HRCT in children: technique and indications

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Abstract High-resolution computed tomography (HRCT) is a very important diagnostic tool, which improves our understanding of many lung diseases in children. However, the technique requires great care in managing the child and attention in using the lowest radiation dose possible. HRCT provides important diagnostic information on pediatric lung disorders for both airway and interstitial lung diseases. In this review we describe in detail the most appropriate technique to be used on children including patient preparation and sedation, discuss indications, and analyze the HRCT appearance of a variety of diseases.

Keywords High-resolution computed tomography · Children · Lung · Technique

Introduction

There is limited experience with high-resolution computed tomography (HRCT) in children, [1–3] and chest radiography remains a very important first step in the evaluation of pediatric lung disease. However, HRCT is being increasingly used to investigate a variety of disorders such as large and small airways disease and diffuse interstitial lung disease. HRCT of the chest is a technique capable of imaging the lung with excellent spatial resolution and with precise anatomic detail. It is more sensitive in detecting abnormalities, providing better information and a more accurate differentiation between different pathologies, than the chest radiograph and conventional CT (Figs. 1, 2). HRCT is more sensitive in differentiating between normal and abnormal lung parenchyma. It can also characterize diseases into interstitial, airway, and airspace processes [4, 5]. All these reasons explain the increasing use of this technique in the investigation and evaluation of many pediatric lung disorders.

Technical considerations

When using HRCT routinely in the evaluation of pediatric lung disorders, it is mandatory to minimize the potential side effects to the child. This is extremely important for extending the indications of HRCT in children so that they can benefit from the excellent diagnostic information it provides. Advances in CT technology have resulted in faster scan acquisition times, thus enabling images of sufficient diagnostic quality to be obtained in children during quiet respiration. The new scanners are remarkably silent when compared with the previous generation of scanners. For this reason, children are not usually frightened and remain quiet. This in itself reduces the need for sedation and improves image quality. In most cases lung HRCT can be performed without sedation and with protocols that deliver very little radiation to the patient. Needless to say, the use of careful CT techniques is extremely important in children [5–7].
Preparing for the CT examination

Careful planning of the CT examination can prevent difficulties during the study and minimize the number of unanswered questions. It is mandatory to check both the patient’s clinical records and all available prior imaging studies before performing a CT scan. This helps in deciding whether the indications for the study are correct and also allows the examination to be tailored to the specific requirements of the patient. This is particularly important with regard to the need for sedation. The radiologist should explain all aspects of the procedure and the objectives of the study to the parents before obtaining parental consent.

Optimal team and environment requirements

The optimal team for performing pediatric CT should include a pediatric radiologist, a technician, and a nurse trained in pediatric care. It is important to ensure a good environment for pediatric patients in the scanning area and every effort should be taken to create a friendly atmosphere that minimizes anxiety. Silence, soft lighting, toys, the presence of a relative, and a room decorated with children in mind all help. It is also essential to have immediate access to a resuscitation cart with appropriate drugs and equipment which are suitable for pediatric patients of all ages.

Fig. 1a, b Chest X-ray vs HRCT technique. A 10-year-old boy who had several episodes of pneumonia. a Chest X-ray is nearly normal, a questionable small density seems to be present in the right lung. b HRCT scan shows peribronchial thickening, bronchiectasis in middle and right lower lobe, loss of volume of these lobes, and areas of decreased attenuation consistent with small airway disease. HRCT provides more diagnostic information.

Fig. 2a, b Conventional CT technique vs HRCT technique. A 14-year-old girl with cystic fibrosis. a Conventional CT scan performed with 120 kVp and 180 mAs shows pulmonary vessels in all its length (10 mm-thick scan), blurring of peripheral structures, and poorly defined parenchyma structures. b On the HRCT scan performed with 120 kVp and 34 mAs, the lung parenchyma is better defined (bronchial wall, bronchial lumen, peripheral structures, fissures, pulmonary aeration etc.)
Fasting requirements

Usually no preparation is required when we perform an HRCT scan. We perform our studies on pediatric patients expecting not to use sedation. However, if sedation proves to be necessary, we rebook the patient. When children need sedation, we follow standard fasting requirements. In such cases the patients, parents, and nursing staff should be informed of fasting requirements before the day of the procedure. We adhere to the following fasting requirements: in newborns fasting is decided only after consultation with the neonatologist; infants receive nothing by mouth (NPO) for 3 h, children for 4 h, and adolescents for 6 h.

Immobilization and other practical tips

Adhesive bandages, blankets wrapped around the patient, or sandbags can be used to immobilize the patient. It is also recommended to wrap a lead apron around the regions adjacent to those to be scanned. This protects the child from scattered radiation and, at the same time, can help to immobilize the patient. Protective bismuth latex should be placed over girl’s breasts and over the thyroid gland in all children to minimize local radiation. All sorts of tricks can be used to keep the patient still. Toys hanging from the gantry can be used to attract the attention of the child and help to keep him or her quiet. To attract the child’s attention, we project cartoon movies of famous characters. Sometimes, we ring the gantry bell to attract the child’s attention and then during this time we take a section of image. It is also very helpful to offer the child a bottle of glucose water. Body temperature can be maintained by using a combination of warming lamps or heating blankets. This is especially important in infants.

