Diagnostic accuracy of dual-source multislice computed tomographic analysis for the preoperative detection of coronary artery anomalies in 100 patients with tetralogy of Fallot

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Objectives: A detailed preoperative evaluation of coronary anatomy is mandatory before surgical intervention for tetralogy of Fallot. In pediatric patients, the preoperative evaluation of coronary anatomy has relied classically on conventional angiographic analysis and, more recently, on echocardiographic analysis, which have well-known limitations and complications. Recent technological improvements allow the use of multislice computed tomographic analysis to evaluate coronary artery anatomy in very young children, even those with high heart rates. The purpose of this prospective study was to assess the accuracy of preoperative dual-source computed tomographic analysis in detecting coronary artery abnormalities by using surgical findings as the reference standard.

Methods: We prospectively evaluated 100 patients with tetralogy of Fallot before surgical intervention between November 2006 and September 2009 by using dual-source computed tomographic analysis with either retrospective, electrocardiographically gated, helical computed tomographic analysis or prospective, electrocardiographically triggered, sequential computed tomographic acquisition. The patients had a median age of 6.8 months (range, 1.2 months–6.8 years) and a median weight of 7.9 kg (range, 3–30 kg).

Results: Compared with surgical findings, dual-source computed tomographic analysis had 100% sensitivity and 100% specificity for detecting coronary artery abnormalities. Major coronary artery abnormalities were found in 7 (7%) patients. The radiation dose was low.

Conclusions: Dual-source computed tomographic analysis is an accurate and noninvasive tool for delineating coronary artery anatomy before surgical intervention in children with tetralogy of Fallot. Dual-source computed tomographic analysis might deserve to be used routinely instead of angiographic analysis and in combination with echocardiographic analysis for the preoperative assessment of patients with tetralogy of Fallot. (*J Thorac Cardiovasc Surg* 2011;142:120-26)

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Accurate preoperative evaluation of coronary artery anatomy is essential for the successful surgical repair of tetralogy of Fallot (TOF). Approximately 5% to 12% of patients with TOF have an anomalous coronary artery crossing the right ventricular outflow tract (RVOT), a configuration that might complicate the operation.^{1,2} Preoperative detection of this abnormality allows the use of an alternative surgical procedure involving the placement of an RVOT patch with either a limited right ventriculotomy

or the creation of a right ventricle–pulmonary artery (RV–PA) conduit to preserve the anomalous vessel.^{3,4}

Major coronary artery abnormalities are a left anterior descending coronary artery (LAD) arising from the right coronary artery (RCA) or a single coronary artery arising from either the right or left sinus with the LAD artery or the RCA, respectively, crossing the RVOT. Other coronary abnormalities can be seen, such as a small or large conal branch that does not reach the anterior interventricular septum or a dual LAD with an accessory LAD artery arising from the RCA.

Various surgical strategies are available for patients with coronary artery abnormalities. A staged approach can be used, with an aortopulmonary shunt early in life followed by the creation of an RV–PA conduit as part of the complete repair procedure. Alternatively, primary complete repair might be performed.⁵

Echocardiographic analysis is performed as part of the preoperative evaluation in patients with TOF but is rarely used as the only imaging study.⁶ In many centers preoperative cardiac catheterization is performed routinely in patients with TOF to evaluate the anatomy of the heart, large vessels, and coronary arteries. The limitations and potential complications of cardiac catheterization are well known.

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Disclosures: Authors have nothing to disclose with regard to commercial support. Received for publication May 29, 2010; revisions received Oct 15, 2010; accepted for publication Nov 5, 2010; available ahead of print Feb 5, 2011.

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0022-5223/\$36.00

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doi:10.1016/j.jtcvs.2010.11.016

Abbreviations and Acronyms

CT	= computed tomography
DLP	= dose-length product
DSCT	= dual-source multislice computed tomography
LAD	= left anterior descending coronary artery
MSCT	= multislice computed tomography
RCA	= right coronary artery
RVOT	= right ventricular outflow tract
RV-PA	= right ventricle–pulmonary artery
TOF	= tetralogy of Fallot

In recent years, technological advances, including the introduction of dual-source scanners, have considerably improved the capabilities of multislice computed tomography (MSCT). The temporal resolution of dual-source multislice computed tomography (DSCT) is now 83 ms, allowing coronary artery evaluation in everyday practice in very young infants with high heart rates.^{7,8}

The purpose of this prospective study was to assess the accuracy of preoperative DSCT for detecting coronary artery abnormalities in patients with TOF. We used surgical findings as the reference standard.

