Published in final edited form as:

Curr Probl Diagn Radiol. 2018 ; 47(1): 14–18. doi:10.1067/j.cpradiol.2017.02.010.

Spirometry-assisted HRCT in children: Is it worth the effort?

Jeffrey Parke Otjen, MD^a, Jonathan Ogden Swanson, MD^a, Assaf Oron, PhD^b, Robert M. DiBlasi, RRT-NPSC^c, Tim Swartzel, BS^d, Jade Adriana Marie van Well, MSc^e, Eva Anna Elisabeth Gommers, MSc^f, and Margaret Rosenfeld, MD,MPH^g

^aDepartment of Radiology, Seattle Children's Hospital, University of Washington, Seattle, WA

^bDepartment of Clinical and Translational Research, Seattle Children's Hospital, Seattle, WA

^cDepartment of Respirator Care, Seattle Children's Hospital, Seattle, WA ^dSeattle Children's Hospital, Seattle, WA ^eSeattle Children's Hospital, Erasmus University, Rotterdam, Netherlands

^fSeattle Children's Hospital, Saint Francis Hospital, Rotterdam, Netherlands ^gDepartment of Pulmonary Medicine, Seattle Children's Hospital, Seattle, WA

Abstract

Background: Image quality of high resolution chest CTs (HRCTs) depends on adequate breath holds at end-inspiration and end-expiration. We hypothesized that implementation of spirometry-assisted breath holds in children undergoing HRCTs would improve image quality over that obtained with voluntary breath holds by decreasing motion artifact and atelectasis.

Methods: This is a retrospective case-control study of HRCTs obtained at a tertiary care children's hospital before and after implementation of a spirometry assisted CT protocol, in which children 8 years of age are first trained in supine slow vital capacity maneuvers and then repeat the maneuvers in the CT scanner, coached by a respiratory therapist. Spirometry-assisted CT scans (cases) were matched by age, gender and diagnosis (cystic fibrosis vs. other) to CT scans obtained with voluntary breath holds in the 6 years prior to implementation of the spirometry assistance protocol (controls), and evaluated by two blinded pediatric radiologists.

Results: Among both cases and controls (N=50 each), 10 carried the diagnosis of cystic fibrosis and 40 had other diagnoses. Mean age was 12.9 years (range 7.5, 20.1) among cases and 13.0 (7.1, 19.7) among controls. Mean (SD) inspiratory image density among cases was -852 (37) Hounsfield units (HU) and -828 (43) among controls ($p=0.006$). Mean (SD) expiratory image density was -629 (95) HU among cases and -688 (83) HU among controls ($p=0.002$). Mean (SD) change in image density between inspiratory and expiratory images was +222 (85) HU among cases and +140 (76) HU among controls ($p<0.001$). Motion artifact was present on inspiratory images in 5 cases and 9 controls ($p=0.39$ by Fisher's exact test), and on expiratory images in 20 cases and 18 controls ($p>0.80$). Atelectasis was present on inspiratory images in 8 cases and 9 controls and on expiratory images in 9 cases and 10 controls ($p>0.80$).

Conclusions: Spirometry assisted CTs had a significantly greater difference in lung density between inspiratory and expiratory scans than those performed with voluntary breath holds, likely

improving the ability to detect air trapping. No appreciable difference in image quality was detected in terms of presence of motion artifact or atelectasis.

