.[9–11] Fahimi et al[9] reported a dramatic increase in CT utilization among children presenting to the emergency department with abdominal pain. Menoch et al[10] showed a decrease in CT utilization in recent years in the pediatric emergency department of a regional pediatric referral center. DeVries et al[11] evaluated CT utilization patterns in children with recurrent headache and reported overuse of head CT despite existing guidelines. However, limited data are available to describe contemporary trends in the utilization of pediatric cardiac CT and catheterizations. The aim of this investigation is to study the impact of cardiac CT on the utilization of cardiac catheterization among children with congenital heart diseases in a tertiary referral general hospital.

Methods

Data collection

This retrospective study was conducted at a 2300-bed tertiary referral general hospital, which treated the majority of children with congenital heart disease in Taiwan. Informed consent was received for every case. The research protocol was approved by the local human research committee.

Consecutive patients who received pediatric cardiac CT, diagnostic catheterization, or interventional catheterization from January 1999 to December 2009 were enrolled into the "CT group," "cath-D group," or "cath-I group," respectively. Patients' age, sex, and diagnosis from each CT and catheterization examination were identified. Patients aged >18 years were excluded from the study. Diagnoses were categorized into 11 groups based on the anatomical structures they primarily affect (Table 1). Some diagnoses from CT including lung agenesis, idiopathic pulmonary hypertension, infectious endocarditis, intracardiac tumor, and thrombi were excluded because these diagnoses were not considered congenital heart diseases.

Radiation dose

CT

We calculated the dose–length product (mGy cm) in each CT scan. The effective radiation doses were determined as the product of the dose–length products and the age-specific conversion factors. The age-specific conversion factors were 0.0766 mSv/(mGy cm) (newborn), 0.0442 mSv/(mGy cm) (1 year), 0.0291 mSv/(mGy cm) (5 years), 0.0217 mSv/(mGy cm) (10 years), and 0.0136 mSv/(mGy cm) (15 years) based on a previous report by Deak et al.[12] The age-specific effective radiation doses (mSv) of CT examinations were calculated accordingly.

Catheterization

We calculated the dose–area product (Gy cm^2) in each catheterization. The effective radiation doses were determined as the product of the dose–area products and the age-specific conversion factors. The age-specific conversion factors were 3.7 mSv/(Gy cm^2) (newborn), 1.9 mSv/(Gy cm^2) (1 year), 1 mSv/(Gy cm^2) (5 years), 0.6 mSv/(Gy cm^2) (10 years), and 0.4 mSv/(Gy cm^2) (15 years) based on the work of Karambatsakidou et al.[13] The age-specific effective radiation doses (mSv) of catheterization were calculated accordingly.

Data analysis

Excel 2007 (Microsoft, Redmond, WA, USA) was used for data recording and presentation. Using general linear model on multivariate and repeated measures by SPSS (version 18; SPSS Inc., Chicago, IL, USA), trends between groups (CT vs. diagnostic catheterization) as well as annually within groups were analyzed. A p value of <0.05 was considered statistically significant.

Table 1 Eleven disease groups of all major diagnosis of congenital heart disease.

Disease groups	Diagnosis
VA connection disorder	CCTGA, DORV, TGA
Septal disorder	ASD, ECD, PFO, VSD
Tetralogy of Fallot	Tetralogy of Fallot, extreme tetralogy of Fallot
Heterotaxy	LAI, RAI
Myocardial disorder	ARVD, cardiomyopathy, EFE, myocarditis
Pericardial disorder	Constrictive pericarditis
Coronary arterial disorder	ALCAPA, coronary AVF, Kawasaki disease
Great vessel disorder	Marfan syndrome, PA atresia, PA sling, PDA, vascular ring, CoA, HLHS, IAA
Pulmonary vein disorder	PAPVR, PVO, TAPVR
Semilunar valvular disorder	AS, AR, PS
AV connection disorder	Criss-cross heart, DILV, DIRV, Ebstein anomaly, MA, TA