MATERIALS AND METHODS**Patients**

Between November 2006 and September 2009, 100 consecutive patients given diagnoses of TOF and referred to our institution for surgical treatment were included prospectively. We did not include patients who had complex TOF, which was defined as TOF with pulmonary atresia, complete atrioventricular canal, double-outlet right ventricle, absent pulmonary valve syndrome, or aortopulmonary window. Of our 100 study patients, 35 had abnormalities in addition to TOF diagnosed before surgical intervention: patent ductus arteriosus (n = 13), atrial septal defect (n = 9), anomalous systemic venous return (n = 6), anomalous aortic arches (n = 3), multiple ventricular septal defect (n = 2), or bicuspid pulmonary valve (n = 4).

All DSCT evaluations were done as part of the standard care provided at our institution. Our institutional review board approved the study, and informed consent was obtained from all parents before study inclusion. The information supplied to parents included explanations about possible adverse effects of contrast medium injection and radiation exposure.

Preoperative Evaluation

In addition to DSCT, all patients underwent echocardiographic analysis. Preoperative echocardiographic analysis caused us to suspect an anomalous coronary artery in 4 patients: 3 left anterior arteries arising from the RCA and a single RCA with the LAD crossing the RVOT. All 4 cases were confirmed at DSCT, with total correlation with surgical findings. The radiologists interpreting the computed tomographic (CT) examination results were not aware of the suspected anomaly at the time of examination.

Diagnostic cardiac catheterization was performed in a single patient, early in the study to confirm DSCT findings, suggesting a large conal branch. Therapeutic cardiac catheterization was performed in 8 patients, ei-

ther for percutaneous pulmonary valve dilatation before complete surgical repair or for systemic–pulmonary shunt thrombosis.

DSCT Protocol

Short-term sedation, if needed, was achieved by using oral hydroxyzine dihydrochloride at 1 mg/kg, with rectal midazolam hydrochloride at 0.3 mg/kg. Neonates were given only saccharose syrup. None of the patients received β -blocker therapy to decrease the heart rate.

A Somatom Definition DSCT scanner (Siemens AG, Forchheim, Germany) was used in all patients. Technological improvements that occurred over the 3-year study period, together with the experience accumulated by the study radiologists, led to a switch from retrospective (helical) electrocardiographically gated acquisition early in the study to prospective (sequential) electrocardiographically gated acquisition after December 2008. The helical protocol involved 2 acquisitions, namely a nongated helical thoracic acquisition followed by a retrospective, electrocardiographically gated, helical cardiac acquisition. The nongated helical acquisition from the upper thoracic inlet to the diaphragm was obtained by using a collimation of 64×0.6 mm, pitch of 1.4, rotation time of 330 ms, and a 1-mm slice thickness with a 0.75-mm reconstruction interval by using a medium convolution filter (B30 kernel) for soft tissue. Immediately afterward, a retrospective, electrocardiographically gated, helical cardiac acquisition was obtained. This acquisition was limited to the level of the coronary arteries to minimize radiation exposure. Parameters were a collimation of 64×0.6 mm, pitch of 0.2 to 0.4 depending on heart rate, rotation time of 330 ms, and a 1-mm reconstruction slice thickness with a 0.75-mm reconstruction interval and soft convolution filter (B20 kernel). Eight data sets were reconstructed at 10% R-R interval increments, from 20% to 90% of the R-R interval, with a 1-mm slice thickness. A low-dose protocol involving an 80-kV tube voltage and weight-based adjustment of tube current was used in all patients. Tube current for the nongated helical acquisition was 30 mA in patients weighing up to 3 kg and 30 mA plus 5 mA per additional kilogram in patients weighing more than 3 kg; for the retrospective, electrocardiographically gated, helical cardiac acquisition, tube current was 150% of the value used for the nongated acquisition.