Introduction

Optimizing image protocols for various clinical indications allows radiologists and clinicians to ensure the highest possible sensitivity and specificity for disease processes. This is particularly important for CT, where radiation dose and cost makes repeat examinations for poor quality undesirable. High resolution chest CT (HRCT) is often used to monitor patients with cystic fibrosis (CF) and to evaluate patients for interstitial lung disease. While there are many potential findings possible, in these settings we are often searching for bronchiectasis, air trapping, and patterns of parenchymal interstitial disease. These findings can be subtle, especially early in the disease process.¹ In addition, respiratory motion hinders image interpretation.² Bronchiectasis is best evaluated on images obtained at end-inspiration (total lung capacity) and air trapping on images at the end of a full expiratory maneuver (residual volume).³ In most centers, voluntary breath-holds are used during scanning. Patients are instructed to breath-hold after a maximal inhalation maneuver for the inspiratory scan and then to maximally exhale and breath-hold for the expiratory scan. As many patients, particularly children, have difficulty following these instructions, images are often not obtained at true end-inspiration or end-expiration. In a pediatric study of 20 CF patients, (mean age 12 years), voluntary breath hold lung volumes were compared with lung volumes measured by plethysmography prior to scanning.⁴ Mean inspiratory volume was 77% of total lung capacity but ranged from 55% to 106%. Mean expiratory volume was 140% of residual volume (range 83% to 293%). Thus, while inspiratory images were generally obtained near total lung capacity, end-expiratory scans were obtained at lung volumes closer to functional residual capacity than residual volume.

Lung volumes can be controlled and motion artifact minimized in infants and toddlers under anesthesia using the controlled ventilation technique.⁵ The impact of suboptimal lung volumes on detection of bronchiectasis and air trapping was documented in a study of 16 young children undergoing sedated HRCT either with controlled ventilation or during tidal breathing. Bronchiectasis was identified on 30% of images obtained at end-inspiration compared to 6% of images obtained during tidal breathing. Air trapping was detected on 45% of images obtained at end-expiration, compared to 19% of images obtained near functional residual capacity.⁵ In school-age children, spirometry assistance is an alternative to voluntary breath holds to ensure reproducible lung volumes. In this technique, patients are first trained in the pulmonary function lab to perform a supine slow vital capacity maneuver to obtain full inflation and complete exhalation. They then perform this same maneuver in the CT scanner during image acquisition, coached by a trained respiratory technician.⁶ This technique may be particularly suitable for patients with prior experience with spirometry, such as cystic fibrosis patients. While spirometry-assisted HRCT has been shown to improve image quality in adults,⁷ it has been minimally evaluated in children. Kongstad, et al showed that spirometry-assisted HRCT in pediatric cystic fibrosis patients improved detection of gas trapping on expiratory images. However, they did not evaluate overall image quality.⁸ The objective of the current study was to test the hypothesis that spirometry-assisted HRCT

would yield improved image quality (decreased motion artifact and atelectasis) as compared to scans obtained with voluntary breath holds.

Materials and Methods

Study design and eligibility:

We conducted a retrospective case-control study of chest HRCTs obtained at Seattle Children's Hospital before and after implementation of a spirometry assisted CT protocol in July, 2013. Eligibility to participate included age $\geq$ 8 years, ability to cooperate with a slow vital capacity maneuver and being a patient of the Pulmonology or Rheumatology services (inpatient or outpatient). Spirometry-assisted CT scans (cases) obtained from July, 2013 to August 2014 were matched 1 to 1 by age (within one year), gender and diagnosis (cystic fibrosis vs. other) to CT scans obtained with voluntary breath holds from July, 2007 to June 2013 (controls). Patients who had serial imaging contributed a single scan selected at random to the analysis. The Seattle Children's Hospital Institutional Review Board approved this study.

Test procedures:

In the spirometry-assisted HRCT protocol, children were first trained in supine slow vital capacity maneuvers by a respiratory therapist, who then accompanied the patient to the CT scanner. Spirometry was accomplished with a portable Vmax spirometer (Carefusion, San Diego, CA, USA) with a custom adjustable holder for use in the CT gantry. After an initial scout CT image, the patient performed slow vital capacity maneuvers with coaching by the respiratory therapist while supine on the CT gantry. When adequate maximal inhalation or exhalation breath holds were achieved based on the personal best values acquired during the practice session, the CT scan was performed. In the historical voluntary breath hold maneuver (control patients), patients were instructed by the CT technician to take a deep breath in and breath-hold, and then exhale fully and breath-hold.

