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Title	Development of low-dose protocols for thin-section CT assessment of cystic fibrosis in pediatric patients.
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Publication date	2010-12-01
Original Citation	O'Connor, O. J., Vandeleur, M., McGarrigle, A. M., Moore, N., McWilliams, S. R., McSweeney, S. E., O'Neill, M., Chroinin, M. N. and Maher, M. M. (2010) 'Development of Low-Dose Protocols for Thin-Section CT Assessment of Cystic Fibrosis in Pediatric Patients', Radiology, 257(3), pp. 820-829. doi:10.1148/radiol.10100278
Type of publication	Article (peer-reviewed)
Link to publisher's version	https://pubs.rsna.org/doi/abs/10.1148/radiol.10100278 - 10.1148/radiol.10100278
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Download date	2026-11-08 20:39:27
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Development of Low-Dose Protocols for Thin-Section CT Assessment of Cystic Fibrosis in Pediatric Patients[1]

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Purpose: To develop low-dose thin-section computed tomographic (CT) protocols for assessment of cystic fibrosis (CF) in pediatric patients and determine the clinical usefulness thereof compared with chest radiography.

Materials and Methods: After institutional review board approval and informed consent from patients or guardians were obtained, 14 patients with CF and 11 patients without CF (16 male, nine female; mean age, 12.6 years ± 5.4 [standard deviation]; range, 3.5–25 years) who underwent imaging for clinical reasons underwent low-dose thin-section CT. Sections 1 mm thick (protocol A) were used in 10 patients, and sections 0.5 mm thick (protocol B) were used in 15 patients at six levels at 120 kVp and 30–50 mA. Image quality and diagnostic acceptability were scored qualitatively and quantitatively by two radiologists who also quantified disease severity at thin-section CT and chest radiography. Effective doses were calculated by using a CT dosimetry calculator.

Results: Low-dose thin-section CT was performed with mean effective doses of 0.19 mSv ± 0.03 for protocol A and 0.14 mSv ± 0.04 for protocol B ($P < .005$). Diagnostic acceptability and depiction of bronchovascular structures at lung window settings were graded as almost excellent for both protocols, but protocol B was inferior to protocol A for mediastinal assessment ($P < .02$). Patients with CF had moderate lung disease with a mean Bhalla score of 9.2 ± 5.3 (range, 0–19), compared with that of patients without CF (1.1 ± 1.4; $P < .001$). There was excellent correlation between thin-section CT and chest radiography ($r = 0.88–0.92$; $P < .001$).

Conclusion: Low-dose thin-section CT can be performed at lower effective doses than can standard CT, approaching those of chest radiography. Low-dose thin-section CT could be appropriate for evaluating bronchiectasis in pediatric patients, yielding appropriate information about lung parenchyma and bronchovascular structures.

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Cystic fibrosis (CF) was first recognized as a clinical entity in the 1930s (1). It is an autosomal recessive disorder characterized by viscid exocrine gland and acinar secretions causing tubular obstruction and bronchiectasis (2,3). Irreversible airway disease and lung destruction are the most relevant sources of disease-related mortality and are responsible for more than 80% of deaths (3,4). Modern treatments continue to extend the life expectancy of patients with CF with effective early treatment of *Pseudomonas aeruginosa* colonization in centralized CF centers, improving survival and yielding an 80% probability of living 40 years after diagnosis (5,6). Methods used to monitor disease and guide treatment include imaging studies (chest radiography and thin-section computed tomography [CT]), biochemical assessment (levels of C-reactive protein and albumin and white blood cell counts), microbiologic examination (sputum samples), physiologic evaluation (pulmonary function tests), and measures of quality of life (7–10).

Traditionally, bronchography was used for the definitive diagnosis of bronchiectasis because the sensitivity of chest radiography was insufficient for this purpose (11). Thin-section CT superseded bronchography as the reference standard for imaging bronchiectasis because CT is noninvasive and yields the correct diagnosis more often than does chest radiography (12). Mucous plugging is considered the earliest radiologic manifestation of bacterial overgrowth, and bronchiectasis is the first radiologic sign of irreversible lung disease in CF (3,13). Evidence suggests that intensive treatment of disease exacerbations in CF may lessen the severity of bronchiectasis (14). In addition, prompt diagnosis of architectural distortion in patients with CF may aid in disease treatment, because early treatment with antiinflammatory agents may help slow disease progression (15).

The deficiencies of chest radiography are also important in the context of non-CF bronchiectasis, which frequently is missed at chest radiography, substantially delaying diagnosis and treatment (16). Findings at chest radiography correlate with those at thin-section CT in only 5% of patients with non-CF bronchiectasis. It is estimated that delay in performance of thin-section CT delays definitive diagnosis of bronchiectasis in such patients by 3 years.

Although thin-section CT is more accurate than chest radiography, the higher radiation dose imparted with standard-dose thin-section CT is a major limitation (17). Posteroanterior and lateral chest radiography have an effective dose of approximately 0.1 mSv (18). The effective dose of standard helical CT ranges from 1.7 mSv in a newborn to 5.4 mSv in an adult (19). A low-dose helical CT protocol in a 5-year-old patient (100 kV, 20 mAs, pitch of 1.5) can help reduce effective doses from 2.1 to 0.55 mSv (19). Standard thin-section CT (120 kV, 40 mAs, section thickness of 1.25 mm at 10-mm intervals) in a 10-year-old patient has been reported to impart an effective dose of approximately 0.55 mSv (20).