The sequential protocol used after December 2008 consisted of a single prospective, electrocardiographically triggered, sequential thoracic acquisition. This protocol allowed a 1-step evaluation of cardiac and other thoracic structures with less radiation exposure. The settings were a collimation of 64×0.6 mm, rotation time of 330 ms, and reconstruction of a 1-mm slice thickness with a 0.75-mm interval and a soft convolution filter (B20 kernel). Experience acquired during the first part of the study, before December 2008, indicated that the optimal reconstruction time point was usually end-systole. Therefore reconstructions in the prospective protocol were set at the end-systolic phase, starting at the T-wave peak (at 40% to 50% of the R-R interval) without padding. Acquisition length was adjusted between 2 and 4 table moves to encompass the heart and great vessels. All patients received the same low-dose protocol involving 80-kV tube voltage and weight-based adjustment of tube current with 10 mA/kg up to 3 kg and then 30 mA plus 5 mA/kg at greater than 3 kg.

The helical protocol was used in 42 patients, and the sequential protocol was used in 58 patients. Of the 58 patients examined by using the sequential protocol, 5 required a second acquisition because of agitation during the first acquisition. In these patients only the data from the second acquisition were recorded. After December 2008, despite the availability of sequential acquisition, the helical protocol was used in 5 patients who had mild agitation, suggesting a risk of poor image quality with sequential acquisition.

Intravenous Contrast Medium Injection

In all patients an iodinated contrast medium (iopromide, 300 mg/mL; Ultravist 300; Bayer Schering Pharma, Berlin, Germany) was injected with a single-head power injector (Stellant; Medrad, Indianola, Pa) to ensure a continuous and regular flow rate. The dose was 2 mL/kg for both acquisition protocols, and the injection rate ranged from 0.4 to 3 mL/s

according to body weight. Time from injection to scanning was 15 seconds for injection at the arm, 18 seconds for injection at the foot, and 10 seconds for injection into a central vein. Automatic bolus detection was not used. Special care was taken to exclude air bubbles from the connection tube to prevent venous air embolism. Contrast extravasation or adverse reactions to contrast medium were to be recorded. No adverse reactions to contrast medium injection were recorded.

Image Postprocessing and Analysis

All images were transferred to an external workstation (Leonardo, Siemens AG). Three-dimensional techniques, such as multiplanar reformation, maximum intensity projection, and volume rendering, were used. A trained senior cardiac radiologist interpreted the reconstructed images as part of the standard care offered to patients at our institution. For each patient, the anatomic description of the coronary artery configuration and of any major or minor coronary artery abnormalities written by the radiologist was compared with the findings during surgical repair.

DSCT allowed an evaluation of pulmonary artery anatomy, right-sided aortic arch anatomy, and any major aortopulmonary collateral arteries.

Surgical Findings

Surgical repair of TOF was performed at our institution in all patients. The DSCT findings were communicated to the surgeons before the procedure. For each patient, the surgeons wrote a detailed description of coronary artery anatomy as assessed during surgical intervention.

Radiation Dose

The dose-length product (DLP) displayed on the CT scanner was recorded as the mean $\pm$ standard deviation for each acquisition and each protocol. The effective radiation dose (E) was estimated by using DLP conversion factors for chest imaging in pediatric patients given for a 16-cm phantom: 0.039 before 4 months of age, 0.026 between 4 months and 1 year of age, 0.018 from 1 to 5 years of age, and 0.013 from 5 to 10 years of age.⁸ On the CT scanner used for the study, DLP per body area is given for a 32-cm phantom and must be multiplied by 2 to obtain the best estimate of actual DLP in children examination.⁹ Therefore we applied the conversion factor 2 to the DLP value displayed to obtain the effective radiation dose estimate.

Statistical Analysis

We compared the DSCT findings with the surgical findings on a case-by-case basis. Then we computed sensitivity and specificity with the 95% confidence intervals, positive predictive value, and negative predictive value of DSCT versus surgical intervention for detecting coronary artery abnormalities.

True-positive results were defined as patients with coronary artery abnormalities identified by means of both DSCT and surgical intervention. True-negative results were defined as patients without coronary artery abnormalities identified by means of either DSCT or surgical intervention. False-positive results were defined as patients with coronary artery abnormalities identified by means of DSCT but not by means of surgical intervention, and false-negative results were defined as patients with coronary artery abnormalities identified by means of surgical intervention but not DSCT.

RESULTS

Patients

There were 62 male and 38 female patients (sex ratio, 1.6) with a median age at repair of 6.8 months (range, 1.2 months to 6.8 years) and a median weight at repair of 7.9 kg (range, 3–30 kg). Surgical repair was performed during the first year of life in 77 patients and the second year in

7 patients; the remaining 16 patients were older because they were referred to us from developing countries by a heart surgery sponsorship program.