ALCAPA = anomalous left coronary artery from the pulmonary artery; AR = aortic regurgitation; ARVD = arrhythmogenic right ventricular dysplasia; AS = aortic stenosis; ASD = atrial septal defect; AV = atrioventricular; AVF = arterial venous fistula; CCTGA = congenitally corrected transposition of the great arteries; CoA = coarctation of the aorta; DILV = double-inlet left ventricle; DIRV = double-inlet right ventricle; DORV = double-outlet right ventricle; ECD = endocardial cushion defect; EFE = endocardial fibroelastosis; HLHS = hypoplastic left heart syndrome; IAA = interrupted aortic arch; LAI = left atrial isomerism; MA = mitral atresia; PA = pulmonary artery; PAPVR = partial anomalous pulmonary venous return; PDA = patent ductus arteriosus; PFO = patent foramen ovale; PS = pulmonary stenosis; PVO = pulmonary vein occlusion; RAI = right atrial isomerism; TA = tricuspid atresia; TAPVR = total anomalous pulmonary venous return; TGA = transposition of the great arteries; VA = ventriculoarterial; VSD = ventricular septal defect.

Results

Patient characteristics

From January 1999 to December 2009, clinicians performed 2648 pediatric cardiac CT examinations (female/male ratio = 1:1.42; age range, from 1 day to 17 years; mean 4.2 years). The total number of CT examinations gradually increased annually (1.2% increase per year). In the same period, clinicians performed 3814 cardiac catheterizations (female/male = 1:1.15; age range, from 1 day to 17 years; mean 4.5 years). The total number of diagnostic catheterizations decreased dramatically (6.2% decrease per year), whereas the total number of interventional catheterizations increased annually (2.7% increase per year). Both CT and catheterization case numbers declined in 2003 owing to the outbreak of severe acute respiratory syndrome in Taiwan. Many patients were afraid of visiting hospitals during this endemic period (Fig. 1A). A total of 2021 diagnostic catheterizations and 1793 interventional catheterizations were recorded within the study period. Of the interventional catheterizations, there were 748 balloon dilatations, 498 occluder placements, 307 coil embolizations, 20 pacemaker placements, 184 radiofrequency ablations, and 36 stent placements.

Analysis of temporal trends of utilization

Table 2 presents the 11 disease groups classified into two categories according to findings from trend analyses of the number of CT and diagnostic catheterizations per year. In Category A (Fig. 1B), the numbers of CT and diagnostic catheterizations per year are significantly different ($p < 0.05$). Category A consists of atrioventricular connection disorder, coronary arterial disorder, great vessel disorder, septal disorder, tetralogy of Fallot, and ventriculoarterial connection disorder. In Category B (Figure 1C), there are no significant differences between the numbers of CT and diagnostic catheterizations per year ($p > 0.05$). Category B consists of semilunar valvular disorder, heterotaxy, myocardial disorder, pericardial disorder, and pulmonary vein disorder.

There are no significant trend differences between the total numbers of CT examinations and total cardiac catheterizations (including interventional and diagnostic types) per year ($p > 0.05$). However, the trend differences in the total numbers of interventional and diagnostic catheterizations are significantly different ($p < 0.05$; Fig. 1A).

Radiation dose comparison

The mean effective radiation doses of CT were 8.0 mSv (newborn), 7.5 mSv (1 year), 9.2 mSv (5 years), 14.4 mSv (10 years), and 15.6 mSv (15 years). The mean effective radiation doses of cardiac catheterizations were 19.1 mSv (newborn), 9.9 mSv (1 year), 10.8 mSv (5 years), 19.8 mSv (10 years), and 19.7 mSv (15 years; Fig. 2).

Discussion

Our results indicated that the numbers of CT and interventional catheterizations increased (1.2% per year and 2.7% per year, respectively) from 1999 to 2009. In the same period, the number of diagnostic catheterization decreased by 6.2% annually. We compared the utilization trend of CT and diagnostic catheterization. We summarized two disease categories according to utilization trend analyses of CT and diagnostic catheterizations.

