Application of helical computed tomographic angiography with differential color imaging three-dimensional reconstruction in the diagnosis of complicated congenital heart diseases

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Three-dimensional (3D) imaging technology, such as magnetic resonance imaging (MRI),^{1,2} helical computed tomography (CT),^{3,4} and electron-beam CT,⁵ has markedly progressed and allows 3D visualization of congenital heart anomalies from any angle of view and perspective.⁶ However, it is sometimes difficult to understand the accurate morphologic conditions, even with the 3D images, because the anomalous components are generally intricate and tortuous. To obtain more understandable 3D images, we have proposed the differential color-imaging technique of helical CT angiography⁷ by modifying the color-coded 3D reconstruction.⁸ After arteries and veins were carefully demarcated according to the shape, continuity, and CT density of sequential tomographic images, the 3D image of each component was displayed in red and blue. Here we report a summary of the helical CT angiography examination with 3D color coding and assess the safety, utility, reliability, and limitation of the helical CT examination.

Methods

Patients. Between April 1998 and March 2001, differential color-imaging 3D reconstruction was applied for 77 examinations in 66 patients (24 neonates, 22 infants, and 20 children; 38 male and 28 female patients). The study population included patients with pulmonary atresia (PA) with ventricular septal defect (VSD; n = 10), coarctation of the aorta (n = 8), hypoplastic left-heart syndrome (HLHS; n = 7), total anomalous pulmonary venous drainage (TAPVD; n = 7), tetralogy of Fallot (n = 7), peripheral pulmonary stenosis (n = 5), partial anomalous pulmonary venous drainage (n = 4), interruption of the aortic arch (IAA; n = 4), asplenia with pulmonary atresia (n = 3), and so on. The median age of the 66 patients was 3.0 months (range, 5 days-16 years).

Helical CT. Helical CT angiography (X Vigor Laudator, single scan detector, Toshiba) with a differential color-imaging technique was performed with an oral sedation of chloride hydrate for infants and young children or with a breath hold for older children. In 20 patients who were treated with mechanical ventilation because of heart failure, pulmonary congestion, or pulmonary hypertension (HLHS, n = 7; TAPVD, n = 7; pulmonary atresia with VSD, n = 4; IAA, n = 4), the CT examination was done during a short breath hold (approximately 15 to 20 seconds of the scanning time) using a muscle relaxant (vecuronium bromide, 1.0 mg/kg) and sedative (midazolam, 1.0 mg/kg). In these patients blood pressure of the radial artery, arterial oxygen saturation, and electrocardiographic results were carefully

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Figure 1. A and B, Helical CT angiography obtained by using conventional 3D reconstruction (A) and 3D color coding (B). C, Separation of the systemic and pulmonary arteries (red), pulmonary veins (blue), and systemic veins (green) on a tomographic image of the same patient. LSVc, Left superior vena cava; LPA, left pulmonary artery; PDA, patent ductus arteriosus; PV, pulmonary vein; VV, vertical vein; dAo, descending aorta.

monitored. Contrast medium (iopamidol, 61%) was diluted with an equal amount of saline solution and was intravenously administered at a dose of 2.0 mL/kg (300 mg of iodine per kilogram) and at a rate of approximately 1 mL/s. Fifteen to twenty-five seconds after the initial injection, neonates, infants, and small children were scanned with 2-mm collimation width and 2-mm second-table shift, and adolescents were scanned with 3-mm collimation width and 3-mm second-table shift. Electrocardiographic gating was not applied in this study.

After systemic and pulmonary arteries, veins, and bronchial components (if necessary) were manually demarcated on the basis of the shape, continuity, and CT density on sequential CT images (Figure 1, C), 3D images of each component were reconstructed with an image analyzer (Sun software, X-tension, Toshiba) with a reconstruction width of 0.7 mm. Arteries, systemic veins, and pulmonary veins were displayed in red, green, and blue, respectively.

Results

Reconstruction of color images. All the helical CT examinations were safely accomplished in approximately 15 (neonate) to 40 (adolescent) seconds of scanning time. No circulatory or respiratory collapse was noted during the examination, even in patients with congestive heart failure or pulmonary congestion. The total number of images manually traced was approximately 30 in neonates and 50 in adolescents. Figure 1, A and B, show 3D images of helical CT angiography obtained by means of the conventional reconstruction simply determined by the CT density (Figure 1, A) and postprocessed by the differential color-imaging technique with manual tracing (Figure 1, B). The diagnosis of the neonatal patient is right isomerism heart, double-inlet right dominant ventricle, and infracardiac-type TAPVD.

Figure 2. A and B, A neonate with HLHS from the anterior (A) and right posterior (B) view. Arrows indicate ascending aorta. C and D, An infant with supracardiac-type TAPVD of the anterior (C) and posterior (D) views. Arrows indicate stenosis of the vertical vein. SVC, Superior vena cava; Ao, aorta; PA, pulmonary artery; PDA, patent ductus arteriosus; dAo, descending aorta; rPV, right pulmonary vein; Ao, aorta; lPV, left pulmonary vein; INV, innominate vein.