Intravenous Contrast Medium Injection

Overall, the mean total amount of contrast medium injected was 16 ± 5 mL (range, 5–60 mL). The mean flow rate was 1 ± 0.5 mL/s (range, 0.5–3 mL/s). The mean total amount of contrast medium injected was 20.2 ± 4 mL (range, 16–60 mL) with the helical protocol and 17.2 ± 2.6 mL (range, 6–60 mL) with the sequential protocol. No adverse reactions to contrast medium injection were recorded.

Diagnostic Performance of DSCT Versus Surgical Intervention (Reference Standard)

DSCT showed 5 different coronary artery configurations among the 6 coronary patterns described in TOF^{1,2} (Table 1). The usual configuration was found in 69 patients. Because of the counterclockwise rotation of the aortic root in patients with TOF, the left ostium was usually located at 6 to 7 o'clock and the right ostium at 1 to 2 o'clock. In 24 patients we found a variant of the usual configuration with a conal branch arising from the RCA but did not preclude infundibulotomy. The remaining 7 patients had major coronary artery abnormalities determined by means of DSCT. Among them, 4 had an anomalous LAD arising from the RCA, and the other 3 patients had a single coronary artery: 2 with a single RCA (Figure 1) and 1 with a single left coronary artery.

Surgical findings confirmed the DSCT results in all patients. Thus there were 7 true-positive and 93 true-negative results, with no false-positive or false-negative results.

Of the 7 patients with major coronary artery abnormalities, 4 had a coronary artery configuration that precluded right ventriculotomy and required an RV-PA conduit.

Radiation Dose

With the helical protocol, mean DLP was 8.6 ± 2.2 mGy/cm (range, 5–27 mGy/cm) for thoracic CT and 27.1 ± 7.5 mGy/cm (range, 10–63 mGy/cm) for electrocardiographically gated cardiac CT. The mean total DLP for the helical protocol was 28.7 ± 9 mGy/cm, yielding a mean effective radiation dose of 1.49 mSv. With the prospective sequential protocol, the mean DLP was 8.9 ± 2.8 mGy/cm (range, 2–25 mGy/cm), yielding a mean effective radiation dose of 0.46 mSv.

DISCUSSION

In 100 consecutive patients with TOF, DSCT was perfectly accurate for detecting major coronary artery abnormalities by using surgical findings as the reference standard.

For many years, cardiac catheterization has been the reference standard for evaluating pediatric patients with

TABLE 1. Detection of coronary artery abnormalities by using dual-source multislice computed tomography in 100 infants and children with tetralogy of Fallot

Usual configuration: RCA, from right ostium (*) LCA, from left ostium (**) 69/100		LAD (♣) arising from RCA, crossing the RVOT; Cx: normal configuration 4/100
Variant of usual configuration: large conal branch (♠) from RCA 24/100		Single coronary artery from the right sinus, LAD (♠) crossing the RVOT 2/100
Accessory/dual LAD (♣) arising from RCA 0/100		Single coronary artery from the left sinus, RCA (♣) crossing RVOT anteriorly 1/100

RCA, Right coronary artery; LCA, left coronary artery; LAD, Left anterior descending coronary artery; RVOT, right ventricular outflow tract; Cx, circumflex artery. *Right ostium. **Left ostium.

congenital heart disease. In our institution thoracic and cardiac MSCT have been increasingly used since 2002. We used 4-, then 16-, and finally 64-slice MSCT before switching to 64-slice DSCT, the method used in the present study. Initially, pulmonary artery anatomy and systemic and pulmonary venous returns were evaluated on thoracic CT scans. Later, improvements in temporal resolution and the introduction of systolic reconstruction provided increasingly accurate images of the coronary arteries. Several studies described the appearance of the coronary arteries on chest or cardiac CT scans in infants and children.^{8,10,11} However, to the best of our knowledge, this is the first large case series study of patients with TOF who underwent surgical repair after echocardiography and DSCT without cardiac catheterization. We found 100% agreement between DSCT and surgical findings.

