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Original Article

Three-dimensional computed tomography in children with compression of the central airways complicating congenital heart disease

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Abstract *Purpose:* We investigated the quality and usefulness of spiral computed tomography and three-dimensional reconstruction in children with obstruction of the central airways as a complication of congenital heart disease. *Materials and methods:* Spiral computed tomography with three-dimensional reconstruction was performed in 49 children with obstruction of the central airways seen as a complication of congenital heart disease. Spiral scanning was performed during breathing in 40, and after sedation with chloral hydrate in 38. Contrast medium was administered through a pedal venous route in 42. We analyzed the motion artifact, additional information provided by, and clinical usefulness, of the three-dimensional images. We also investigated the factors influencing the quality of the images. *Results:* Stenoses were seen in the trachea in 21 patients, and in bronchuses in 28. Their causes were an anomaly of the aortic arch in 6, posterior displacement of the aortic arch in 7, posterior displacement of the ascending aorta in 5, compression of the brachiocephalic artery in 5, absent pulmonary valve syndrome in 6, displaced or dilated cardiovascular structure in 17, and pulmonary arterial sling in 2. Motion artifact caused mild or negligible degradation of images in all patients except 6. Breath-holding in non-sedated children produced more severe motion artifact than did cardiovascular pulsation. Three-dimensional images provided additional information over two-dimensional images in 11, and provided clinically useful information in 10. Contrast injection via the pedal route was better for the quality of three-dimensional images than brachiocephalic injection ($p = 0.013$). *Conclusions:* Three-dimensional computed tomography is useful in evaluation of obstruction of the central airways in children with congenital heart disease. Despite the fact that motion artifact is unavoidable, the quality of three-dimensional images is acceptable for making a proper and accurate diagnosis. A pedal route is recommended for injection of contrast medium.

Keywords: Heart, diseases, congenital; trachea, stenosis or compression; bronchus, stenosis or compression; computed tomography, three-dimensional

OBSTRUCTION OF THE MAJOR AIRWAYS, including the trachea and proximal bronchuses, may complicate the natural and surgical course of children with congenital heart disease. The obstruction produced by an anomalous or dilated cardiovascular structure does not always cause significant symptoms. Even if the stenosis produced by compression is mild, causing only subclinical symptoms, its recognition is important because the pre-existing subclinical stenosis may become clinically apparent subsequent to respiratory infection or associated peri-operative problems. It can thus result in unexpected respiratory deterioration, or prevent weaning from ventilation.

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Though spiral computed tomography offers a faster scanning than conventional computed tomography, it seems too slow to image a rapidly moving cardiovascular structure in the uncooperative child who cannot hold breath. And spiral computed tomography using the transverse cross-sectional images has its limitations in the difficult mental reconstruction needed for complex mediastinal structures, and inaccurate measurement of the horizontally or obliquely oriented structures such as the main bronchuses. Three-dimensional imaging using the volumetric data of spiral computed tomography has generally been accepted as a good complement for the cross-sectional computed tomographic images.[1–7] But spiral computed tomography with subsequent three-dimensional imaging has not been widely used in children with congenital heart disease associated with major airway obstruction. And its quality and clinical usefulness has not been fully studied except a few case reports.[8–12] We have now applied spiral computed tomography and obtained diagnostic three-dimensional images in a series of children with obstruction of the major airways. We analyzed the motion artifact and the clinical usefulness of the three-dimensional images. We report on our experience, and discuss some of the technical aspects.

Materials and methods

We studied 49 consecutive children with congenital heart disease in whom obstruction of the major airways was proven by spiral computed tomography with three-dimensional reconstruction. There were 27 boys and 22 girls. The ages ranged from 10 days to 25 years, with a median age of 9 months. Of the patients, 30 (61%) were neonates or infants. The body weight ranged from 2.8 to 30 kg, with a median weight of 7.5 kg. The underlying malformation was tetralogy of Fallot with or without pulmonary atresia in 18, congenitally corrected transposition in 6, complete transposition in 2, double outlet right ventricle in 5, ventricular septal defect in 5, patency of the arterial duct in 2, coarctation of the aorta in 3, and other miscellaneous lesions in 8 patients. As an additional diagnostic test, bronchoscopy was performed in 5, and barium esophagography in 5.