Breath-holding information

In general, older children who can follow breath-holding commands are carefully instructed in breath-holding before the study. Children who cannot follow breath-holding commands (usually under 6 years of age) are examined under normal quiet respiration. In this age group, attempts at breath-holding usually result in examinations severely compromised by artifacts.

Sedation

The need for sedation should be decided upon by observing the behavior of the child once inside the gantry. Infants under 3 months of age can often be successfully imaged after normal feeding and swaddling. Sleep deprivation the night before the examination has no proven benefit in decreasing the number of sedation procedures and can be disruptive for the patient. In our institution, informed consent for sedation is covered by the standard consent for admission and CT scan examination. An important clue at reducing the aggressiveness of HRCT is to avoid anesthesia and use sedation as little as possible. We never use general anesthesia for HRCT in children and we have reduced the use of sedation to 2.4% in children under 6 years old, out of total sedation rate of 1%.

The introduction of faster and silent modern scanners has also been very helpful in reducing the need for sedation. With the old scanners our incidence of sedated patients was approximately 15%. Since we did not know in advance which patient would require sedation (and aspiration is a major clinical concern in sedated children), all our patients had to fast. However, with the extremely low incidence of sedation currently required for HRCT, we have changed our policy. Nowadays, none of our patients is kept NPO and those who, once in the gantry, behave poorly and require sedation are rescheduled. Since well-fed infants behave better than hungry ones, this policy will undoubtedly further reduce the 2.4% of patients needing sedation.

We use all sorts of tricks to keep nonsedated patients still. When all our methods fail, we reschedule the study, keep the patient NPO for 3, 4, and 6 h (depending on the age), and administer sedation before the examination. If sedation is required, we use oral chloral hydrate. This is used mainly in children under 18 months of age, but can also be used in older children. Chloral hydrate is administered at the dose of 50 mg/kg, with a maximum dosage of 2,000 mg. Children are given an initial dose of 50 mg/kg. If after 20–30 min the patient has not fallen asleep, a second dose of chloral hydrate [usually half the initial dose (25 mg/kg)] is given. In exceptional cases, we may go up to a total dose of 100 mg/kg. The onset of action is usually within 25–30 min and the duration of sedation is 30–40 min. Chloral hydrate has a bitter taste that children dislike and the use of sweeteners is not very helpful. Consequently, we always use undiluted chloral hydrate administered directly by syringe or with a nipple connected to the syringe. Patients 18 months of age and older are given intravenous sodium pentobarbital, 6 mg/kg to a maximum dose of 200 mg, diluted in 10 cc saline. The syringe containing the sedation must be appropriately labeled with the drug name. A dose of 2–3 mg/kg should be given initially as a slow bolus over 1–2 min. For most children, this dose is adequate and they will fall asleep within 4–5 min. If not, an additional dose of 2–3 mg/kg may be given. If the patient remains awake an additional dose of 2 mg/kg can be given some 30 min later, but this is rarely necessary. Pediatric sedation techniques have been extensively described in the literature [8–10].

Chloral hydrate is a successful sedative in 95–99% of children [9, 10] and has a very low incidence of side ef-
fants. Transient respiratory depression (oxygen desatura
tion 10% below baseline for more than 15 s) is the most
common complication during or after sedation (1% of
patients). Vomiting, irritability, and mild respiratory
difficulty as delayed complications are rare [8]. Children
with mental retardation, patients receiving chemotherapy
or antiseizure medication, and those habituated to seda-
tion are sometimes difficult to sedate [11].

Every child undergoing sedation in CT suites should
receive oxygen either by mask or nasal prongs to in-
crease pulmonary oxygen reserve (with the possible ex-
ception of neonates who are at risk for retinopathy of
prematurity). In such cases a neonatologist should be
consulted. Continuous monitoring of the vital signs must
be made during and after an examination when sedation
is used. This should include the monitoring of oxygen-
ation (by pulse oximetry), heart rate, respiratory rate, and
temperature. The alarm on the pulse oximeter is usually
set at 90% oxygen saturation, but any decrease below
95% should be investigated immediately. The majority
of cases of apparent desaturation are usually due to pa-
tient motion with loss of sensor contact and are quickly
corrected by repositioning the head and extending the
neck. A suction device and size-appropriate recovery
equipment must be on hand during each sedation proce-
dure. Children who have the following medical condi-
tions may not be appropriate candidates for sedation
by personnel who do not routinely deal with children:
craniofacial defects, obstructive adenotonsillar hyper-
plasia, acute respiratory infection, uncontrolled asthma,
and significant cardiopulmonary, neurologic, and hepato-
renal disorders that require special attention with respect
to cardiopulmonary monitoring and airway management.
Life-threatening airway obstruction or respiratory de-
pression with hypoxia can occur in these children [12].
When examining critically ill patients, we always require
the assistance of a pediatrician from the intensive care
unit.