In category A—which includes atrioventricular connection disorder, coronary arterial disorder, great vessel disorder, septal disorder, tetralogy of Fallot, and ventriculoarterial connection disorder—CT examinations outnumbered

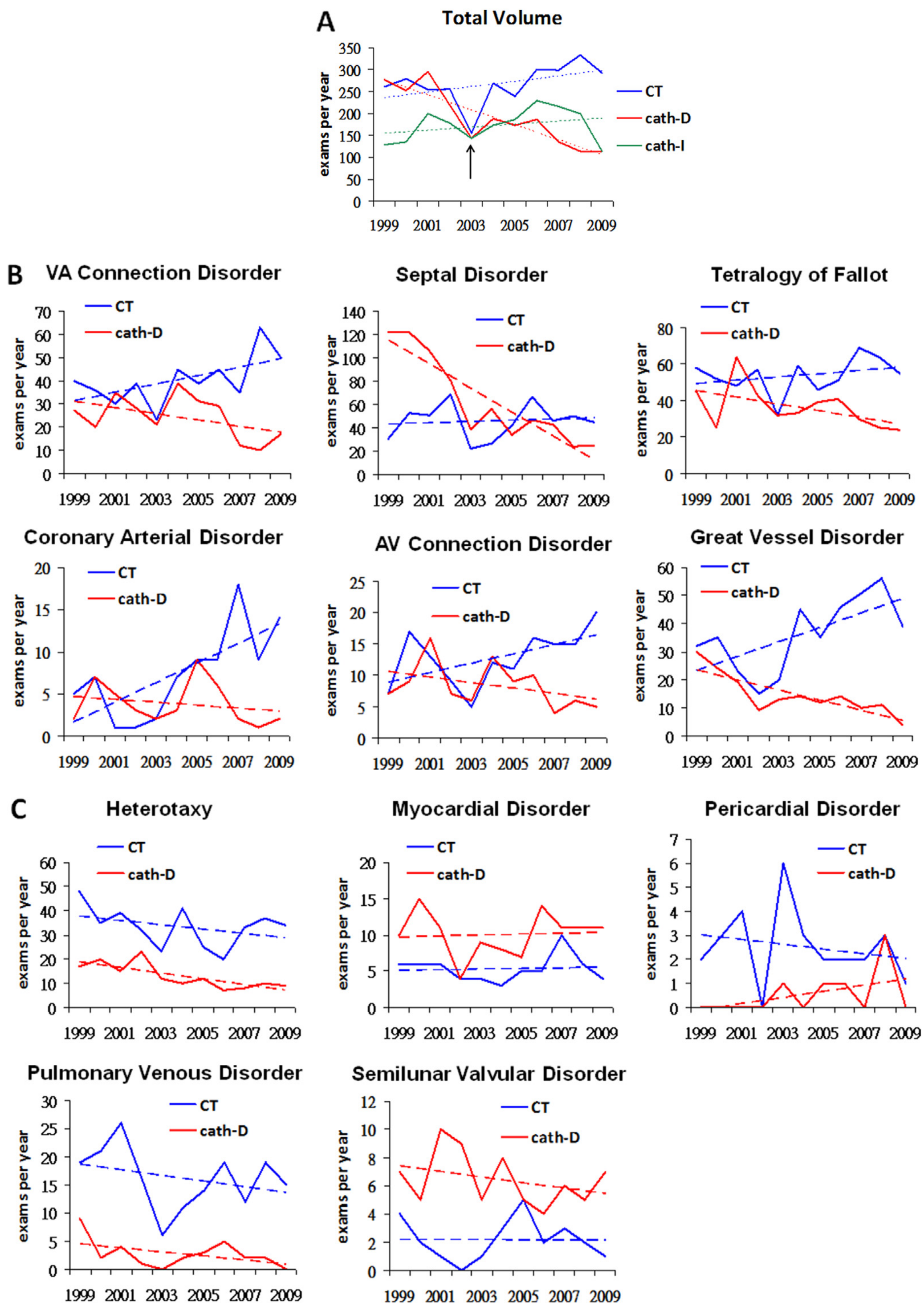

Figure 1 Number of CT performed per year. (A) Total number of CT and interventional and diagnostic catheterization (cath-I and cath-D) in each year. Note the decline in 2003 (arrow) due to SARS in our country. Broken lines indicate trend linear regression. CT and interventional catheterization had a slight annual increase of 1.2% and 2.7%, respectively. Diagnostic catheterization had an annual decrease of 6.2%. (B) There are significant trend differences between the number per year of CT and diagnostic catheterization in VA connection disorder, septal disorder, tetralogy of Fallot, coronary arterial disorder, AV connection disorder, and great vessel disorder. (C) There are no significant trend differences between the number per year of CT and diagnostic catheterization in heterotaxy, myocardial disorder, pericardial disorder, pulmonary venous disorder and semilunar valvular disorder. AV = atrioventricular; cath-D = diagnostic catheterization; cath-I = interventional catheterization; CT = computed tomography; SARS = severe acute respiratory syndrome; VA = ventriculoarterial.