Low-dose thin-section CT, at effective doses approaching those of chest radiography, has the potential to yield much more definitive and clinically useful diagnostic information than can chest radiography. Thin-section CT in patients with CF and pediatric patients without CF who are suspected of having bronchiectasis is appropriate for the application of low-dose techniques because the main focus of the examination is assessment of the bronchi, bronchioles, and lung parenchyma for ground-glass

Advances in Knowledge

- Low-dose thin-section CT of the chest can be performed in young patients at an effective dose of 0.14 mSv, which is slightly less than that of 1.5 frontal and lateral chest radiographs.
- At this level of exposure, images are excellent for examination of the lungs at lung window settings but barely acceptable for examination of the mediastinum at soft-tissue window settings.
- Low-dose thin-section CT depicts typical pathologic changes in the lung parenchyma in pediatric patients with CF and correlates well with chest radiographic findings.
- Results suggest that low-dose thin-section CT is technically feasible in pediatric patients with CF.
- Low-dose CT also may be useful in pediatric patients without CF who are suspected of having bronchiectasis.

Implications for Patient Care

- Low-dose thin-section CT provides detailed assessment of bronchopulmonary anatomy and appears suitable for the examination of pediatric patients with CF and those without CF who are suspected of having bronchiectasis.
- Low-dose thin-section CT yields appropriate information regarding bronchiectasis and bronchioloectasis in patients with CF and those without CF with slightly less radiation exposure than that at chest radiography.
- If used judiciously, low-dose thin-section CT could replace chest radiography for the detection of bronchiectasis in pediatric patients.

Published online before print
10.1148/radiol.10100278

Radiology 2010; 257:820–829

Abbreviations:
CF = cystic fibrosis
SNR = signal-to-noise ratio

Author contributions:
Guarantors of integrity of entire study, O.J.O., M.M.M.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; approval of final version of submitted manuscript, all authors; literature research, O.J.O., M.V., M.M.M.; clinical studies, O.J.O., M.V., N.M., M.O., M.N.C., M.M.M.; experimental studies, M.O., M.N.C., M.M.M.; statistical analysis, S.R.M.; and manuscript editing, O.J.O., S.E.M., M.O., M.M.M.

Authors stated no financial relationship to disclose.

or consolidative changes, and detailed evaluation of the peripheral interstitium rarely is required (3). Thin-section CT has advantages over chest radiography for the assessment of CF, but with higher radiation exposure. The purpose of this study was to develop low-dose thin-section CT protocols for assessment of CF in pediatric patients and to determine the clinical usefulness thereof, compared with chest radiography.

Materials and Methods

This prospective study was initiated after we received institutional review board approval. Written informed consent was obtained from the parents or guardians of 14 patients with CF (nine male and five female patients; mean age, 13 years ± 6 [standard deviation]; range, 3.5–25 years) before performance of low-dose thin-section CT. The nine male and five female patients with CF had mean ages of 14 years ± 6 and 12 years ± 6, respectively. Imaging findings in the study group were compared with those from 11 age-matched patients without CF (seven male and four female patients; mean age, 11 years ± 5; range, 4–19 years) in whom low-dose thin-section CT was requested by the referring physician because the patient was suspected of having bronchiectasis. The seven male and four female patients were considered the control group and had mean ages of 13 years ± 6 and 9 years ± 4, respectively. In total, the 16 male and nine female patients had a mean age of 12.6 years ± 5.4 (range, 3.5–25 years). Patients in both groups underwent imaging with one of two low-dose thin-section CT protocols.

Thin-Section CT Technique

Thin-section CT images were obtained by using a four-section multidetector CT scanner (Aquilion 4; Toshiba Medical Systems, Otawara, Japan) without intravenous contrast material. Planning scanograms were used to identify six levels, evenly spaced, at which images were acquired. Images were obtained with the patient at full inspiration through the lung apices, aortopulmonary window, and carina; below the pulmonary hila; and at the widest cardiac and thoracic diameters, as described previously (21). A tube voltage of 120 kV and a rotation time of 0.5 seconds were used for all examinations. Automatic exposure control was unavailable on the CT unit. The tube current and the field of view were chosen on the basis of patient age. Children younger than 5 years underwent imaging with a 24-cm field of view, and patients older than 5 years underwent imaging with a 32-cm field of view. A tube current between 30 and 50 mA was used without automatic exposure control because this facility was not available on our CT scanner. Patients younger than 5 years underwent imaging with a current of 30 mA, patients aged between 5 and 15 years underwent imaging with a current of 40 mA, and patients older than 15 years underwent imaging with a current of 50 mA. The first 10 patients (eight male and two female patients; mean age, 14 years ± 5; range, 4–25 years) underwent imaging at each of the six levels with use of four 1-mm-thick sections (protocol A). These sections were reconstructed in stacks of two, each 2 mm thick. The next 15 patients (eight male and seven female patients; mean age, 11 years ± 5; range, 3.5–20 years) underwent imaging with four 0.5-mm-thick sections reconstructed in stacks of two, each 1 mm thick (protocol B), facilitating a further reduction in dose over that in protocol A.