All sedated patients are either discharged or moved to
the inpatient ward where the postanesthesia care unit dis-
charge criteria recommended by the American Academy
of Pediatrics should be observed [5, 13]. Cardiovascular
function and airway patency should be satisfactory and
stable, and protective reflexes should be checked. Par-
ents are instructed not to feed the children until their lev-
el of consciousness and motor function have returned to
pre sedation ranges. They should also be instructed not to
use the children’s car seat on their way home as the child
may fall asleep and the head fall forward, thereby ob-
structing the upper airway [14].

Other sedation regimes are practically never required
for HRCT. However, there have been some reports in the
literature on the use of oral pentobarbital sodium, with
claims that its rate of acceptance is better than that of
chloral hydrate [15]. However, we have no experience
with its use.

The HRCT technique involves the use of thin sections.
However, there is no precise definition of collimation
width which delineates a CT examination as high reso-
novation. Published protocols for HRCT examinations in
children vary from 1-mm to 1.5-mm slice thickness, 1-s
to 2-s acquisition time, 120–140 kVp, and 100–280 mA
[16, 17]. Murata et al. have shown that there is no diag-
nostic difference between the use of 1.5-mm and 3-mm
section thicknesses [18]. Since the radiation dose with a
1.0-mm section at 10-mm intervals is lower than 3-mm
scans at the same intervals, we recommended using the
thinner section [19]. In our institution we use 1.0-mm
collimation every 10-mm intervals.

The images must be reconstructed with a high-spatial
resolution algorithm when performing HRCT of the
lungs. The high-spatial frequency algorithm reduces im-
age smoothing and increase spatial resolution, making
the structures appear sharper. Mediastinal images have
poor quality with this technique, because low-contrast
structures (mediastinum) are affected more by noise than
high-contrast structures (lung). We reconstruct mediasti-
nal images with a low-spatial frequency algorithm to im-
prove their quality.

The smallest field of view (FOV) possible should be
used for every patient. Decreasing the FOV reduces pix-
el size and improves spatial resolution [20]. The pixel
size is 0.78 mm when we use a 512+512 matrix and a
40-cm FOV. With an FOV of 25 cm, pixel size decreases
to 0.49 mm, and for an 18-cm FOV, pixel size is further
reduced to 0.35 mm. For neonates and small infants we
recommend the use of an FOV of 15–18 cm, an FOV of
25 cm for larger infants, and 35–45 cm for older chil-
dren. The HRCT technique increases image noise. This
can be reduced by increasing the kilovolt peak or mil-
liamperes during the examination. Noise is inversely
proportional to the square root of the product of the mil-
liamperage and scan time [4]. Many authors recom-
manded a 120–140-kVp and 100–200-mAs technique for
HRCT in children [2, 16, 21]. On the contrary, diagnos-
tic scans can also be obtained when using significantly
lower milliamperage [22, 23].

In our institution, since 1995, we have used 50 mA
and 0.6 s (34 mAs) for cooperative children who are able
to follow breath-holding commands and 50 mA and 1 s
(50 mAs) for uncooperative children. We performed a
study comparing visualization of the vessels, bronchi,
and fissures and peripheral structure sharpness in scans
performed with 34 or 50 and 180 mAs keeping all the
other technical parameters constant. We found that there
were no differences in diagnostic image quality between
scans performed with 50 and 180 mAs. However, there
were small differences (consisting of slight blurring of
peripheral structures and fissures), which were apparent
in patients unable to follow breath-holding commands, there was an increased incidence of streak artifacts on the 34-mAs scans. The study demonstrated that HRCT performed with a 180- or 50-mAs technique produced similar quality images regardless of the child’s ability to cooperate. Good-quality images were obtained with the 34-mAs technique, but its use should be reserved for cooperative children [24, 25] (Fig. 3).

During the last 2 years we have reduced our milliampere values. Most patients are now studied with 25 mA and 1 s (Fig. 4). We have also tried to reduce the kilovolt peak as much as possible, without reducing the diagnostic quality of the image, especially in smaller children. Nowadays, with the better resolution provided by new scanners, we routinely use 90 kVp and 40 mAs in patients under the age of 14, and 120 kVp and 25 mAs in patients over the age of 14 years. Radiation dose is reduced to 47% by reducing the kilovolt peak from 120 to 90.

As children are more radiosensitive than adults and have a longer life span in which to manifest radiation-related disease, great care must be taken with the use of radiation. In children, the potential side effects of radiation exposure should always be kept in mind. We have also conducted a study in which we measured and compared radiation dose scans performed with 180 mAs vs 34 and 50 mAs. HRCT dose results were 5.4±1.6 mSv for 180 mAs, 1.5±0.5 mSv for 50 mAs, and 1.1±0.3 mSv for 34 mAs. As compared to the 180 mAs technique, the low-dose technique resulted in a dose reduction of 72% for 50 mAs and 80% for 34 mAs [25]. Mayo et al. [26] described that combining HRCT scans at 20-mm intervals with low-dose scans (40 mA) would result in an average skin dose comparable to that associated with chest radiography. With a properly performed HRCT examination, one can manage to study the lung with less radiation to the female breast than with conventional radiography.