Table 2 Two categories based on the statistical significance on temporal tend analysis in the utilization of cardiac CT and diagnostic cardiac catheterization.

Category	Disease groups	*p*
A:	AV connection disorder	0.049*
Difference between trend on number of cardiac CT and diagnostic cardiac catheterization	Coronary arterial disorder	0.045*
	Great vessel disorder	0.014*
	Septal disorder	0.006*
	Tetralogy of Fallot	0.022*
	VA connection disorder	0.019*
B:	Semilunar valvular disorder	0.203
No difference between trend on number of cardiac CT and diagnostic cardiac catheterization	Heterotaxy	0.206
	Myocardial disorder	0.879
	Pericardial disorder	0.172
	Pulmonary vein disorder	0.367

*$p < 0.05$.
AV = atrioventricular; CT = computed tomography; VA = ventriculoarterial.

diagnostic catheterizations. Owing to the high spatial resolution, CT evaluates the course of the coronary artery more effectively than diagnostic cardiac catheterization.[14] CT can also produce postprocessing images, such as three-dimensional volume-rendering images,[15] which clearly demonstrate the anatomical relationships in great vessel disorder. If patients refuse cardiac catheterization, CT may provide vital information, in three-dimensional volume-rendering images, and reveal the intracardiac pathology.[15] In patients with Marfan syndrome, a subtype of great vessel disorder, CT can reveal dilatation of the sinus of Valsalva and effacement of the sinotubular junction.[16] CT can also provide volumetric measurements of the right ventricle prior to and after atrial septal defect closure. Catheterization cannot effectively perform this task.[17] Cardiac catheterization reportedly induces transient or complete heart block in congenitally corrected transposition of the great arteries.[18] In patients suspected to have congenitally corrected transposition of the great arteries, noninvasive CT is, therefore, useful for diagnosis without incurring such a life-threatening event.[19]

In Category B—which includes semilunar valvular disorder, heterotaxy, myocardial disorder, pericardial disorder, and pulmonary vein disorder—whether CT or diagnostic cardiac catheterization is the more useful modality remains to be determined. The benefits of CT include good spatial resolution and powerful postprocessing techniques. Diagnostic cardiac catheterization, however, can provide dynamic images and pressure gradient measurements.[20] Clinicians may select either catheterization or CT, or both examinations, depending on the clinical conditions. CT can provide excellent visualizations of mitral and aortic valves, including the number of valve leaflets, opening and closing of leaflets, leaflet thickness, and leaflet calcifications.[21] However, CT is unable to fully evaluate valvular stenosis or regurgitation, which diagnostic cardiac catheterization can easily detect.[22] Determinations of aortic valve area by CT correlate well with catheterization findings.[23] In myocardial disorder, a diagnosis of myocarditis or rejection of heart transplantation usually requires referring to histological specimen(s). In such cases, catheterization is superior to CT.[24] For the diagnosis of constrictive pericarditis, the ratio of the right ventricular to the left ventricular systolic area during inspiration and expiration is a reliable catheterization criterion.[25] CT can also diagnose constrictive pericarditis via demonstration of calcified pericardium.[26] Utilization of catheterization or CT for diagnosis of constrictive pericarditis is, therefore, mainly based on clinicians' decisions and the availability of diagnostic modalities.

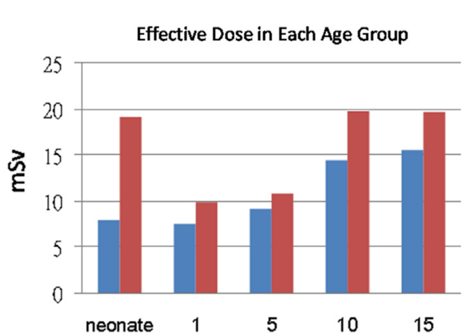

Figure 2 Mean effective doses in each age group of cardiac computed tomography (CT) (blue) and catheterization (red) in the study institute.

There were no significant differences between the total numbers of CT and total catheterization examinations per year. This finding might suggest that the number of total catheterizations per year remained constant. However, in the present study, the number of diagnostic catheterizations demonstrated a decreasing trend during the evaluation period, whereas the number of interventional catheterizations demonstrated an increasing trend. Decreased numbers of diagnostic catheterizations may have released more time, space, and availability of faculty facilities with which to perform interventional catheterizations in response to increasing clinical demands.