CT scans:

All HRCTs were performed on GE Lightspeed VCT 64 or GE Discovery DST 64 model scanners (GE Healthcare Corporation, Milwaukee, WI, USA), at either 100 kVp (patients less than 40.5 kg) or 120 kVp (patients over 40.5 kg). After a scout image for anatomic landmarks and automated exposure modulation, the inspiratory breath hold was performed. During the breath hold, a contiguous helical acquisition from the lung apices through the diaphragm was obtained. Then, the exhalation breath hold was performed. An attempt was made to obtain 5 axially acquired evenly spaced images during this breath hold. If all 5 images could not be obtained with a single end-exhalation breath hold, additional breath holds were performed as needed in order to obtain a total of 5 images. Inspiratory images were reconstructed in a high special resolution edge sharpened (lung) algorithm at 1mm thick axial and 3mm thick coronal and sagittal planes. Axial and coronal 5 mm maximum intensity projection (MIP) and 3.75 soft tissue algorithm axial images were additionally constructed. The exhalation images were constructed with the same edge sharpened algorithm.

Analysis:

Examinations were evaluated in random order by two experienced, board-certified pediatric radiologists (JO and JS), blinded to scan type, date and all clinical and demographic information, on a PACS workstation (GE Centricity PACS 4.0, GE Healthcare, Barrington, IL). Lung density in Hounsfield units (HU) was measured in the most normal area of lung (i.e. no air trapping, atelectasis, or other pathology) within a representative region on each expiratory image and a matching region on the inspiratory images. (Figure 1) Transverse and anteroposterior inner thoracic wall dimensions were measured at the level closest the carina and to the xiphoid on inspiratory and expiratory images as another measure of change in lung volume. The presence or absence of bowing of the posterior tracheal membrane was recorded as another marker for expiratory effort. (Figure 2) The subjective overall image quality (on a 5 point Likert scale), amount and location of atelectasis, and the presence and amount of motion artifact were recorded. Data were recorded using REDCap research database software version 6.8.2.

Patient characteristics were summarized with descriptive statistics. Characteristics of images obtained with spirometry assistance vs. voluntary breath hold were compared using Fisher's exact test for continuous variables and Chi-square test for categorical variables. A p value of <0.05 was considered statistically significant. No correction for multiple comparisons was made. All analyses were conducted using R 3.2.3 (R Foundation for Statistical Computing, Vienna, Austria).

Results

Participant characteristics (Table 1):

Among both cases and controls (N=50 each), 10 carried the diagnosis of cystic fibrosis and 40 had other diagnoses. Mean age was 12.9 years (range 7.5, 20.1) among cases and 13.0 (7.1, 19.7) among controls.

Lung volumes and image density:

Among the cases, the slow vital capacity maneuvers performed in the CT scanner achieved a median (IQR) inspiratory volume of 95.0% (91.0% - 98.9%) and a median (IQR) expiratory volume of 95.0% (89.2% - 97.8%) of the best respective volumes achieved during the practice session. Image density and measured chest wall diameter of inspiratory and expiratory images are shown in Table 2. Mean inspiratory ($p=0.006$) and expiratory ($p=0.002$) image density as well as change in density between inspiratory and expiratory images ($p<0.001$) were significantly different between cases and controls. In addition, the AP diameter of the chest wall measured at the carina was significantly larger on inspiratory images ($p < 0.001$) and significantly smaller on expiratory images ($p = 0.01$) among cases compared to controls. The AP diameter of the chest measured at the xiphoid on expiration was also significantly lower among cases than controls ($p = 0.04$). The other chest wall measurements were not significantly different between the two groups.

Image quality:

Image quality results are presented in Tables 3 and 4. Overall image quality was high, with no significant difference between cases and controls. Motion artifact was detected in a greater proportion of expiratory than inspiratory images, though with no difference between cases and controls. Atelectasis was detected in similar proportions of inspiratory and expiratory images (Table 4), again with no difference between cases and controls.