In A-bomb survivors it has been predicted that the delivery of 1 Rad (0.01 Gy) of radiation to a woman’s breast before the age of 35 increases her risk of breast cancer by 13.6% over the expected spontaneous rate for the general population [27]. This is one of the reasons why we support the use of low-dose techniques for children. We also routinely protect the breasts of girls with thin layers of radiation-absorbent material such as bismuth-coated shields, which provide protection without affecting the diagnostic quality of the image [5, 28].

Fig. 3a, b HRCT technique vs low-dose HRCT technique. A 12-year-old boy with Langerhans’ cell histiocytosis with multiple cysts in both lungs. a HRCT scan performed with 120 kVp and 180 mAs. b HRCT scan performed with 120 kVp and 34 mAs. Image quality is similar with the two HRCT techniques and the information provided is diagnostic in both cases, but low-dose HRCT technique resulted in an 80% reduction in radiation dose.

Fig. 4 Protection from radiation during HRCT examination: bismuth-coated shield on the breast and neck (thyroid gland). A 2-month-old girl with bronchopulmonary dysplasia. HRCT of the lungs performed at 25 mAs, with placement of 1-mm-thick bismuth-coated latex shield over the child. Note there are no significant artifacts.
Over the last 3 years, we have used 1-mm-thick bismuth-coated latex shielding in girls examined with low-dose (50 mA) HRCT. In our experience this saves an average of 40% of radiation dose to the breast without affecting the quality of the CT image. We now routinely use a 1-mm-thick bismuth-coated latex shield over the breast and a 2-mm over the thyroid gland in all patients without adversely affecting the quality of the CT images. In neonates we use a 0.5-mm-thick bismuth-coated latex shield to avoid the existence of more artifacts caused by using a thicker shield (1 mm). The ideal lung CT scan image is the HRCT scan obtained with 90–120 kVp, 25 mAs, and using a 0.5-mm- or 1-mm-thick bismuth-coated shield over the breast (Fig. 4). Scout views should be spared in HRCT exams to minimize further the radiation exposure to the child. We start imaging at the pulmonary apex level and finish the examination at the diaphragmatic level.

There is no ideal window setting for demonstrating lung anatomy when photographing an HRCT study. In children under 8 years of age, the attenuation value of normal lung ranges from $-500$ to $-700$ HU and in those 8 years or older it is about $-800$ HU. In healthy adults it is between $-700$ and $-800$ HU. However, the precise window width and levels chosen are often a matter of personal preference. It is important that one lung window setting can be used consistently in all patients to develop an understanding of what appearances are normal and abnormal and to be able to compare cases or compare sequential examinations in the same patient. In general, level and width settings of approximately $-700/1,000$ HU are appropriate for a routine lung window. Window level/width settings of $50/350$ are the best for evaluating the mediastinum and hila [4]. The recommended scanning parameters for HRCT of the chest in children are shown in Table 1.

| Table 1 Recommended scanning parameters for HRCT of the chest in children |
|-----------------------------|------------------|
| Slice thickness | 1 mm |
| Interval      | 10 mm |
| Kilovolt peak     | 90 (under the age of 14 ) 120 (over the age of 14 ) |
| Milliamperage       | 40 (under the age of 14 ) 25 (over the age of 14 ) |
| Seconds          | 1 |
| Field of view     | 15–40 |
| Algorithm         | High-spatial frequency algorithm (use standard for mediastinum) |

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**HRCT special techniques**

To tailor the examination to diagnostic needs, the radiologist should know the patient’s clinical features and previous imaging findings. Furthermore, to obtain the greatest diagnostic information that HRCT can provide, the radiologist should directly supervise the study and decide whether focal chest CT or sampling chest CT should only be performed (minimizing radiation exposure to the patient) or whether additional or special slices (prone, lateral decubitus, expiratory, etc.) are required to improve diagnostic accuracy.