We studied 38 patients under sedation with oral administration of 60–80 mg/kg of chloral hydrate, and 4 patients were anesthetized. When the patient was resistant to sedation, 0.1 mg/kg of midazolam (Roche, Swiss) was injected intravenously up to three times. The remaining 7 patients were studied without sedation or anesthesia. Computed tomography was performed with Somatom Plus 4 spiral computed tomography unit (Siemens, Erlangen, Germany) by using 140 kV, 129 mA and 512 × 512 matrix. The scanning time ranged from 22 to 40 seconds. The scanning was performed with breath-holding in 5, and without breath-holding in 40. To prolong the period of breath-holding, or to induce quiet respiration, oxygen was supplied through a facial mask or nasal prong prior to and during the scanning. In 4 intubated patients, ventilation was temporarily stopped during the scanning, the patient being hyperventilated with oxygen before and after the scanning. Collimation width was selected as thin as possible, ranging from 1 to 3 mm. Pitch was selected from 1 to 2 to cover a desirable scan range that was usually the upper two-thirds of the thorax.

For vascular enhancement, we injected non-ionic contrast medium (Ultravist 370; Schering, Germany) at an average rate of 0.075 ml/sec/kg. A pedal route was used for injection of contrast medium in all except 7 patients. The scan delay after initiation of injection of the contrast medium was 15–25 seconds for pedal injection, and 10–18 seconds for brachiocephalic injection. For three-dimensional reconstruction, axial images were reformatted with overlapping of 20–50% of section thickness. Image reconstruction was performed on a Magic View or Prominence workstation (Siemens, Germany). For the airway, we utilized minimum intensity projection, shaded surface display, and curved planar reformation. For the contrast-enhanced vessels, we utilized shaded surface display, curved or oblique multiplanar reformation, and maximum intensity projection. Shaded surface displays of the airway was generated by setting double thresholds with the upper threshold of −300 Hounsfield unit and the lower threshold of −800 Hounsfield unit. Shaded surface display images of the contrast-enhanced vessels were generated by setting a single lower threshold at 170 ~ 220 Hounsfield unit. The Prominence workstation allowed generation of color-coded shaded surface display images for both airways and vessels. Additional time required for three-dimensional imaging process was about 10 to 40 minutes for each patient. All three-dimensional images of the airway and cardiovascular structures were reviewed by two cardiac radiologists to assess their diagnostic value and motion artifact. The clinical usefulness was retrospectively reviewed by one pediatric cardiologist and one cardiac surgeon in terms of whether spiral computed tomography with three-dimensional reconstruction modified management and/or surgical options.

Results

The causes and the sites of stenosis of the central airways are summarized in Table 1. Compression was present in the trachea in 21, the left main bronchus in 19, right main bronchus in 4, both main