Coronary Anatomy Evaluation and Benefits

Major coronary artery abnormalities were found in 7 of our 100 patients. Similarly, earlier studies detected anomalous coronary arteries in 5% to 12% of patients with TOF.^{1,2,6} Coronary artery abnormalities might preclude performance

of the usual procedure for RVOT repair, and their preoperative detection is consequently crucial, particularly because damage to a coronary artery would compromise the viability of part of the myocardium.³ There are several surgical options for complete repair of TOF. Usual surgical repair includes patch infundibuloplasty with or without pulmonary arterioplasty. Although coronary anatomy is readily assessed at surgical intervention, the knowledge of an anatomic variant is relevant information for the surgeon to discuss surgical options and plan for the procedure.

In case of a branch crossing the RVOT, placement of an RV-PA conduit might be required to preserve the coronary vessel. In some patients alternate procedures include separate right ventricular and pulmonary artery patches or transatrial subpulmonary resection, avoiding the conduit while preserving the anomalous coronary vessel.^{4,5} In our institution complete repair is usually performed between 3 and 6 months of age. Depiction of an anomalous coronary disposition at preoperative evaluation for complete repair will modify the therapeutic approach: if present, the operation will be postponed for a few months because an anomalous coronary artery might require the use of an

FIGURE 1. Anomalous coronary artery in patients with tetralogy of Fallot. A 3-dimensional volume-rendering view shows the left anterior descending artery arising from the right coronary artery and anteriorly crossing the right ventricular outflow tract. Right coronary ostium (*), left anterior descending artery (↗). PT, Pulmonary trunk.

RV-PA conduit. Meanwhile, if required, a temporary Blalock-Taussig shunt is performed and planned more accurately based on the pulmonary artery morphology provided by means of preoperative DSCT, with either a right or left thoracotomy approach instead of sternotomy. Later, for complete repair, a larger tube will be used, if necessary, because the child has grown.

The presence of a conal branch must be indicated to the surgeon but rarely interferes with surgical intervention. Three-dimensional imaging provides the surgeon with valuable details about thoracic anatomy, the anatomic relations of the coronary arteries and RVOT, and the anatomy of the pulmonary arteries (Figure 2). Thus in our patients DSCT supplied important information about pulmonary artery morphology, aortic position, and the presence of major aortopulmonary collateral arteries, although this was not the focus of our study. Previous studies focusing on the pulmonary arteries showed that DSCT was accurate for detecting pulmonary artery abnormalities in pediatric patients with congenital heart defects.¹²

Radiation Exposure

The detection of coronary artery abnormalities requires electrocardiographically gated imaging. Despite several studies indicating that the coronary arteries were visible on non-gated acquisitions, image quality was significantly better with electrocardiographically gated spiral DSCT ($P < .001$).^{8,10} The main consequence is a higher radiation exposure caused by gated acquisition. Moreover,

FIGURE 2. Benefit of 3-dimensional imaging. Three-dimensional volume rendering produces virtual anatomic images that are very helpful for the preoperative assessment of the patient's anatomy. Ao, Aorta; PA, pulmonary artery. *Infundibular stenosis.

considerable variability in radiation exposure is observed, depending on technical parameters.^{13,14} Pediatric patients are highly sensitive to radiation, and patients with congenital heart defects might require multiple imaging studies to monitor their disease. Cardiac CT, especially in pediatric patients, must comply with the “as low as reasonably achievable” principle. Therefore low tube voltage (80 kV) must be used, and tube current must be adjusted to the patient's weight.^{8,15,16} Moreover, at 80 kV, intravenous contrast produces better vascular contrast than higher kilovoltage and therefore better delineation of the blood vessels.¹⁶

Prospective, electrocardiographically triggered, sequential cardiac CT significantly decreases radiation exposure by up to 83% compared with retrospective, electrocardiographically gated, helical CT.^{17,18} In our study the sequential protocol decreased radiation exposure by 70% compared with the helical protocol and required only half the dose of contrast medium (Table 2).

Role for DSCT

Although echocardiographic analysis remains the first step in the evaluation of patients with congenital heart defects, it might be limited to depict anomalous coronary arteries in patients with TOF. Thus, as mentioned earlier, in 3 of 7 cases, an anomalous coronary artery was missed by means of echocardiographic analysis. Also, in addition to noninvasive coronary evaluation, DSCT supplies valuable additional information on the anatomy of the heart and the morphology of the great vessels, especially the pulmonary arteries.