Focal chest CT

We recommend a focal chest technique for patients with known localized lung disorders. We perform 1-mm slices at 10-mm intervals through the abnormal area of the lung. In general, the rest of the lung should not be scanned in patients with known localized disease whose clinical symptoms and/or chest radiographs do not suggest progression to other lobes. The focused scan is used in the follow-up of localized bronchiectasis, right middle lobe syndrome, cystic emphysema, cavitated pneumonia, and some pulmonary malformations not considered tributary of surgical treatment (Fig. 5). In many of these cases, three or four low-dose HRCT slices will provide more information with a similar radiation dose than PA and lateral chest radiographs. As mentioned earlier, we always try to skip the scout view to save on radiation exposure, but sometimes we may use it especially when we reduce the examination to only two or three slices. When examining the upper lobes, we start the study at the level of the clavicles and stop at the inferior border of the abnormal lobe. When examining the right middle lobe, lingula, and both

**Table 1** Recommended scanning parameters for HRCT of the chest in children

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Slice thickness</td>
<td>1 mm</td>
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<td>Interval</td>
<td>10 mm</td>
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<tr>
<td>Kilovolt peak</td>
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<td>Seconds</td>
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<td>Field of view</td>
<td>15–40</td>
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<tr>
<td>Algorithm</td>
<td>High-spatial frequency algorithm (use standard for mediastinum)</td>
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**Fig. 5** Focal chest HRCT technique. A 7-year-old boy with asthma and a persistent consolidation in the right middle lobe. Follow-up HRCT scan shows a consolidation in the right middle lobe and a bilateral mosaic pattern. The focal chest CT technique involved scanning from the carina to the diaphragm to monitor the persistent lung consolidation.
lower lobes, we start the study midway between the sternal manubrium and the xiphoid (level of the carina) and stop at the level of the diaphragm [24, 25].

Sampling chest CT

The sampling chest technique is one that can be used for studying known generalized lung disorders. We performed the examination with 1-mm slices at 20-mm intervals. This is particularly useful in the follow-up of patients with chronic lung disorders who require repeated examinations, since the radiation dose is halved with this technique without losing diagnostic information [24, 25]. The main indication for a sampling scan is in the follow-up of patients with cystic fibrosis, bronchopulmonary dysplasia, Langerhans’ cell histiocytosis, alveolar proteinosis, and interstitial pneumonia (Figs. 3, 6).

In our experience, the use of both “focal” and “sampling” techniques has increased over the last few years, particularly when examining female patients with chronic lung disorders. These techniques permit a reduction in radiation exposure to the breast and provide reliable diagnostic information. We only obtain AP or PA views if radiographs are still required in this group of patients. The lateral projection is not routinely performed.

Expiratory slices, lateral decubitus and prone views

Expiratory slices are extremely helpful when examining patients suspected of having airway abnormalities. They can also be helpful in patients with a history of repeated pulmonary infections who are found to have a normal or questionable inspiratory CT scan [29] (Fig. 7). They are also useful when an inspiratory CT scan demonstrates a mosaic pattern with visible differences in lung attenuation. In children a mosaic pattern is almost always due to small airway disease with obstruction, as children do not usually suffer pulmonary thromboembolic disorders.

When we suspect, on clinical or radiological grounds, disease with small airway disease disturbances, we complete the HRCT examination with three expiratory slices, one in the upper lobes, one in the middle lobe/lingula, and one in the lower lobes. To choose the table level, we

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**Fig. 6a–c** Sampling chest HRCT technique. Bronchopulmonary dysplasia. Premature 2-month-old infant with respiratory symptoms requiring oxygen at corrected 36 gestational weeks. Sampling chest HRCT technique was adequate for the diagnosis and follow-up. a HRCT scan shows considerable septal thickening with some cystic-like areas corresponding to hyperaerated lung surrounded by thickened interlobular septa in both lungs. b HRCT scan at 1 year of age shows mosaic attenuation pattern, septal thickening, parenchymal bands, peripheral wedge-shaped subpleural opacities, and architectural distortion. c HRCT scan at 3 years of age shows important improvement of both lung parenchymas.
use the information obtained from the previous inspiratory CT examination. The level of the upper lobes and the middle lobe/lingula do not change significantly on expiration. The level of the lower lobes will move upward from 2–5 cm, depending on the size of the patient. Thus, we need to choose a table level 2–5 cm higher than the level in inspiratory CT examinations. To obtain good expiratory scans it is mandatory to spend some time teaching the cooperative child how to exhale well.

In 1972, Capitanio and Kirpatrick [30] used lateral decubitus chest radiographs to obtain expiratory radiographs in order to determine the presence of air-trapping in children. Following this account, expiratory scans in uncooperative children can be obtained using the lateral decubitus technique [24, 29, 31]. Patients could be scanned in both lateral decubitus positions with this technique. The dependent hemithorax is splinted and the movement of the thoracic cage is restricted on that side, the lung being underareated. Conversely, the hemithorax facing upward is not restricted and the lung is well aerated. The lung, lobe, or segment in the dependent position will remain hyperlucent if air-trapping is present (Fig. 8).

As mentioned, in the lateral decubitus position the lung facing upward is usually well aerated. This technique can therefore also be used when trying to obtain good inspiratory scans in uncooperative patients (Figs. 9, 10). This technique is particularly helpful when examining uncooperative patients whose supine scans show a ground-glass pattern consistent either with lung disease or with normal lung expiration. When the lungs are normal, the ground-glass pattern, due to expiration, will no longer persist in the lung facing upward (Fig. 11). Conversely, the ground-glass pattern will persist in the abnormal lung facing upward. This same principle of gravity-dependent aeration can be applied using prone CT scans to obtain good inspiratory scans of the lower lobes (Figs. 12, 13).