Discussion

We have shown that a spirometry-assisted CT protocol resulted in significantly greater inspiratory lung volumes and significantly lower expiratory volumes compared to voluntary breath holds, as measured by lung density and chest wall diameter. Patients were able to achieve a median of 95% of their best inspiratory slow vital capacity during CT scanning, and an expiratory effort also a median of 95% of their best expiratory effort. Nonetheless, we were not able to detect an effect of the spirometry protocol on overall image quality. Image quality was higher on inspiratory than expiratory scans in both cases and controls, with no suggestion of decreased motion artifact or atelectasis with spirometry assistance. Because expiratory images obtained with spirometry assistance were obtained at significantly lower lung volumes (i.e., closer to residual volume) than those obtained by voluntary breath hold, spirometry-assisted CT scans are likely to result in improved detection of air trapping, as shown previously by Kongstad, et al⁸ and Goris, et al⁹ but may not improve detection of abnormalities on inspiratory images such as bronchiectasis and interstitial or parenchymal changes.

Air trapping is an important indicator of early peripheral airway obstruction in CF lung disease¹ and can also be prominent in advanced CF lung disease.¹⁰ The progression of air trapping over time is quite variable, however, making changes over time in an individual patient difficult to interpret from a clinical standpoint. In addition, the utility of evaluating air trapping in other diseases for which HRCTs may be performed, such as collagen vascular diseases, is less clear.

Instituting this HRCT protocol required significant effort on the part of respiratory therapists and CT technologists. It added time to the examination and required coordination between the PFT lab and the radiology department, which can be an additional challenge. The combined expense of spirometry along with the CT is higher than that of the CT alone. These factors should also be considered when deciding to implement a new protocol. Additionally, this protocol requires the child be able to adequately perform spirometry, making it suitable primarily for children over 5 to 8 years of age. In younger children, if sensitive evaluation of gas trapping is considered critical, controlled ventilation CT scanning under anesthesia may be indicated.

Limitations of our study include that we utilized a retrospective design employing historical controls. The radiation associated with CT scans precluded concurrent evaluation of spirometry-assisted and voluntary breath hold CTs. Nonetheless, the CT algorithm was otherwise stable during this time period, cases and controls were matched in terms of disease indication and age, and the two radiologists were blinded to type of scan. An additional

strength is the larger size of our cohort compared to the previously published study in pediatric patients,⁸ the fact that we evaluated CTs performed for indications other than CF and the fact that all our patients were at a single institution, thereby avoiding possible underlying true biologic differences between cases and controls due to different exposures or treatment practices.

Conclusion

Spirometry assistance during CT scanning improves the lung volumes at which inspiratory and, particularly, expiratory images are obtained and allows quantification of lung volumes relative to the patient's best slow vital capacities. However, the additional time, cost and scheduling considerations necessary for spirometry-assisted scans may make this protocol difficult to justify for routine use in all HRCT examinations. Spirometry assistance may be of greatest benefit when precise delineation of subtle changes in air trapping on expiratory images is important, such as in a clinical trial or in monitoring response to treatment or disease progression in individual CF patients. It may also be helpful in individual patients who have difficulty with voluntary respiratory control and would benefit from spirometry coaching. These are areas of possible further research. In our own institution, based on these results, we no longer incorporate spirometry assistance routinely into all HRCT scans among Pulmonary and Rheumatology patients, but rather leave the decision to the discretion of the ordering provider.