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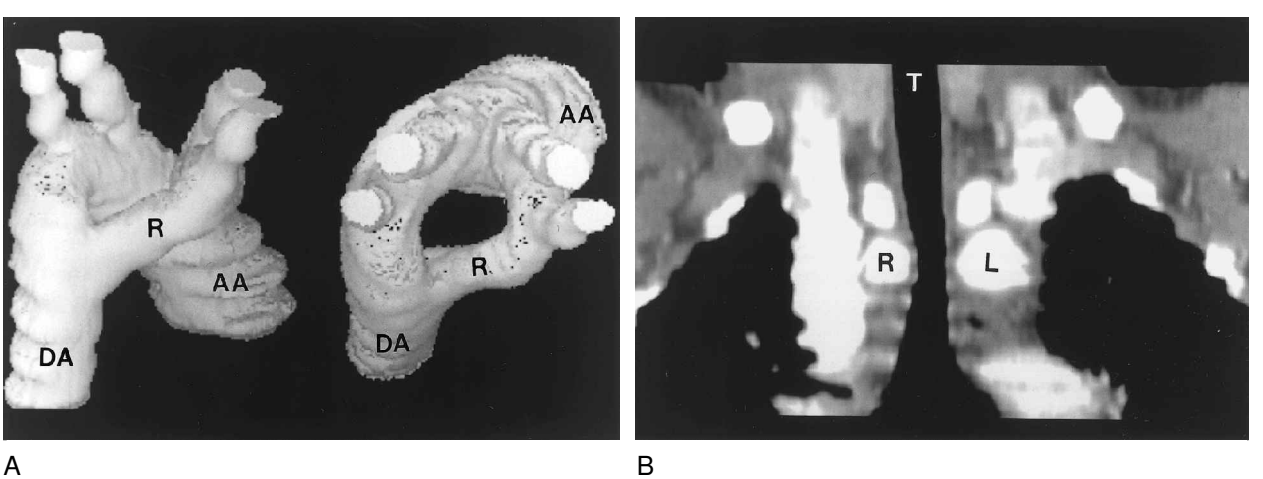
bronchuses in 2, and in the right intermediate bronchus in 3. The tracheal stenosis was focal in 18 and diffuse in 3, including 1 patient with complete tracheal rings. Anomalies of the aortic arch caused the focal stenosis of the trachea in 6 patients, including 3 patients with a double aortic arch (Fig. 1). Posterior displacement of the aortic arch also caused tracheal compression in association with corrected transposition in 6 patients (Fig. 2), and pulmonary atresia in 1. Bronchial stenosis was focal in 19 and diffuse in 9. It was produced by posterior displacement of the ascending aorta (Fig. 3), absent pulmonary valve syndrome (Fig. 4), displaced or dilated pulmonary arteries, and the pulmonary arterial sling (Fig. 5). In cases of compression due to a displaced or dilated cardiovascular structure which was otherwise normally formed, the compression was against the descending aorta in 9, the vertebral body in 21, and both in 5. Surgical interventions to alleviate the stenosis were performed in 25 patients in whom the problem was clinically significant. These involved aortopexy in 5, pulmonary arteriopexy in 2, pulmonary arterial aneurysmorrhaphy in 5, transposition of one pulmonary artery in 2, division of an anomalous vessel in 5, thymectomy in 3, the Lecompte maneuver in 1, and lobectomy in 2.

Table 1. The causes and sites of central airway stenosis.

Cause of central airway stenosis	Site of stenosis	n
Posterior displacement of ascending aorta	Bronchus	5
Posterior displacement of aortic arch	Trachea	7
Compression of brachiocephalic artery	Trachea	5
Aortic arch anomaly	Trachea	6
Absent pulmonary valve syndrome	Bronchus	6
Displaced or dilated cardiovascular structure	Bronchus	17
Pulmonary arterial sling	Trachea	2
Complete tracheal ring with horse-shoe lung	Trachea	1
Total		49

Motion artifact was seen in 38 patients, being negligible in 11. Despite some degradation by motion artifact, the quality of the three-dimensional images was acceptable for making the diagnosis of obstruction in all but 6 patients in whom the artifact was severe. In 4 of 5 patients who were studied holding their breath without sedation, the three-dimensional images showed severe motion artifact caused by cardiovascular pulsation (Fig. 6). In 3 patients, inadequate contrast enhancement resulted in a "moth-eaten" appearance of the vascular surface. In 5 of 7 patients in whom contrast medium was injected through a brachiocephalic vein, dense contrast medium in the superior caval vein produced streak artifacts that degraded the quality of the three-dimensional images. Three-dimensional images facilitated perception of the severity and extent of the stenosis in 11 patients, or provided easy understanding for complex anatomy. It significantly modified the management, and influenced the surgical options, in 10 patients. In some patients, the cardiac surgeon attended the workstation room and planned