After the manual tracing and color coding (Figure 1, B), the image became more understandable.

Representative images. Figure 2, A and B, shows images of a 5-day-old neonate with HLHS. The spatial relationship of the hypoplastic ascending aorta (arrows in Figure 2, A and B), the pulmonary artery, the patent ductus arteriosus, and the superior vena cava was clearly visualized. Figure 2, C and D, show a 1-month-old infant with

Figure 3. A and B, An infant with PA with VSD accompanying MAPCA from the posterior (A) and right posterolateral view (B). Arrows indicate aortopulmonary collateral arteries. C-E, Helical CT bronchograms (C, anterior view; D and E, transverse section). The left upper bronchus (arrow in C) was compressed by one of the major collateral arteries (arrows in D and E). dAo, Descending aorta; CPV, common pulmonary vein.

supracardiac-type TAVD. As shown in Figure 2, D, the 4 pulmonary veins joined to form a vertical vein that runs across the left pulmonary artery and drains into the innominate vein. A severe stenosis (arrows in Figure 2, C and D) was found where the vertical vein passes across the dilated left pulmonary artery. Figure 3, A and B, show CT angiograms of a 1-month-old infant with PA with VSD accompanying major aortopulmonary collateral arteries (MAPCAs). Most of the pulmonary flow was supplied with 4 MAPCAs (arrows in Figure 3, A and B). The origin and direction of the MAPCAs were clearly identified. The helical CT bronchograms were also reconstructed from the same volumetric data (Figure 3, C-E). The left upper bronchus (arrow in Figure 3, C) was severely compressed by one of the major collateral arteries (arrows in Figure 3, D and E).

In 11 of the 20 patients who had been treated with mechanical ventilation, the arterial blood gas and blood pressure data were analyzed to ensure the safety of the short breath hold. There were no significant differences in Pao_2 (40.0 ± 5.2 vs 41.8 ± 7.3 mm Hg), $Paco_2$, (46.8 ± 9.5 vs 46.8 ± 9.0 mm Hg), pH (7.422 ± 0.055 vs 7.422 ± 0.047), and blood pressure (60.7 ± 11.4 vs 59.4 ± 11.3 mm Hg)

before and after the CT examination ($P > .05$). We also compared the diameter of the anomalous blood vessels of the neonatal patients measured with the helical CT scan, and confirmed our findings by means of conventional angiography or retrograde radial arteriography. There was a good correlation in the diameter of the MAPCA ($y = 0.918x + 0.501$, $r = 0.897$, $P < .001$, $n = 10$) in VSD with PA and in vertical veins ($y = 1.102x - 0.214$, $r = 0.984$, $P < 0.01$, $n = 5$) in TAPVD and the ascending ($y = 0.958x - 0.835$, $r = 0.94$, $P < .01$, $n = 7$) and descending aorta in HLHS or IAA ($y = 0.829x + 0.681$, $r = 0.933$, $P < .01$, $n = 7$).

Discussion

Helical CT angiography, in combination with differential color 3D reconstruction, provides high-resolution and high-contrast images and provides reliable diagnosis and measurement in various kinds of complicated congenital heart diseases. These color 3D images are very informative not only for the precise anatomic diagnosis but also for planning a successful cardiovascular operation.^{7,9,10}

Advantages. Helical CT angiography can be safely done within approximately 15 to 40 seconds of acquisition time by administering minimum contrast medium through the peripheral veins. No case of circulatory or respiratory collapse was noted, even in the neonates with congestive heart failure or pulmonary congestion.

MRI has distinct advantages over helical CT imaging, which include no radiation exposure, excellent soft-tissue contrast, and visualization of an intracardiac anomaly. MRI technology also allows accurate quantification of volumes and mass of cardiac chambers, regurgitation volumes, and regional ventricular function.^{11,12} However, mechanical ventilation, electrocardiographic monitoring equipment, or infusion pumps are problematic in the strong magnetic field. In combination with Doppler echocardiography, we have been using helical CT angiography as a noninvasive and reliable examination, especially for neonates and infants with mechanical ventilation.

Limitations. Color coding of the helical CT angiogram has several limitations. It takes approximately 1 hour to accomplish the 3D reconstruction for expert radiology technicians because the manual demarcation of arteries and veins is essential to obtain reliable images. This problem could be resolved by improvement of the computer software. The helical CT scanners, especially single-detector-row scanners, are not currently suitable for neonates and infants, whose heartbeats are usually faster than 120 beats/min.

Future perspective. Recently, multiple-detector-row helical CT equipment has been devised.^{13,14} This CT scan will be used for the intracardiac anomalies and evaluation of the cardiac functions in association with the electrocardiographically and respiratory gated mode. In the near future, the volume data sets obtained by the multiple-detector-row

helical CT, as well as magnetic resonance angiography, could work for noninvasive evaluation of cardiac function, such as ejection fraction, valvular regurgitation, and shunt ratio in congenital heart disease. These noninvasive examinations perhaps alternate the conventional and invasive angiography in children.

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