Verification of Dose Measurements

The tolerance of CT dose index and dose-length product values calculated with the CT scanner were verified by using standard polymethyl methacrylate phantoms, a 10-cm ionization chamber (Victoreen; Fluke Biomedical, Cleveland, Ohio), with an x-ray test device (NERO mAx; Fluke Biomedical). The 32-cm phantom was imaged at tube currents of 40 and 50 mA with a 32-cm field of view, and the 16-cm phantom was imaged at a tube current of 30 mA with a 24-cm field of view. Radiation measurements were obtained for each protocol with the pencil chamber inserted at the central and peripheral locations of the appropriate phantom. Three measurements at each location were averaged and used to calculate corresponding CT dose index values, which subsequently were converted to a weighted CT dose index. The displayed CT dose index and dose-length product values of the CT console were recorded, and the percentage error was calculated by using ionization chamber measures. The CT unit was calibrated once per week in accordance with the manufacturer's instructions.

Dose Measurements

A patient CT dosimetry calculator (ImPACT, version 0.99x; ImPACT, London, England) was used to calculate effective doses by using original scanning parameters for each section corrected for the anatomic area being imaged and for patient age. Effective doses for each image were summed to yield a total effective dose for each patient.

Measurement of Disease Severity at Thin-Section CT

Thin-section CT images were reviewed on a picture archiving and communication system (Impax 6.3.1; Agfa HealthCare, Mortsel, Belgium) in a Digital Imaging and Communications in Medicine format on a monitor with a resolution of 3 megapixels. Data sets were studied randomly at lung (window width, 1500 HU; window level, −500 HU) and soft-tissue (window width, 350 HU; window level, 50 HU) window settings. Reviewers were blinded to CF diagnosis. Disease severity was scored in consensus by two radiologists, a pediatric radiologist (M.O., with 36 years of experience) and a chest radiologist (M.M.M., with 14 years of experience), by using a validated scoring system (8). The presence and severity of nine morphologic changes were sought and scored. The minimum score was zero, and the maximum potential score was 25.

Measurement of Disease Severity at Chest Radiography

CT examinations in patients with CF were performed during nonacute phases of their disease. Disease severity at the most contemporaneous posteroanterior chest radiography was scored by using the Northern (Conway) method (22) and

modifications to the Chrispin-Norman method by Benden et al (23) and the results were compared with thin-section CT Bhalla scores (8).

Qualitative Analysis

Image quality was quantified subjectively by the same two radiologists who scored disease severity; they used five indexes at a combination of lung and mediastinal window settings (24,25). Image noise, peripheral bronchovascular structure depiction within 2 cm of the pleural margin, streak artifact, and diagnostic acceptability were scored at each of the six levels that were imaged by using a five-point scale: 1, unacceptable; 2, minimally acceptable; 3, acceptable; 4, highly acceptable; and 5, excellent. One of the observers (M.M.M.) was familiar with these methods of assessment, because he had previously used them successfully (24,25). This radiologist trained the second radiologist before analysis by using a training set of five standard thin-section CT scans. Image noise was assessed at mediastinal window settings on the basis of the amount of image mottle present. If peripheral blood vessels and interfaces between adjacent tissues were seen adequately, then a score of 3 (acceptable) was assigned. Scores of 1 and 5 were given for intrusive graininess or minimal graininess, respectively. Diagnostic acceptability also was scored on a five-point scale at mediastinal and lung window settings. Images were considered acceptable (score of 3) if soft-tissue structures were sufficiently well depicted for diagnostic purposes. Scores of 1 and 5 were allocated for images considered unacceptable or excellent for diagnosis, respectively. The presence of a streak artifact at mediastinal window settings was examined qualitatively on a three-point scale: 1, no streak artifact; 2, streak artifact present but not interfering with image interpretation; and 3, streak artifact present and interfering with image interpretation.

Quantitative Analysis of Image Noise

Attenuation values were measured in Hounsfield units in the aorta and paraspinal muscles of the posterior chest wall at three levels—the aortic arch, the descending aorta at the level of the carina, and the maximum cardiac diameter—by using circle histograms of equal size. Signal-to-noise ratio (SNR) in regions of interest was calculated by dividing the mean Hounsfield unit value by its standard deviation (26).

Statistical Analysis

The mean ± standard deviation of the effective doses, the five qualitative measures of image quality, and the SNR were reported for each subset of patients (protocols A and B). A power calculation indicated that a minimum sample size of 13 was necessary to detect a one-point difference in mean qualitative values (27). Each of the qualitative measures of image quality used in protocol A (1-mm section thickness) was compared with those used in protocol B (0.5-mm section thickness). The quantitative measure of image quality (SNR) in the chest wall and aorta measured in protocol A was compared with that measured in protocol B at each of the three levels assessed. Bhalla scores in patients with CF were compared with those in patients without CF. Significant differences between these groups were determined by using an unpaired Student *t* test. Quantitative image noise scores (SNR) were compared with qualitative image noise scores by using a Pearson correlation coefficient. The Pearson correlation coefficient was used to compare Bhalla thin-section CT scores with Northern and Benden chest radiography scores. The thin-section CT and chest radiography scores were tested for normality with Kolmogorov-Smirnov tests. A difference with a *P* value of less than .05 was considered significant. Data were analyzed with software (SPSS version 16; SPSS, Chicago, Ill).