Cardiac CT has the important advantage of obviating the need for cardiac catheterization in patients with TOF. Major

TABLE 2. Comparison of radiation and iodine doses with the helical and sequential imaging protocols

	Helical (n = 42)			Sequential (n = 58)
Weight (kg)	7.5 ± 2.1			8.2 ± 2
	Nongated	Gated	Total	
DLP (mGy/cm)	8.6 ± 2.2 (5–27)	27.1 ± 7.5 (10–63)	28.7 ± 9	8.9 ± 2.8 (2–25)
mA	39 ± 3 (25–80)	71 ± 8 (48–104)	NA	62 ± 9 (30–120)
Effective dose (mSv)			1.49	0.46
IV contrast (mL)	11.8 ± 1.7	13.7 ± 2.4	22.5 ± 5	17.2 ± 2.6

DLP, Dose-length product; IV, intravenous.

coronary artery abnormalities might escape detection on standard 2-dimensional angiographic projections. In patients with TOF, coronary artery evaluation can be challenging because it might require several views of the RVOT, increasing radiation exposure.¹⁹ A study in adults found significantly greater radiation exposure from spiral 16-slice CT coronary angiographic analysis than from conventional diagnostic angiographic analysis (14.7 vs 5.6 mSv).²⁰ Comparison between published data on radiation exposure during angiographic analysis in children and MSCT sequential low-dose protocols enlightens the role of MSCT in those patients. The mean radiation dose to children undergoing diagnostic cardiac catheterization has been estimated at 3.71 mSv.²¹ In our study the mean effective radiation dose with the sequential protocol was only 0.46 mSv. Thus DSCT performed with a low-dose sequential protocol involves less radiation exposure than other methods for coronary artery evaluation.

Magnetic resonance imaging used for coronary artery evaluation has produced promising preliminary results in older children with Kawasaki disease. However, this imaging modality is not suitable for coronary artery evaluation in young pediatric patients, given its poor spatial resolution and long scan time.^{22,23} Magnetic resonance angiographic evaluation of coronary arteries in the youth is a work in progress, and the technique will improve soon. However, magnetic resonance imaging acquisition might not be as fast as MSCT examination, which provides complete cardiac and great vessels evaluation in less than 1 second and requires little or no sedation and a very limited radiation dose.

Limitations

Prospective, electrocardiographically triggered, sequential cardiac CT in adults is limited by high heart rates. With this protocol, stair-step artifacts increase with body weight and with heart rate variability, as opposed to absolute heart rate.²⁴ With DSCT, the high acquisition speed on DSCT allows the evaluation of spontaneously breathing infants with high heart rates because very few artifacts occur. Heart and coronary artery anatomy can be evaluated accurately despite noise, slight blurring, and stair-step artifacts. Agitation remains a limitation to DSCT. In contrast to

helical acquisition, sequential acquisition is not continuous. Instead, several sets of images are acquired successively, and the table is moved between sets. Movement of the child might produce a gap. Small gaps, known as stair-step artifacts, do not usually impair diagnostic accuracy (Figure 3), but larger gaps might require a new acquisition. In 5 of our patients imaged with the sequential protocol, the acquisition had to be repeated. Furthermore, in 5 additional patients we deliberately used the helical protocol because of mild agitation, suggesting a high risk of failure of sequential acquisition. Despite excellent correlation between MSCT findings and surgical results, the small number of coronary anomalies is definitely a weakness in regard to the 100% sensitivity and specificity of the study. Finally, DSCT requires the injection of iodinated contrast medium, a drawback shared by conventional angiographic analysis. However, none of our patients experienced adverse effects caused by the contrast medium injection.

CONCLUSIONS

DSCT is a noninvasive tool that is highly accurate for detecting coronary artery abnormalities in infants and young children with TOF. It provides 3-dimensional images that

FIGURE 3. Stair-step artifacts on sequential acquisitions. Three different acquisition sets (*) are seen with a decrease in contrast over time and slight stair-step artifacts that do not impair image analysis.

are extremely valuable to surgeons. The radiation dose is very low when a prospective, sequential, electrocardiographically triggered acquisition protocol is used. Although transthoracic echocardiographic analysis remains the first-line imaging modality for the preoperative evaluation of patients with TOF, cardiac catheterization is no longer required to assess coronary artery anatomy.

We acknowledge the excellent assistance and dedicated support for this project from all radiologic personnel at Centre Chirurgical Marie Lannelongue.

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