**HRCT findings and patterns**

HR CT is more sensitive and accurate than either chest radiographs or conventional CT and helical CT scans for demonstrating normal or abnormal lung parenchyma and for differentiating between different pathologies. It has
greater accuracy in characterizing diseases in airway and airspace processes or interstitial diseases and gives a more accurate depiction of the extent of disease.

Normal lung anatomy and the most common features of lung diseases have all been described using HRCT [4, 5]. The identification and analysis of these features of lung disease are important for the diagnosis. Sometimes, HRCT features are nonspecific, but when correlated to the clinical findings they can suggest the proper diagnosis.

The most common HRCT features of lung disease in children are the following [32].

a. A *ground-glass opacity* is a hazy increased attenuation of the lung with preservation of the bronchial and vascular margins [33]. It is caused by partial filling or collapse of the alveoli, interstitial thickening, or increased capillary blood volume.

In children who do not cooperate with breathing commands, an increase in lung attenuation can be recognized as a uniform ground-glass appearance which corresponds to a normal lung on expiration. In practical terms, small children are often imaged during different phases of the respiratory cycle, and an apparent increase in lung atten-
ation on expiratory images may potentially be confused with ground-glass attenuation due to lung disease. Lateral decubitus scanning can be useful in demonstrating that the hemithorax facing upward recuperates its normal attenuation as it is on full inspiration (Fig. 11). A useful indication of an expiratory image is to see the trachea with a flat shape, signifying that we are in the expiratory phase of respiration. The attenuation value of normal lung parenchyma in young children is greater and gradually decreases with age [34]. Any increase in attenuation may correspond to infiltrative lung disease. In this case

Fig. 12a, b Prone HRCT technique in an uncooperative patient. A 3-year-old boy with repeated episodes of pneumonia. a HRCT scan in supine position shows architectural distortion of left lower lobe lung parenchyma. b HRCT in prone position (lower lobes well aerated) nicely depicts some bronchiectasis and architectural distortion of this lobe

Fig. 11a–c Lateral decubitus HRCT technique in an uncooperative patient. Normal ground-glass pattern of the lower lobes in supine position. A 6-month-old infant with fever for 3 weeks and questionable pneumonia. a HRCT scan in supine position shows ground-glass in the dependent position (both lower lobes are under-aerated). b, c Ground-glass is no longer identified in lateral decubitus views. Both hemithoraces facing upward show well-aerated, normal-appearing lungs
no changes in lung attenuation will occur in lateral decubitus or prone views of a lung at full inspiration (Fig. 13).

When the ground-glass pattern is patchy it results in a mosaic pattern which is usually due to small airways disease (Fig. 14). Such a ground-glass pattern is due to airspace or interstitial disease. It can be seen in any entity involving the alveoli such as pneumonia, edema, and hemorrhage or in any interstitial disease.

b. **Consolidation** is an increase in pulmonary parenchymal attenuation which obscures the margins of the bronchi and vessels and is due to a replacement of the alveolar air by cells, fluid, or tissue. Consolidation can be seen in pneumonia, edema, or hemorrhage (Fig. 5).

c. **Pulmonary nodules** are rounded opacities of varying size with well or ill-defined margins. They can be located in an airspace or in the interstitium and can be classified according to their size and distribution.

Nodules less than 5 mm are considered small nodules and can be centrolobular or distributed at random. Centrolobular nodules are located in the bronchioarteriolar region at 5–10 mm from the pleural surface or interlobar septa and are usually secondary to bronchiolar disease in
children. They can be seen in bronchiectasis, cystic fibrosis, immotile cilia syndrome, infectious bronchitis, bronchogenic tuberculosis, asthma, hypersensitivity pneumonitis, or in bronchiolitis obliterans [35] (Fig. 15). Randomly distributed small nodules can be seen near the pleural surface or interlobular septa. They are found in miliary tuberculosis, hematogenous metastasis, fungal infections, and Langerhans’ cell histiocytosis [5] (Fig. 16).

Pulmonary nodules larger than 5 mm can be seen in tuberculosis, mycotic infections, bronchiolitis obliterans with organizing pneumonia, metastatic disease, lymphoproliferative disorders, Langerhans’ cell histiocytosis, septic emboli, vasculitis, or in lipid granulomas in parenteral nutrition [36] (Fig. 17).

d. A halo sign is a ground-glass opacity surrounding a nodule or a mass. This sign may be found in invasive pulmonary aspergillosis, lymphoproliferative diseases, Wegener’s granulomatosis, pulmonary hemorrhage, and metastasis [37].