Results

Radiation Exposure

CT outputs measured by using the ionization chamber were used to confirm that the displayed CT dose index readings on the CT console were within acceptable tolerance limits of ±20% (28). The average percentage error was 6.8% (six of 40.6) ± 3.9 (range, 1%–10%). Low-dose thin-section CT was performed with mean effective doses of 0.19 mSv for protocol A and 0.14 mSv for protocol B (Table 1). Mean CT dose index and dose-length product for the two protocols differed significantly from one another (Table 1). The mean CT dose index for protocol A was smaller than that for protocol B because a smaller amount of tissue received a similar dose when section thickness was reduced from 1 to 0.5 mm. Effective doses were reduced by 65%– 75% compared with standard thin-section CT doses in pediatric patients. Mean effective doses were reduced by approximately 26% by reducing section thickness from 1 mm in protocol A to 0.5 mm in protocol B. The difference in mean effective doses between protocols A and B was significant ($P < .005$).

Image Quality

At mediastinal window settings, each of the three qualitative indexes of low-dose thin-section CT image quality (diagnostic acceptability, image noise, and streak artifact) was graded as significantly worse for protocol B than for protocol A (Table 2, Fig 1). At mediastinal window settings, image noise was graded as highly acceptable for protocol A but just less than acceptable for protocol B. Similarly, diagnostic acceptability was graded between highly acceptable and excellent for protocol A but between acceptable and highly acceptable for protocol B. Streak artifact was observed more often in protocol B than in protocol A images, but it did not interfere with image interpretation. Although the qualitative assessment of diagnostic acceptability was significantly better at thin-section CT with protocol A than with protocol B ($P < .02$) viewed at mediastinal window settings, there was no significant difference in diagnostic acceptability when images were viewed at lung window settings ($P = .29$). In addition, it was possible to examine bronchovascular structures within 2 cm of the pleural margin with equal effectiveness irrespective of

Table 1

Summary of Low-Dose Thin-Section CT Effective Doses for Protocols A and B

Dose Measurement	Low-Dose Thin-Section CT*		*P* Value
	Protocol A ($n = 10$)	Protocol B ($n = 15$)	
Effective dose (mSv)	0.19 (0.03)	0.14 (0.04)	<.005†
Dose-length product	1.4 (0.14)	1.1 (0.28)	.01†
CT dose index (mGy)	3.4 (0.38)	5.1 (1.4)	.002†

* Data are means, and numbers in parentheses are standard deviations.

† Value showed a significant difference (two-tailed $P < .05$) when the dose measurements in protocols A and B were compared.

Table 2

Qualitative Indexes of Image Quality for Low-Dose Thin-Section CT with Protocols A and B

Index	Low-Dose Thin-Section CT*		*P* Value
	Protocol A ($n = 10$)	Protocol B ($n = 15$)	
Mediastinum			
Noise	3.8 (0.5)	2.6 (0.9)	<.001†
Diagnostic acceptability	4.3 (0.5)	3.5 (0.8)	<.02†
Streak artifact‡	1.6 (0.5)	2 (0.3)	<.004†
Lung parenchyma			
Depiction of bronchovascular structures within 2 cm of pleural margin	4.6 (0.4)	4.7 (0.5)	.47
Diagnostic acceptability	4.6 (0.5)	4.8 (0.4)	.29

* Data are mean scores, and numbers in parentheses are standard deviations.

† Value showed significant difference (two-tailed $P < .05$) when indexes of quality in protocols A and B were compared.

‡ Streak artifact was assessed on mediastinal window settings and was a global assessment of the image.

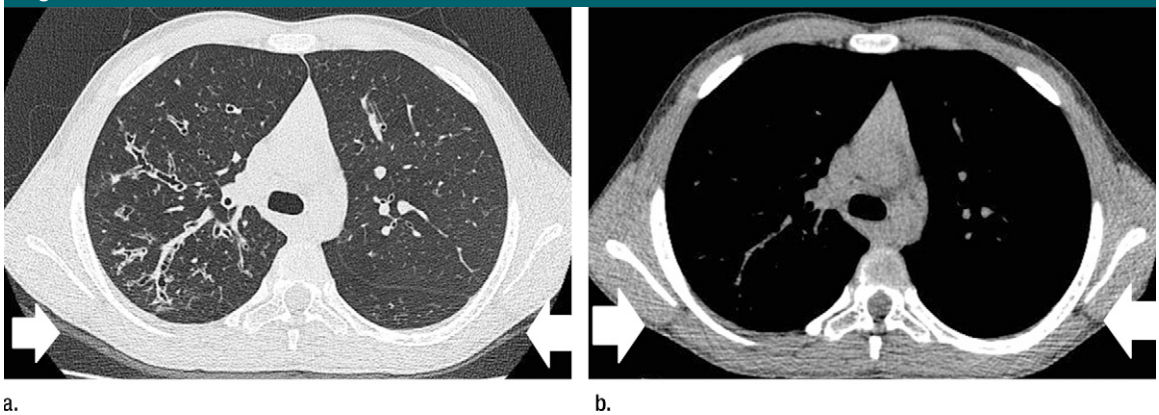
the protocol used. Therefore, an effective dose reduction of 26% (reduced from 0.19 to 0.14 mSv) was achieved by using protocol B instead of protocol A without limiting parenchymal examination.

Quantitative measurements of image quality demonstrated that SNR was significantly higher in patients examined by using protocol A in both the chest wall and aorta at the level of the aortic arch, the aorta at the level of the carina, and the chest wall at the level of the maximum cardiac diameter (Table 3, Fig 2). There was a strong correlation between image noise scored qualitatively and measured quantitatively at all levels, with *r* values ranging between 0.67 and 0.75 ($P < .001$).