A B

Figure 1.
Four-year-old boy with double aortic arch. ***A:*** *Posterior and superior views of shaded surface display image showing both aortic arches connecting the ascending (AA) and descending (DA) aorta. Common carotid and subclavian arteries arise from each aortic arch. The right aortic arch (R) is non-dominant and is posteriorly located.* ***B:*** *On coronal reformatted image, the trachea (T) is mildly compressed by the vascular ring of double aortic arch. The right aortic arch (R) is smaller than the left aortic arch (L).*

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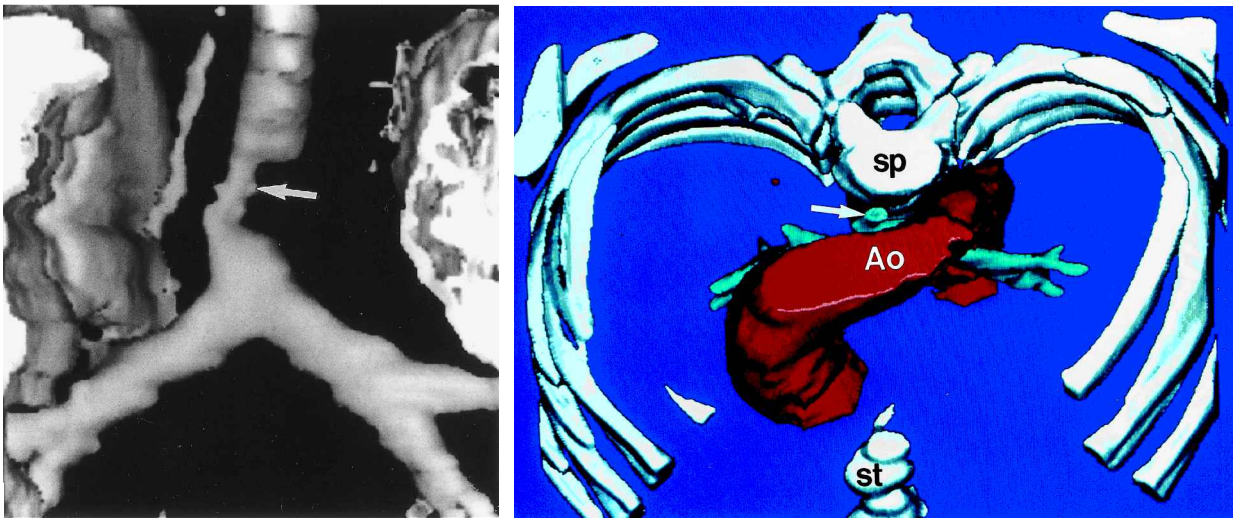

Figure 2.
One-year-old boy with congenitally corrected transposition and pulmonary atresia who had been admitted frequently due to repeated pneumonia. ***A:*** *Shaded surface display image shows severe eccentric segmental narrowing of the distal trachea (arrow).* ***B:*** *Color-coded shaded surface display image viewed from above demonstrates that the trachea (arrow) is compressed between the posteriorly positioned aortic arch (Ao) and the spine (sp). The aortic arch is far away from the sternum (st).*