e. Tree-in-bud pattern is lung opacity seen as a branching structure and represents bronchiolar dilatation and its impaction with mucus, pus, or inflammatory material. In cross-section these filled bronchioli appear as nodules. The tree-in-bud pattern is very frequently seen in bronchiolar disease of any etiology. Bronchiolar thickening, bronchiolar dilatation, and luminal impaction are HRCT findings in bronchiolar disease. The tree-in-bud pattern can be seen in cystic fibrosis, allergic bronchopulmonary aspergillosis, immotile cilia syndrome, bronchiolitis obliterans, panbronchiolitis, follicular bronchiolitis, asthma, or in endobronchial spread of tuberculosis [38] (Fig. 15).

f. Septal thickening is a fine linear opacity pattern of 1–2 cm in length which runs perpendicular to and near the pleural surface or is located in the central lung. It represents interlobular interstitial septal thickening. This pattern can be seen in pulmonary lymphangectasia, pulmonary edema, bronchopulmonary dysplasia, infectious processes, pulmonary fibrosis, Niemann-Pick disease, Gaucher’s disease, collagen vascular disorders, sarcoidosis, tuberous sclerosis, or in lymphatic spread of tumor [2, 19] (Figs. 4, 6, 10).

g. Parenchymal bands are elongated opacities of 2–5 cm in length which represent either several joined thickened septa, areas of bronchiovascular fibrosis, and atelectasis or a combination of all of them. They can reach the pleural surface and produce a pleural retraction that is seen as triangular opacity with a pleural base. This pattern is frequently seen in long-standing bronchopulmonary dysplasia [39] (Fig. 6b).
h. An *air-trapping pattern* is due to the retention of air in all or part of the lung as a result of air obstruction. It is depicted much better on expiratory scans. When a mosaic perfusion pattern is present on inspiratory scans (suggesting air-trapping) it is necessary to perform expiratory scans to demonstrate the air-trapping. Inspiratory scans can show either normal or subtle abnormal findings in children with clinical evidence of airway disease. In such cases expiratory scans should always be included when performing an HRCT examination (Fig. 7). An air-trapping pattern can be found in cystic fibrosis, bronchiectasis, asthma, or bronchiolitis obliterans. Bronchiolitis obliterans usually exists distal to bronchiectasis. This concept is important when examining children with suspected bronchiectasis. The presence of air-trapping favors the diagnosis [40] (Fig. 9).

I. A *mosaic perfusion pattern* is when lung parenchyma appears with a patchy attenuation with lower attenuation regions and higher attenuation regions. It may be difficult to determine which areas of the lung are normal when a mosaic pattern of lung attenuation is seen. It is a nonspecific HRCT finding and can be due to: (1) airway disease where the lucent areas correspond to air-trapping with secondary vasoconstriction and small vessels; (2) ground-glass infiltrates where the higher attenuation areas correspond to infiltrated lung parenchyma with normal vessels; or (3) pulmonary vascular disease where the lucent areas have small vessels with reduced vascularity. Deciding on whether the areas of diminished attenuation represent small airway disease or vascular disease or the areas of increased attenuation (ground-glass opacity) represent diffuse infiltration may be challenging. Expiratory scans, lateral decubitus or prone scans can be useful in determining the abnormal region [31]. A mosaic perfusion pattern can be seen in asthma, bronchiolitis obliterans, cystic fibrosis, bronchopulmonary dysplasia, interstitial or airspace infiltrates of any etiology, thromboembolism, or pulmonary hypertension [41] (Fig. 14).

j. An *architectural distortion pattern* is when bronchi, vessels, and fissures are abnormally distributed in the pulmonary field. Bronchi and vessels lose their branching pattern. This pattern is quite common in small airway obstruction diseases where it may be the only finding seen on inspiratory CT scans. Expiratory scans at these levels will show air-trapping (Fig. 18). This pattern can also be found in pulmonary hypoplasia.

k. *Cystic patterns* (bullae, pneumatoceles, cysts) are intrapulmonary walled air collections of different wall thickening. Depending only on the imaging findings, most of the time it is very difficult to differentiate between all of them. Clinical findings and evolution of the radiological image can help in the final diagnosis. These cystic patterns may be found in congenital cysts, pneumatoceles secondary to infectious pneumonia, pneumatoceles secondary to hydrocarbon ingestion, traumatic pneumatoceles, pseudocysts secondary to barotraumas, Langerhans’ cell histiocytosis, tuberous sclerosis, septic emboli, Wegener’s granulomatosis, papillomatosis, etc. [5, 32] (Figs. 3, 17b).

l. A *signet-ring sign* is the combination of radiological findings: the thick-walled dilated bronchus (cystic image appearance) next to a rounded opacity corresponding to the pulmonary artery. This sign corresponds to bronchiectasis [42] (Fig. 19).

m. *Emphysema* is a focal lung region of low attenuation without a surrounding wall that corresponds to an abnormal and permanent enlargement of the lung air spaces with destruction of their walls. It can be centrolobular, panlobular, and paraseptal and is usually associated with air-trapping [32].

n. A *honeycomb pattern* is the combination of a clustered cystic pattern with thick walls that do not change...
on expiratory scans [43]. It is not frequently found in children and is usually seen in peripheral lung regions, representing a loss of acinar and bronchiolar architecture due to fibrosing lung disease. This pattern can be seen in any chronic interstitial lung disorder and in any pulmonary fibrosis disorder [3, 44] (Fig. 20).