Quantification of Lung Disease

All but one of the patients with CF had *Pseudomonas* colonization of longer than 6 months in duration at the time of thin-section CT. Patients with CF with *Pseudomonas* colonization had an average forced expiratory volume of 68% ($n = 13$) ± 22.3 (range, 18%–95%). One patient who was aged 3.5 years did not have *Pseudomonas* colonization and was too young to undergo pulmonary function tests. Six (46%) of 13 patients with *Pseudomonas* infection had a mucoid variety of the disease.

Figure 1



a. b.

Figure 1: Representative transverse low-dose thin-section CT images (0.11 mSv, protocol B, 0.5-mm section thickness, 20 mAs) in a 12-year-old male patient with CF with qualitative scores of image quality near that of the mean. **(a)** At window settings, diagnostic acceptability and depiction of bronchovascular structures within 2 cm of the pleural margin were both considered excellent (score 5). **(b)** At mediastinal window settings, image noise and diagnostic acceptability were considered minimally acceptable (score 2). Streak artifact (arrows) did not interfere with image interpretation (score 2).

The mean Bhalla score in patients with CF was significantly higher than that in patients without CF ($P < .001$) (Table 4, Fig 3). Bronchiectasis was the most severe and consistent lung abnormality identified at low-dose CT in patients with CF. Twelve (86%) of 14 patients with CF had bronchiectasis, and it was considered either moderate or severe in six patients. All but one patient with CF with bronchiectasis had involvement of more than nine bronchopulmonary segments. Peribronchial thickening was found in four patients with CF but only in those with moderate or severe bronchiectasis. All but two patients with bronchiectasis had disease involving sixth-generation bronchial divisions. Only one patient with sacculation was identified among patients with CF. One patient with CF had evidence of early emphysema, and three had moderate atelectasis or consolidation.

Chest radiography was performed within a mean of 3.3 months ± 2.5 (range, 9 days to 5.8 months) before or after thin-section CT. The maximum possible scores of disease severity at chest radiography according to the Northern and Benden methods were 20 and 38, respectively. The mean disease severity score at chest radiography according to the Northern scoring system was 9.7 ± 3.9 (range, 2–14). The mean disease severity score at chest radiography according to the Benden method was 15.8 ± 8.9 (range, 1–30). Correlation between the Northern and Benden scores and the Bhalla thin-section CT scores was excellent, with r values of 0.92 and 0.88, respectively ($P < .001$).

Thin-section CT imaging results were completely normal in almost one-half (five of 11) of the patients without CF (Fig 4). Two had mild bronchiectasis that affected fewer than six bronchopulmonary segments and was limited to the first four bronchial generations. Two control patients had subsegmental atelectasis, and one had evidence of mild pulmonary overinflation with air trapping.

Discussion

Respiratory disease remains the most relevant source of disease-related mortality

Table 3

SNRs at Low-Dose Thin-Section CT with Protocols A and B

Tissue	SNR at Low-Dose Thin-Section CT*		
	Protocol A ($n = 10$)	Protocol B ($n = 15$)	*P* Value
Aortic arch			
Aorta	3.7 (1.0)	1.3 (1.9)	<.002†
Chest wall	3.3 (1.3)	1.3 (2.1)	.012†
Carina			
Aorta	3.1 (1.0)	1.2 (1.2)	<.001†
Chest wall	2.7 (1.2)	1.3 (2.4)	.11
Maximal cardiac diameter			
Aorta	1.3 (0.5)	1.1 (1.7)	.66
Chest wall	3.1 (1.1)	1.3 (2.0)	.014†

* Data are mean SNRs, and numbers in parentheses are standard deviations.

† Value showed significant difference (two-tailed $P < .05$) when SNRs of protocols A and B were compared.

Figure 2

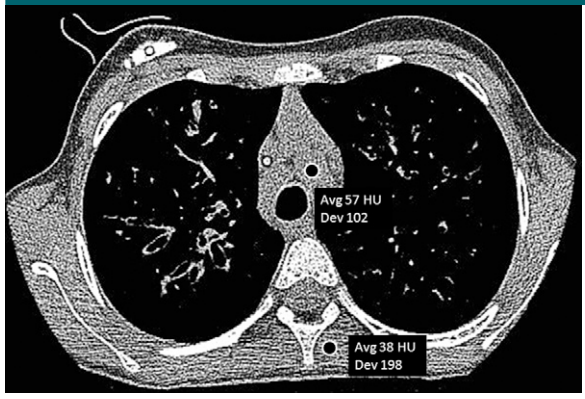


Figure 2: Representative transverse low-dose thin-section CT image (0.14 mSv, protocol B, 0.5-mm section thickness, 20 mAs) at the level of the aortic arch in a 10-year-old female patient with CF. Hounsfield unit and standard deviation measurements were obtained by using circle histograms.