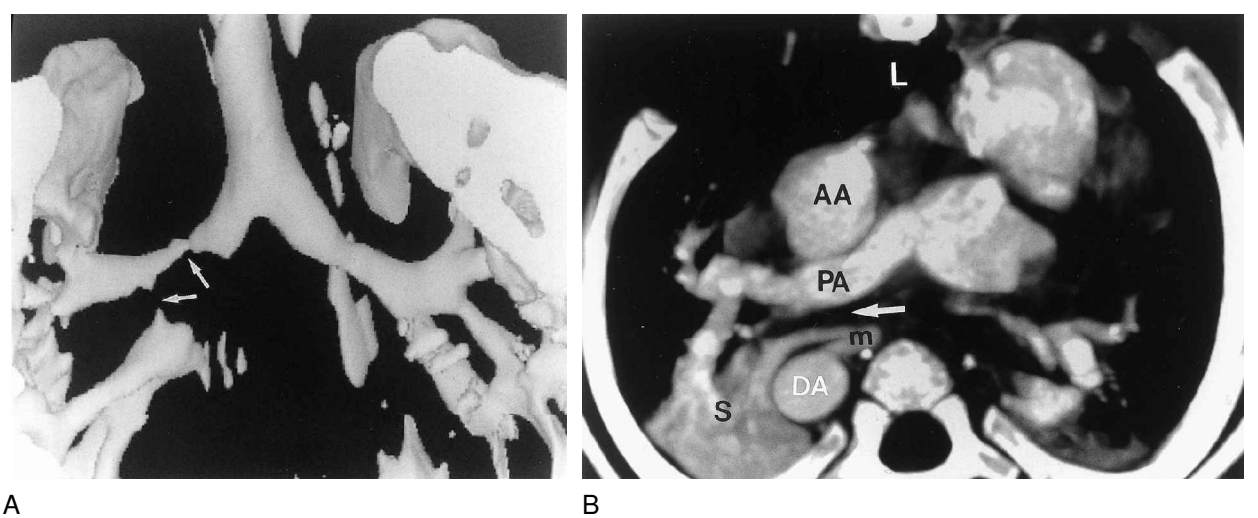

Figure 3.
Three-month-old boy with tetralogy and pulmonary atresia. He was dependant on mechanical ventilation for more than a month after total correction. ***A:*** *Shaded surface display image of airway reveals severe stenosis and occlusion of the right main bronchus and intermediate bronchus (arrows).* ***B:*** *The junction of the right main and intermediate bronchuses shows the obliterated lumen along its medial wall. Axial maximum intensity projection image reveals that these airways (arrow) are positioned in the narrow space between the posteriorly positioned ascending aorta (AA) and right pulmonary artery (PA) anteriorly, and a major aortopulmonary collateral artery (m) and the descending aorta (DA) posteriorly. The right middle lobe (L) is herniated through the anterior mediastinum in front of the ascending aorta and the superior segment (S) of the right lower lung is collapsed.*

the surgical method using interactive rotation of the three-dimensional image on the monitor.

Discussion

Various diagnostic modalities have been used for evaluation of obstructed airways in patients with congenital heart disease. They include high-kilovoltage chest radiography, barium esophagography, bronchography, echocardiography, angiography, computed tomography and magnetic resonance imaging. Magnetic resonance imaging has a number of advantages over spiral computed tomography in the evaluation of congenital heart defects without

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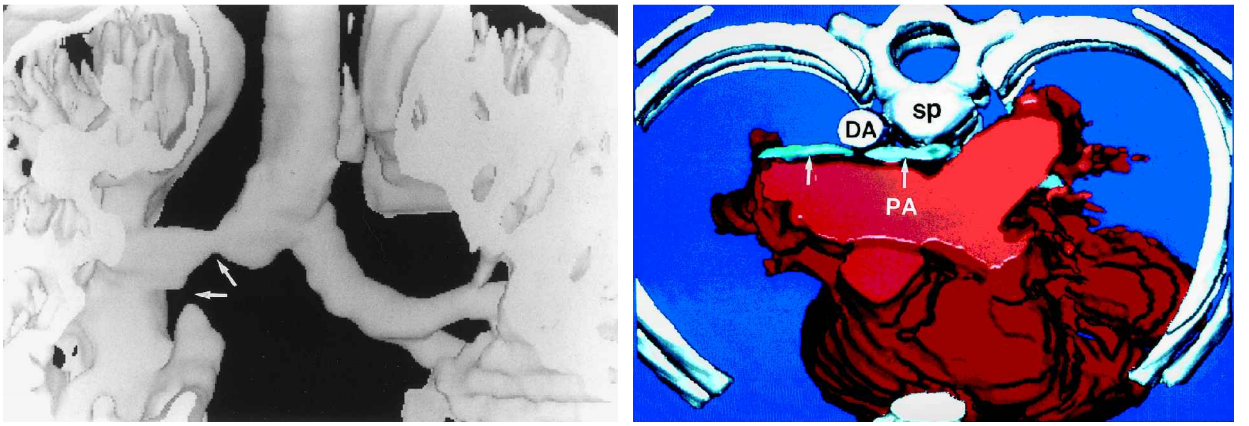