Children are at greater risk than adults from doses of radiation because they are inherently more radiosensitive and have longer life expectancies during which radiation-induced cancers might develop.[7] In the study hospital, each pediatric patient received an individualized CT scan protocol implementing the "as low as reasonably achievable"

(ALARA) concept.[27,28] Several studies described the effective radiation doses in pediatric interventional cardiology. Bacher et al[29] reported the effective radiation doses in 60 children (median, 2.0 years) with congenital heart disease, who underwent diagnostic or therapeutic cardiac catheterization procedures. The median effective doses were 4.6 mSv and 6.0 mSv for diagnostic and therapeutic cardiac catheterization, respectively.[29] Beels et al[30] reported the effective radiation doses in 49 children (median 0.75 years) with congenital heart disease, who underwent diagnostic or therapeutic cardiac catheterization procedures, and the median effective dose approximately ranged from 5.6 mSv to 6.4 mSv.

Pediatric cardiac catheterization has several other shortcomings. The incidences of complications caused by pediatric cardiac catheterizations ranged from 0.3% to 20%.[31–34] Common complications included thrombosis, arteriovenous fistula, pseudoaneurysm formation, hemorrhage, and dissection.[31,35,36] The repeated puncture of femoral vessels correlates with femoral vessel occlusion and asymmetric growth of bilateral legs,[37] and post-procedural monitoring may take several hours in a recovery ward. Cardiac catheterization may require general anesthesia. Pediatric cardiac CT, however, does not require the same level of deep sedation as cardiac catheterization, requiring only adequate peripheral venous access.[32,38] A recent study also reported temporal trends of cardiovascular imaging at a single institute and concluded that the use of cardiac CT increased and the use of diagnostic catheterization decreased.[39]

Asian doctors were more inclined to use CT than magnetic resonance imaging (MRI) to evaluate congenital heart diseases.[40] The relatively limited resources and busy clinical working environment in Asia result in Asian radiologists developing special techniques and workflow using cardiac CT for congenital heart diseases to answer important clinical questions.[1,41–44] The current criteria for cardiac CT scans, provided by Western professional societies, are not appropriate for Asian cultures. The Asian Society of Cardiovascular Imaging considered cardiac CT as an appropriate modality for complex congenital heart disease and postoperative congenital heart disease in follow-up and in symptomatic patients.[45] In addition, according to Asian Society of Cardiovascular Imaging 2010 appropriateness criteria for cardiac CT,[45] appropriate indications for pediatric cardiac CT include Kawasaki disease, preoperative evaluation prior to the endovascular treatment, and evaluation of intracardiac and extracardiac structures (e.g., cardiac valve, pulmonary vein, pericardium, coronary artery, and coronary vein).

Common indications for pediatric cardiac magnetic resonance (CMR) under general anesthesia include aortic arch abnormalities, preoperative evaluation of univentricular heart, pulmonary vein abnormalities, and cardiomyopathy.[46] For example, in patients with suspected cardiomyopathy, CMR can provide information about myocardial characterization and ventricular scarring. Common indications for pediatric CMR without anesthesia include valve regurgitation, repaired tetralogy of Fallot, and postoperative evaluation of univentricular heart. Meanwhile, recommendations for diagnostic catheterization include assessment of filling pressure, and pulmonary resistance.[47] Despite the recent advances in noninvasive imaging study, diagnostic catheterization remains the "final authority" to provide definite anatomical and hemodynamic information for very complex lesions.[47]

The relationship of radiation dose by medical imaging and incidence of malignancy is relatively controversial nowadays. One previous study (2009) claimed that approximately 29,000 future cancers could be related to 1 year of CT scan in the United States.[48] However, a recent study[49] published in 2014 claimed that zero radiation-induced malignancy were detected after routine CT scans. They evaluated 104 children who underwent cerebrospinal fluid shunt placement prior to the age of 6 years and with at least 10 years of follow-up data. These children had a total of 1584 CT scans over a follow-up period of 1622 person-years. There were no subsequent benign or malignant tumors, or leukemia detected in their enrolled children. This single-institution study did not adequately define the actual risk. Further collaborative efforts should be made to define the actual risk to patients.