Table 4

Prevalence of Lung Abnormalities at Low-Dose Thin-Section CT in Patients with and without CF

Lung Abnormality	Bhalla Score*		
	Patients with CF ($n = 14$)	Patients without CF ($n = 11$)	*P* Value
Overall Bhalla score	9.2 (5.3)	1.1 (1.4)	<.001†
Bronchiectasis	1.5 (1.0)	0.3 (0.5)	<.002†
Peribronchial thickening	0.7 (1.1)	0	
Extent of bronchiectasis	2.4 (1.2)	0.3 (0.5)	<.001†
Extent of mucous plugging	1.3 (1.1)	0	
Sacculations or abscesses	0.07 (0.3)	0	
Generations of bronchial divisions	2.3 (1.1)	0.3 (0.5)	<.001†
Bullae	0.07 (0.3)	0	
Emphysema	0.07 (0.3)	0.2 (0.6)	.5
Collapse or consolidation	0.6 (0.7)	0.2 (0.4)	.1

* Data are mean scores, and numbers in parentheses are standard deviations.

† Value showed a significant difference with a two-tailed *P* value of less than .05 when Bhalla scores in patients with CF and those without CF were compared.

Figure 3

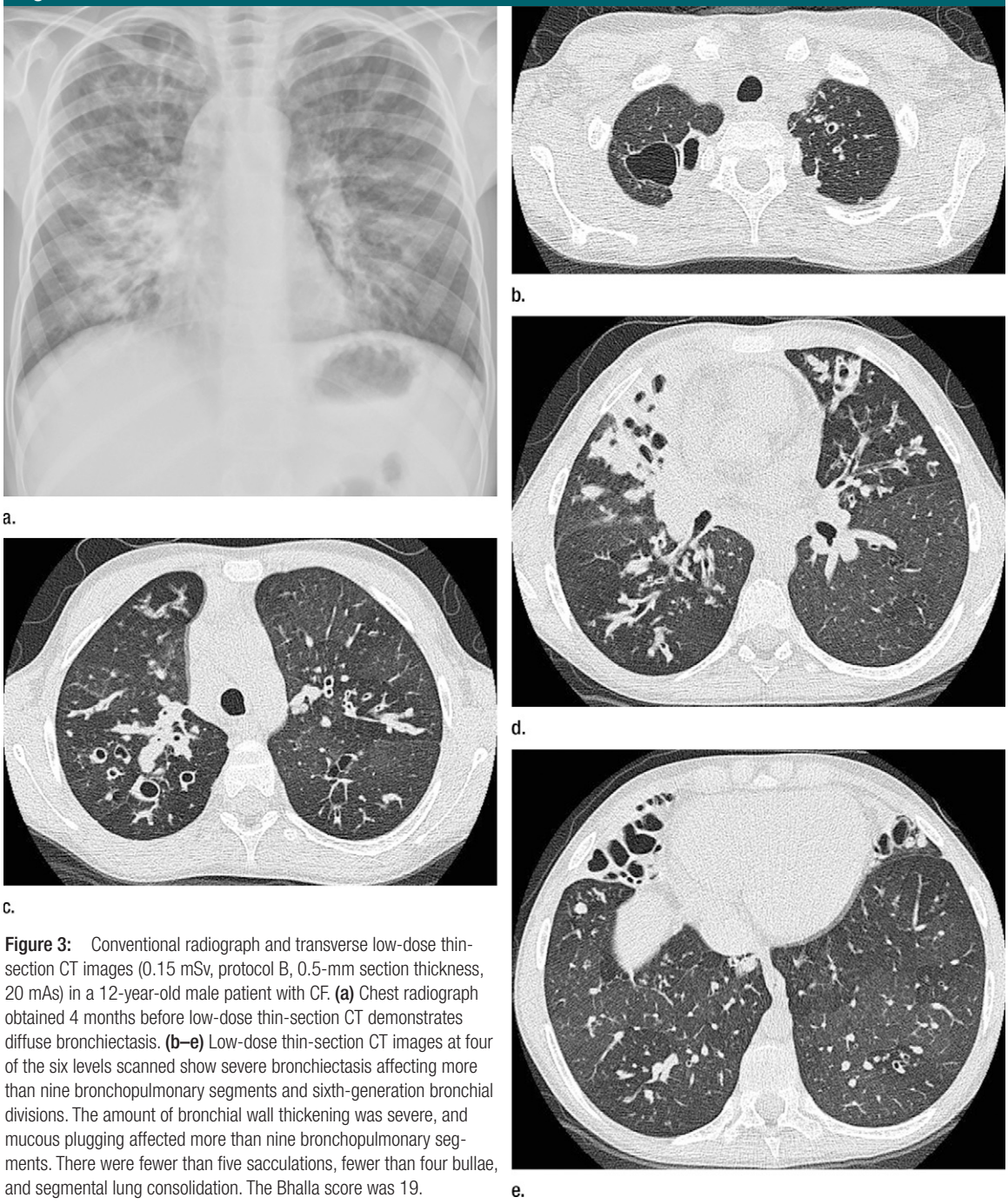
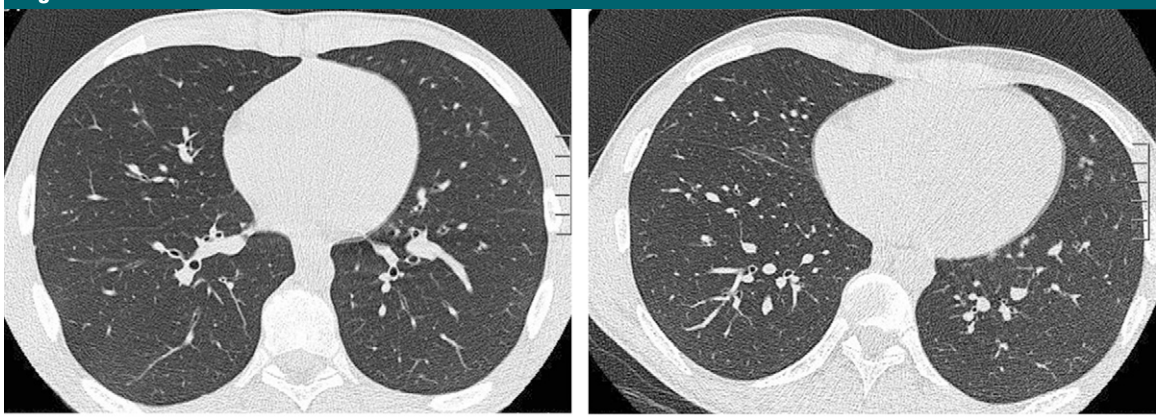