Figure 4.
Seven-month-old girl with tetralogy of Fallot and absent pulmonary valve syndrome complicating frequent respiratory infection. ***A:*** *Shaded surface display image of the airway shows severe steno-occlusion of the right main bronchus and intermediate bronchus (arrows).* ***B:*** *Color-coded shaded surface display image seen from above demonstrates that the airway (arrows) is compressed between the aneurysmally dilated pulmonary artery (PA) anteriorly and the descending aorta (DA) and spine (sp) posteriorly.*

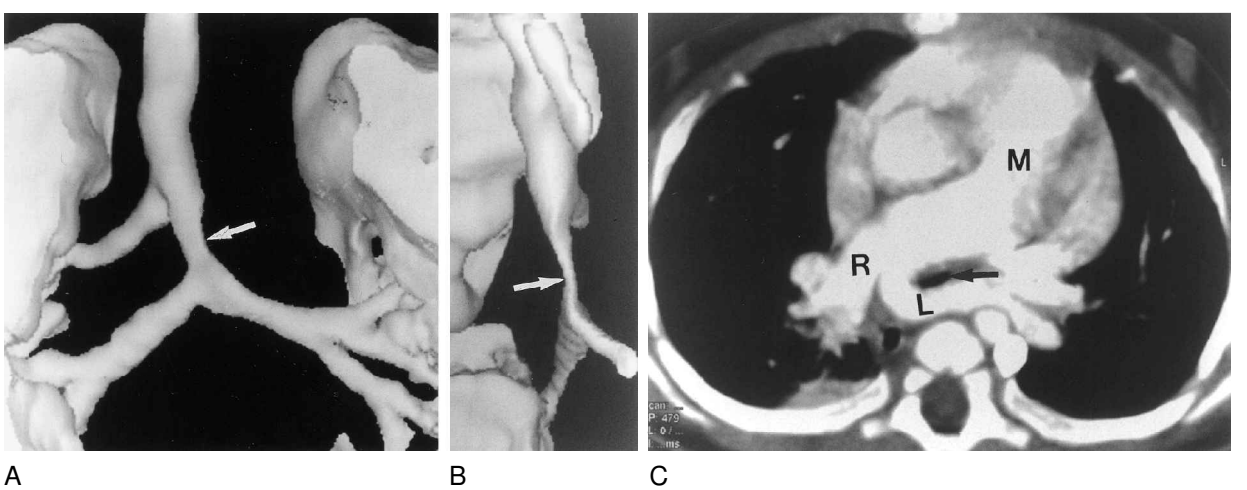

Figure 5.
Four-month-old girl with isolated pulmonary arterial sling. ***A:*** *Shaded surface display image of the airway shows a tracheal bronchus and low-lying carina. The distal trachea shows focal stenosis (arrow).* ***B:*** *Shaded surface display image viewed from the left shows that the tracheal stenosis is more severe in anteroposterior direction (arrow).* ***C:*** *Axial maximum intensity projection images show main (M), right (R), and left (L) pulmonary arteries. The trachea (arrow) is sandwiched between the pulmonary trunk and the abnormal left pulmonary artery.*