In order to explain the situation to parents who are concerned about the possible development of malignancy, we need to emphasize the benefits of CT and catheterization. Multidetector CT is faster than MRI and catheterization, thus reducing the need for general anesthesia. Each pediatric patient receive an individualized CT scan protocol implementing the ALARA concept.[27,28] Radiologists should restrict the area scanned as much as possible to fine-tune the CT protocols based on the indications and the child's body size. Diagnostic catheterization could be performed if noninvasive imaging modalities are not able to provide enough information.

There are several limitations that need to be addressed. This study describes the utilization patterns of cardiac CT, and diagnostic and interventional cardiac catheterization in only one institution and may not reflect the patterns of utilization in other hospitals or other countries. The authors did not evaluate MRI for comparison owing to a lack of required equipment for children in the institute. The available information did not allow us to investigate the appropriateness of the imaging modalities performed. The selection of diagnostic modalities might reflect the referring cardiologist's judgment of necessity. Moreover, we could not directly infer that the increase in CT scans is the cause of the decrease in diagnostic catheterization. Because of the retrospective design of this study, we cannot infer causality but only association.

In conclusion, this study describes the changing trend in the utilization of cardiac CT and cardiac catheterization for patients with congenital heart diseases in a tertiary referral general hospital during an 11-year period. Results suggest that CT might replace diagnostic catheterization in selected congenital heart disease conditions: great vessel disorder, coronary artery disorder, atrioventricular connection disorder, septal disorder, tetralogy of Fallot, and ventriculoarterial connection disorder. In patients with other disorders, clinicians may select either catheterization or CT, or both examinations, depending on the clinical conditions. Cardiac CT uses lower radiation doses than cardiac catheterization. The use of CT releases time, manpower, and facilities in the catheterization laboratory with which to meet the increasing demands of cardiac intervention.