Figure 3: Conventional radiograph and transverse low-dose thin-section CT images (0.15 mSv, protocol B, 0.5-mm section thickness, 20 mAs) in a 12-year-old male patient with CF. **(a)** Chest radiograph obtained 4 months before low-dose thin-section CT demonstrates diffuse bronchiectasis. **(b–e)** Low-dose thin-section CT images at four of the six levels scanned show severe bronchiectasis affecting more than nine bronchopulmonary segments and sixth-generation bronchial divisions. The amount of bronchial wall thickening was severe, and mucous plugging affected more than nine bronchopulmonary segments. There were fewer than five sacculations, fewer than four bullae, and segmental lung consolidation. The Bhalla score was 19.

in CF, responsible for more than 80% of deaths (3,4). Low-dose CT potentially may be used instead of chest radiography in CF for more accurate assessment of bronchiectasis and mucous plugging, which may help direct treatment (8,29). The present protocol also may have a role in screening for non-CF bronchiectasis, which represents approximately 10% of new referrals to tertiary pediatric respiratory centers; in 50% of these new referrals, patients initially receive a misdiagnosis of asthma before thin-section CT (16,30,31).

Thin-section CT at effective doses comparable with those of chest radiography represents a potential method of reducing pediatric CT doses and, at the same time, provides more useful information than does chest radiography (32). Imaging of bronchiectasis in CF has

Figure 4



a. b.

Figure 4: Transverse low-dose thin-section CT images obtained by using protocols A and B at the levels of at the maximum cardiac diameters in patients without CF. **(a)** Image in a 15-year-old male patient with a normal scan (Bhalla score of 0); imaging was performed at an effective dose of 0.15 mSv (protocol A, 1-mm section thickness, 20 mAs). **(b)** Image in an 18-year-old male patient with mild airway disease (Bhalla score, 3); imaging was performed at an effective dose of 0.12 mSv (protocol B, 0.5-mm section thickness, 25 mAs).

Figure 5

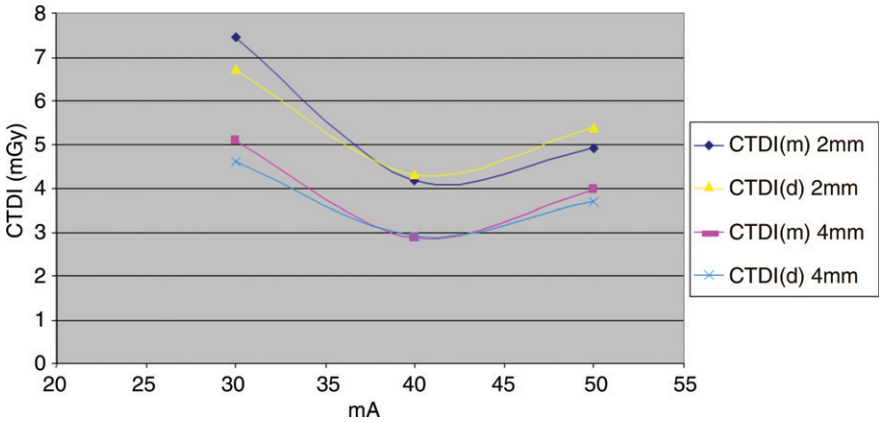


Figure 5: Graph depicts measured *(m)* and displayed *(d)* CT dose index *(CTDI)* as a function of milliampere setting for 2- and 4-mm section thicknesses. The measured and displayed values vary little. Halving section thickness did not halve radiation dose because of the penumbra effect.

been studied by using thin-section CT (120 kV, 100–300 mAs) limited to six sections as in the present study but without reducing the milliampere-second value (21). Jiménez et al (21) reduced doses by 65%, but patients still received a substantial radiation dose of approximately 4 mSv (250 mGy · cm). To minimize radiation dose at thin-section CT, we reduced both the tube current and the number of acquired sections. Thin-section CT of the lung is suitable for low-dose examination protocols for several reasons. Innate contrast between lung parenchyma and bronchovascular structures with reduced x-ray beam attenuation in the chest compared with that in the abdomen means that less radiation is required for imaging. As a result, lung imaging was as effective with protocol B (effective dose, 0.14 mSv) as it was with protocol A (effective dose, 0.19 mSv), despite significantly smaller SNR in the former. There was little doubt, however, that soft-tissue imaging of the mediastinum was suboptimal with protocol B. The inability to evaluate the mediastinum thoroughly is of less concern in most pediatric patients with CF and those without CF who are suspected of having bronchiectasis, because evaluation of the airways and the lung parenchyma is the primary intention. In our opinion, this is, therefore, an acceptable limitation of these low-dose protocols, which is justified by significant reductions in radiation exposure. The low-dose protocols created an unwanted streak artifact. It was reassuring that increased x-ray beam attenuation was noticeable only in the posterior aspect of the chest wall because of overlapping ribs and muscle. This streak artifact was remote from the lungs and did not affect lung evaluation.