employing ionizing radiation or exogenous contrast materials. And it allows cardiac and/or respiratory gating, which may reduce the artifacts caused by respiration and cardiac pulsation. Spiral computed tomography with three-dimensional reconstruction is considered as an accurate method for evaluation of diseased airway in adults.[1–7] Its use in children with obstructed airways complicating congenital heart disease, however, is limited. This is probably related to the significant motion artifact produced by respiration and cardiac pulsation. The present study, however, shows that the quality of the three-dimensional images of the major airway was good enough for appropriate evaluation in most cases. This is primarily related to the anatomic location of the trachea and proximal bronchuses. As they are located posteriorly in the thorax near the spine, they move, on respiration, much less than do the structures that are close to the anterior chest wall or the diaphragm. The acceptable quality of images in our study is also related to administration of oxygen that reduces respiratory effort, along with adequate contrast enhancement and selection of the appropriate scan parameter.

As the sedated patient can move at the time of injection of contrast medium, and the whole study

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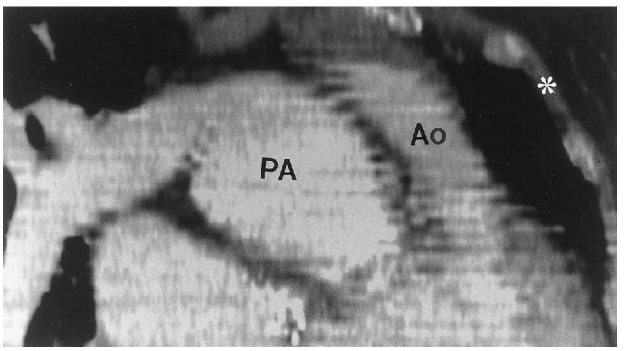

Figure 6.
Obliquely reformatted image showing severe motion artifact by cardiovascular pulsation. It was obtained from a nonsedated patient who underwent spiral scanning with breath hold. The ascending aorta (Ao) and the pulmonary trunk (PA) show severe motion artifact. Note the smooth margin of the chest wall (*), which suggests that respiratory motion artifact was avoided with breath-holding.

can thus be jeopardized, it is important to test the depth of sedation with a bolus injection of saline prior to injection of contrast medium. If the child moved subsequent to injection of saline, we administered a supplementary intravenous sedative. For administration of a contrast medium, we recommend the pedal venous route. When a brachial or cephalic route is used, the superior caval vein is filled with dense contrast medium that produces streaky artifact on the central airway or other vessels within the superior mediastinum. Because the contrast medium is still being infused after the start of scanning, the modified method using the contrast injection followed by injection of saline also gives a streaky artifact.

Meticulously reconstructed three-dimensional images facilitate easy understanding of the nature and severity of the pathology. This is especially true in the evaluation of the bronchial tree, because it has oblique courses and branches, which makes difficult mental reconstruction of the overall arrangement. This technique also facilitates communication with the physicians and surgeons who are not familiar with axial computed tomographic images. It is also extremely helpful in surgical planning, because it provides better spatial orientation and simulation of the surgical view, along with cutting of the structures on the path of the designed surgical procedure. There are certain pitfalls and limitation of spiral computed tomography with three-dimensional reconstruction. As the dimension of the airway is dependent on the window setting and threshold level,[4,12] it is potentially inaccurate when determining the severity of stenosis. To avoid this pitfall, we used the upper threshold level, which is a determinant of the size of an airway, as −300 Hounsfield unit according to the study of Zeiberg et al.[1] using the phantom of sizable air-column. Another limitation of spiral computed tomography is its inability to demonstrate the dynamic change in dimensions of the airways on respiration, or pulsation in the adjacent vessel. As computed tomography offers a composite image, some dynamic component of the obstruction may be missed according to the scanned phase. This limitation may be overcome by bronchoscopy.[13]

In conclusion, spiral computed tomography with three-dimensional reconstruction is useful when evaluating obstruction of the central airways in children with congenital heart disease. Despite the fact that motion artifact by respiration and cardiac pulsation is unavoidable, the quality of three-dimensional images is acceptable for making proper and accurate diagnoses. Quality of images can be improved with adequate sedation and inhalation of oxygen. A pedal route is recommended for injection of contrast medium.

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