References

1. Goo HW, Park IS, Ko JK, Kim YH, Seo DM, Yun TJ, et al. CT of congenital heart disease: normal anatomy and typical pathologic conditions. *Radiographics* 2003;**23**:S147—65.
2. Chen SJ, Li YW, Wang JK, Chiu IS, Su CT, Hsu JC, et al. Three-dimensional reconstruction of abnormal ventriculoarterial relationship by electron beam CT. *J Comput Assist Tomogr* 1998;**22**:560—8.
3. Chen SJ, Li YW, Wang JK, Wu MH, Chiu IS, Chang CI, et al. Usefulness of electron beam computed tomography in children with heterotaxy syndrome. *Am J Cardiol* 1998;**81**:188—94.
4. Chen SJ, Wang JK, Li YW, Chiu IS, Su CT, Lue HC. Validation of pulmonary venous obstruction by electron beam computed tomography in children with congenital heart disease. *Am J Cardiol* 2001;**87**:589—93.
5. Lee WJ, Chen SJ, Wu MH, Li YW. Regression of ductus arteriosus aneurysm in a neonate demonstrated by three-dimensional computed tomography. *Int J Cardiol* 1999;**68**:231—4.
6. Brenner DJ. Estimating cancer risks from pediatric CT: going from the qualitative to the quantitative. *Pediatr Radiol* 2002;**32**:228—31.
7. Brenner DJ, Hall EJ. Computed tomography—an increasing source of radiation exposure. *N Engl J Med* 2007;**357**:2277—84.
8. Shrimpton PC, Edyvean S. CT scanner dosimetry. *Br J Radiol* 1998;**71**:1—3.
9. Fahimi J, Herring A, Harries A, Gonzales R, Alter H. Computed tomography use among children presenting to emergency departments with abdominal pain. *Pediatrics* 2012;**130**:e1069—75.
10. Menoch MJ, Hirsh DA, Khan NS, Simon HK, Sturm JJ. Trends in computed tomography utilization in the pediatric emergency department. *Pediatrics* 2012;**129**:e690—7.
11. DeVries A, Young PC, Wall E, Getchius TS, Li CH, Whitney J, et al. CT scan utilization patterns in pediatric patients with recurrent headache. *Pediatrics* 2013;**132**:e1—8.
12. Deak PD, Smal Y, Kalender WA. Multisection CT protocols: sex- and age-specific conversion factors used to determine effective dose from dose—length product. *Radiology* 2010;**257**:158—66.
13. Karambatsakidou A, Sahlgren B, Hansson B, Lidegran M, Fransson A. Effective dose conversion factors in paediatric interventional cardiology. *Br J Radiol* 2009;**82**:748—55.
14. Dewey M, Zimmermann E, Deissenrieder F, Laule M, Dubel HP, Schlattmann P, et al. Noninvasive coronary angiography by 320-row computed tomography with lower radiation exposure and maintained diagnostic accuracy: comparison of results with cardiac catheterization in a head-to-head pilot investigation. *Circulation* 2009;**120**:867—75.
15. Gopal A, Silvet H, Foster GP. Cardiovascular computed tomographic angiography evaluation following unsuccessful invasive angiography: the clinical utility of 3D volume rendering. *Catheter Cardiovasc Interv* 2010;**75**:753—6.
16. Abad P, Cheong B, Flamm SD. Diagnosis of marfan syndrome by computed tomography. *Tex Heart Inst J* 2006;**33**:536—8.
17. Berbarie RF, Anwar A, Dockery WD, Grayburn PA, Hamman BL, Vallabhan RC, et al. Measurement of right ventricular volumes before and after atrial septal defect closure using multislice computed tomography. *Am J Cardiol* 2007;**99**:1458—61.
18. Van Praagh R, Papagiannis J, Grunenfelder J, Bartram U, Martanovic P. Pathologic anatomy of corrected transposition of the great arteries: medical and surgical implications. *Am Heart J* 1998;**135**:772—85.
19. Chang DS, Barack BM, Lee MH, Lee HY. Congenitally corrected transposition of the great arteries: imaging with 16-MDCT. *AJR Am J Roentgenol* 2007;**188**:W428—30.
20. Braunwald E, Gorlin R, McIntosh HD, Ross RS, Rudolph AM, Swan HJ. Cooperative study on cardiac catheterization. Summary. *Circulation* 1968;**37**:III93—101.
21. Vogel-Claussen J, Pannu H, Spevak PJ, Fishman EK, Bluemke DA. Cardiac valve assessment with MR imaging and 64-section multi-detector row CT. *Radiographics* 2006;**26**:1769—84.
22. Carroll JD. Cardiac catheterization and other imaging modalities in the evaluation of valvular heart disease. *Curr Opin Cardiol* 1993;**8**:211—5.
23. Lembcke A, Kivelitz DE, Borges AC, Lachnitt A, Hein PA, Dohmen PM, et al. Quantification of aortic valve stenosis: head-to-head comparison of 64-slice spiral computed tomography with transesophageal and transthoracic echocardiography and cardiac catheterization. *Invest Radiol* 2009;**44**:7—14.
24. Melvin KR, Mason JW. Endomyocardial biopsy: its history, techniques and current indications. *Can Med Assoc J* 1982;**126**:1381—6.
25. Talreja DR, Nishimura RA, Oh JK, Holmes DR. Constrictive pericarditis in the modern era: novel criteria for diagnosis in the cardiac catheterization laboratory. *J Am Coll Cardiol* 2008;**51**:315—9.
26. Suh SY, Rha SW, Kim JW, Park CG, Seo HS, Oh DJ, et al. The usefulness of three-dimensional multidetector computed tomography to delineate pericardial calcification in constrictive pericarditis. *Int J Cardiol* 2006;**113**:414—6.
27. Shah NB, Platt SL. ALARA: is there a cause for alarm? Reducing radiation risks from computed tomography scanning in children. *Curr Opin Pediatr* 2008;**20**:243—7.
28. Slovis TL. Children, computed tomography radiation dose, and the as low as reasonably achievable (ALARA) concept. *Pediatrics* 2003;**112**:971—2.
29. Bacher K, Bogaert E, Lapere R, De Wolf D, Thierens H. Patient-specific dose and radiation risk estimation in pediatric cardiac catheterization. *Circulation* 2005;**111**:83—9.
30. Beels L, Bacher K, De Wolf D, Werbrouck J, Thierens H. Gamma-h2ax foci as a biomarker for patient x-ray exposure in pediatric cardiac catheterization: are we underestimating radiation risks. *Circulation* 2009;**120**:1903—9.
31. Lin PH, Dodson TF, Bush RL, Weiss VJ, Conklin BS, Chen C, et al. Surgical intervention for complications caused by femoral artery catheterization in pediatric patients. *J Vasc Surg* 2001;**34**:1071—8.
32. Leblanc J, Wood AE, O'Shea MA, Williams WG, Trusler GA, Rowe RD. Peripheral arterial trauma in children. A fifteen year review. *J Cardiovasc Surg (Torino)* 1985;**26**:325—31.
33. Ino T, Benson LN, Freedom RM, Barker GA, Aipursky A, Rowe RD. Thrombolytic therapy for femoral artery thrombosis after pediatric cardiac catheterization. *Am Heart J* 1988;**115**:633—9.
34. Sahn DJ, Goldberg SJ, Allen HD, Valdes-Cruz LM, Canale JM, Lange L, et al. A new technique for noninvasive evaluation of femoral arterial and venous anatomy before and after percutaneous cardiac catheterization in children and infants. *Am J Cardiol* 1982;**49**:349—55.
35. Chaikof EL, Dodson TF, Salam AA, Lumsden AB, Smith 3rd RB. Acute arterial thrombosis in the very young. *J Vasc Surg* 1992;**16**:428—35.
36. Friedman J, Fabre J, Netscher D, Jaksic T. Treatment of acute neonatal vascular injuries—the utility of multiple interventions. *J Pediatr Surg* 1999;**34**:940—5.
37. Cilley RE. Arterial access in infants and children. *Semin Pediatr Surg* 1992;**1**:174—80.
38. Frush DP, Yoshizumi T. Conventional and CT angiography in children: dosimetry and dose comparisons. *Pediatr Radiol* 2006;**36**:154—8.
39. Han BK, Lesser AM, Vezmar M, Rosenthal K, Rutten-Ramos S, Lindberg J, et al. Cardiovascular imaging trends in congenital heart disease: a single center experience. *J Cardiovasc Comput Tomogr* 2013;**7**:361—6.