Radiation exposure may be further optimized by using prepatient collimation, x-ray filters, improved detector geometry, noise reduction filters, and automatic tube current modulation, which can aid in reduction of doses in 87% of examinations (33,34). Automatic tube current modulation was not used in the present study but may potentially further reduce the radiation doses from CT. Reducing tube voltage from 120 to 100 or 80 kV represents another potential method of dose reduction (35). We did not reduce tube voltage in the present study because we believed that altering only one parameter at a time, in this case the milliampere-second value, would facilitate scientific evaluation of the effect of individual parameters, reducing the risk of confounding variables.

Chest CT in pediatric patients has been performed at 80 kV, but some authors observed a beam-hardening artifact that precluded satisfactory assessment of the chest; as a result, they suggested imaging at 100 or 120 kV (35). The optimization of kilovolt and milliampere values for imaging in pediatric patients of different sizes remains a challenge, and image quality for combined alterations in kilovolt and milliampere values has not been validated in a large study (36) and should be investigated in future studies.

Halving section thickness did not help reduce radiation dose by 50% because of reduced geometric efficiency of the x-ray beam at small section thicknesses (37). This phenomenon also was evident during the validation studies performed with the CT scanner (Fig 5). Detectors require a uniform x-ray beam, achieved by ensuring that the beam width is slightly larger than the detector. The component of the beam that overshoots the detector, termed the *penumbra*, is generally constant at 1 to 3 mm. The proportion of the radiation wasted in the penumbra is relatively greater for small sections than for thicker sections, which is a well-described problem with four-section CT scanners (37).

The findings of the present study could strengthen the case for the use of thin-section CT in patients with CF at a time when some experts suggest that low-dose CT should be performed biannually in patients with CF (38). There are a number of limitations in the present study that need to be addressed. Volumetric low-dose CT at an effective dose of 0.4 mSv has been achieved in CF, but it is unclear at present how low-dose thin-section CT at six levels compares with volumetric CT for imaging CF (39); clinically important disease may be missed (40). To date, the detection of malignancy is not a primary consideration in patients with CF because of their shortened life span; however, as life expectancy increases, this situation may change. The present data set is small, which limits the strength of the conclusions drawn. Another limitation of the present study is that thin-section CT images were compared with chest radiographs obtained remote to the time of CT; the patient's lung disease may have altered between the time of CT and chest radiography. However, we believed that an additional radiologic study at the time of CT was not ethically justifiable. Patients with CF in the present study underwent imaging during a stable phase of their disease, which may have helped limit changes in disease severity between the time of CT and chest radiography. It is unclear at present whether better detection of mucous plugging and bronchiectasis will affect patient outcomes; however, intensive treatment of disease exacerbations in CF may lessen the severity of bronchiectasis (6,14).

Ideally, the six-section thin-section CT technique should be compared with contemporaneous total-lung thin-section CT. The most recent chest radiographic results were compared instead for two reasons. The purpose of the study was to reduce radiation dose exposure, and there was insufficient justification to merit the additional radiation dose of standard thin-section CT. Results from the study in which this technique originally was described showed no significant difference between mean scores of disease severity with the six-section technique and contemporaneous total-lung thin-section CT (21). Mean calculated Bhalla scores for modified thin-section CT and total-lung thin-section CT were 5.62 and 5.36, respectively. Similarly, Nathanson scores of 66.51 and 66.11 were obtained for thin-section CT and total-lung CT, respectively. In the present study, comparison of results at six-section thin-section CT with results at recent chest radiography showed good correlation in terms of assessing disease severity and suggests that the potential for missing clinically important disease in an asymptomatic surveillance setting is likely to be small.

Unlike the results from the previous study, which were used to confirm the diagnostic coverage of a six-section technique, the results from the present study address image quality issues that are important in the context of justifying CT radiation dose reduction. We demonstrated excellent correlation between disease severity scores at CT and chest radiography. We also demonstrated that the quality of low-dose thin-section CT images was between highly acceptable and excellent for the purposes of diagnosis and depiction of bronchovascular structures within 2 cm of the pleural margin of the lung at a dose slightly greater than that of frontal and lateral chest radiography.

The six-section technique is susceptible to variations in depth of inspiration. Pulmonary function tests in patients with CF are commenced in our institution when the patient is aged 4 years. Most patients with CF who are older than 4 years appear accustomed to performing controlled respiratory maneuvers for clinical purposes. In the present study, respiratory motion was identified infrequently, suggesting good patient cooperation.

In conclusion, thin-section CT is the reference standard imaging modality for the assessment of bronchiectasis (12). Justifying thin-section CT in pediatric patients requires that the anticipated benefits outweigh the potential risks, particularly in relation to radiation exposure (41). The present study results demonstrated that thin-section CT can be performed in pediatric patients at an effective dose of 0.14 mSv, a dose that approaches that of 1.5 frontal and lateral radiographs. Low-dose thin-section CT could be an appropriate method for the evaluation of bronchiectasis in pediatric patients with good compliance and yields appropriate imaging information about lung parenchyma and bronchovascular structures.

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