- A crazy-paving pattern is a combination of a ground-glass pattern with septal thickening pattern. This pattern may be seen in alveolar proteinosis, adult respiratory distress syndrome, acute interstitial pneumonia, drug-induced pneumonitis, or exogenous lipoid pneumonia [45].

**Clinical indications**

Since the diagnostic sensitivity and specificity of HRCT with regard to lung disease are superior to those provided by conventional chest X-ray and conventional CT scan, the indications for HRCT in children will undoubtedly increase. We are convinced that in the future, HRCT will be the technique of choice for the study of several lung diseases in children. Therefore, we should ensure that the examination is as patient friendly as possible. For this, scans should be tailored to the specific clinical problem and the number of section and exposure parameters decreased as much as possible. A low-dose technique should be used routinely with scout views spared. Needless to say, the routine use of low-dose techniques is mandatory so as to minimize the potential side effects of ionizing radiation exposure. This is extremely important for extending the indications of HRCT in children so they can benefit from the excellent diagnostic information it provides.
HRCT is the imaging technique of choice for the evaluation of most large and small airway diseases or airspace diseases such as bronchiectasis, cystic fibrosis, immotile cilia, constrictive bronchiolitis or bronchiolitis obliterans, bronchiolitis obliterans organizing pneumonia, asthma, allergic bronchopulmonary aspergillosis, invasive pulmonary aspergillosis, recurrent aspiration, foreign body inhalation, and pulmonary infections (especially in immunocompromised patients). Inflammatory damage to the small airways probably represents the most common injury to the lung. In children, postviral infection damage is the most frequent cause [5, 7, 46–48] (Figs. 1, 2, 5, 9, 15, 19, 21, 22).

HRCT is also the imaging technique of choice for the evaluation of diffuse interstitial lung diseases and specific lung diseases such as: pulmonary fibrosis and chronic interstitial pneumonias, lymphocytic interstitial pneumonia (LIP), collagen-vascular disease and pulmonary vasculitis, pulmonary lymphangiectasia, lymphangiomatosis and Gorham’s disease, pulmonary lymphangitic carcinomatosis, pulmonary hemorrhage, pulmonary alveolar microlithiasis, chronic diffuse infiltrative lung disease, sarcoidosis Langerhans’ cell histiocytosis, pulmonary Gaucher’s disease and Niemann-Pick disease, extrinsic allergic alveolitis, pulmonary alveolar proteinosis, and bronchopulmonary dysplasia [5, 7, 39, 46, 49, 50] (Figs. 3, 4, 6, 10, 13, 17, 20, 23, 24).

Fig. 21a, b Bronchiectasis associated with candidiasis-endocrinopathy syndrome (immunologic disorder, mucocutaneous candidiasis, endocrine dysfunction, and frequently in association with aortic calcification). a HRCT scan shows bronchiectasis in the left lower lobe. b HRCT scan with mediastinal window reveals thoracic aortic calcification.

Fig. 22a, b Immotile cilia: Kartagener’s syndrome (situs inversus totalis, paranasal sinusitis, bronchiectasis). A 10-year-old boy with repeated sinusitis and pulmonary infections. a Chest radiograph shows a situs inversus totalis with lung consolidation in the left lower lobe (right location). b HRCT scan shows situs inversus and bronchiectasis in the lower lobe.
HRCT examination is an excellent technique for the study of lung disorders in children. HRCT can be very helpful in confirming the presence and extent of lung disease. In most cases it can be performed without the need for sedation and with protocols that deliver very little radiation to the patient. A careful technique is extremely important in order to be as less invasive as possible. HRCT provides more information than conventional chest films (with a comparable radiation exposure), thus it could be an alternative for routine use in some patients. HRCT has replaced bronchography as the gold standard for diagnosing bronchiectasis in children and may also be diagnostic in diffuse interstitial disease. HRCT features are sometimes nonspecific, but when correlated to the clinical findings, they can suggest the correct clinical diagnosis and thus obviate the need for biopsy. However, further radiological experience is required to reach a better level of diagnostic certainty in children.

\textbf{Fig. 23a–c} Chronic pneumonitis of infancy. A 6-month-old boy with severe respiratory distress. \textbf{a} HRCT scan shows important increase of lung attenuation (extensive ground-glass pattern) with visible bronchogram. \textbf{b} HRCT scan at 7 months of age also shows multiple small cystic images that do not disappear in lateral decubitus view (c) probably corresponding to pulmonary interstitial air or emphysematous parenchymal destruction.

\textbf{Fig. 24} Lymphocytic interstitial pneumonia in immunodeficiency. A 13-year-old girl with fever and cough. HRCT scan shows multiple ill-defined nodules (some in a subpleural location), areas of consolidation, and ground-glass attenuation.
References