40. Tsai IC, Goo HW. Cardiac CT and MRI for congenital heart disease in Asian countries: recent trends in publication based on a scientific database. *Int J Cardiovasc Imaging* 2013;**29**:1—5.
41. 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.
42. Lee T, Tsai IC, Fu YC, Jan SL, Wang CC, Chang Y, et al. Using multidetector-row CT in neonates with complex congenital heart disease to replace diagnostic cardiac catheterization for anatomical investigation: initial experiences in technical and clinical feasibility. *Pediatr Radiol* 2006;**36**:1273—82.
43. Chen SJ, Lin MT, Lee WJ, Liu KL, Wang JK, Chang CI, et al. Coronary artery anatomy in children with congenital heart disease by computed tomography. *Int J Cardiol* 2007;**120**:363—70.
44. Chen SJ, Lee WJ, Lin MT, Liu KL, Wang JK, Lue HC. Coronary artery diameters in infants and children with congenital heart disease as determined by computed tomography. *Am J Cardiol* 2007;**100**:1696—701.
45. Tsai IC, Choi BW, Chan C, Jinzaki M, Kitagawa K, Yong HS, et al. ASCI 2010 appropriateness criteria for cardiac computed tomography: a report of the Asian Society of Cardiovascular Imaging cardiac computed tomography and cardiac magnetic resonance imaging guideline working group. *Int J Cardiovasc Imaging* 2010;**26**:1—15.
46. Ntsinjana HN, Hughes ML, Taylor AM. The role of cardiovascular magnetic resonance in pediatric congenital heart disease. *J Cardiovasc Magn Reson* 2011;**13**:51.
47. Feltes TF, Bacha E, Beekman 3rd RH, Cheatham JP, Feinstein JA, Gomes AS, et al. Indications for cardiac catheterization and intervention in pediatric cardiac disease: a scientific statement from the American Heart Association. *Circulation* 2011;**123**:2607—52.
48. Berrington de González A, Mahesh M, Kim KP, Bhargavan M, Lewis R, Mettler F, et al. Projected cancer risks from computed tomographic scans performed in the United States in 2007. *Arch Intern Med* 2009;**169**:2071—7.
49. White IK, Shaikh KA, Moore RJ, Bullis CL, Sami MT, Gianaris TJ, et al. Risk of radiation-induced malignancies from CT scanning in children who underwent shunt treatment before 6 years of age: a retrospective cohort study with a minimum 10-year follow-up. *J Neurosurg Pediatr* 2014;**13**:514—9.