References

1. Rosenow T, Oudraad MC, Murray CP, et al. PRAGMA-CF. A quantitative structural lung disease computed tomography outcome in young children with cystic fibrosis. *Am J Respir Crit Care Med*. 2015;191(10):1158–1165. [PubMed: 25756857]
2. Long FR. High-resolution computed tomography of the lung in children with cystic fibrosis: Technical factors. *Proc Am Thorac Soc*. 2007;4(4):306–309. [PubMed: 17652491]
3. Loeve M, Krestin GP, Rosenfeld M, de Bruijne M, Stick SM, Tiddens HA. Chest computed tomography: A validated surrogate endpoint of cystic fibrosis lung disease? *Eur Respir J*. 2013;42(3):844–857. [PubMed: 23258780]
4. Loeve M, Lequin MH, de Bruijne M, et al. Cystic fibrosis: Are volumetric ultra-low-dose expiratory CT scans sufficient for monitoring related lung disease? *Radiology*. 2009;253(1):223–229. [PubMed: 19710003]
5. Long FR, Williams RS, Adler BH, Castile RG. Comparison of quiet breathing and controlled ventilation in the high-resolution CT assessment of airway disease in infants with cystic fibrosis. *Pediatr Radiol*. 2005;35(11):1075–1080. [PubMed: 16041581]
6. Robinson TE. Computed tomography scanning techniques for the evaluation of cystic fibrosis lung disease. *Proc Am Thorac Soc*. 2007;4(4):310–315. [PubMed: 17652492]
7. Moroni C, Mascalchi M, Camiciottoli G, et al. Comparison of spirometric-gated and -ungated HRCT in COPD. *J Comput Assist Tomogr*. 2003;27(3):375–379. [PubMed: 12794602]
8. Kongstad T, Buchvald FF, Green K, Lindblad A, Robinson TE, Nielsen KG. Improved air trapping evaluation in chest computed tomography in children with cystic fibrosis using real-time spirometric monitoring and biofeedback. *J Cyst Fibros*. 2013;12(6):559–566. [PubMed: 23810566]
9. Goris ML, Zhu HJ, Blankenberg F, Chan F, Robinson TE. An automated approach to quantitative air trapping measurements in mild cystic fibrosis. *Chest*. 2003;123(5):1655–1663. [PubMed: 12740287]

10. Loeve M, van Hal PT, Robinson P, et al. The spectrum of structural abnormalities on CT scans from patients with CF with severe advanced lung disease. *Thorax*. 2009;64(10):876–882. [PubMed: 19541686]

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Figure 1 -
Inspiratory (a) and expiratory (b) images from a HRCT at the same level, demonstrating the change in lung density, and a representative area of Hounsfield unit measurement (circle).

Figure 2 –.
Representative inspiratory (a) and expiratory (b) images from a single patient demonstrating the change in shape of the posterior tracheal membrane (black arrows) from convex to concave, a sign of respiratory effort.

Table 1 –

Participant demographics

	Case (N=50)	Control (N=50)
Age in years, mean (range)	12.9 (7.5 – 20.1)	13.0 (7.1 – 19.7)
Male/Female (%)	40/60	40/60
Weight, kg, mean (range)	46.5 (18.9 – 106.2)	49.4 (18.1 – 84.3)
Height, cm, mean (range)	149.4 (113 – 189)	150.4 (115 – 197)
Race (%)		
White	64	56
Afr. American	6	6
Asian	6	6
Other/Unknown	24	32

Table 2 –

Characteristics of inspiratory and expiratory scans

	Case	Control	p-value
Mean density, HU of inspiratory scan (SD)	–851 (37)	–828 (43)	p = .006
Mean density, HU of expiratory scan (SD)	–629 (95)	–688 (83)	p = .002
Mean change in HU between inspiratory and expiratory scans (SD)	222 (85)	140 (76)	p < .001
% of inspiratory scans with trachea convex	100	92	p = 0.06
% of expiratory scans with trachea concave	54	61	p = 0.54
Mean Inner chest wall diameter in mm during inspiration (SD)			
At carina, AP	93.4 (15.2)	84.3 (16.1)	p = 0.001
At carina, transverse	207.6 (27.4)	202.4 (27.3)	p = 0.18
At xiphoid, AP	104.8 (18.4)	101.4 (17)	p = 0.22
At xiphoid, transverse	219 (28.4)	219 (26.1)	p = 0.99
Mean inner chest wall diameter in mm during expiration, mm (SD)			
At carina, AP	54.2 (12.5)	60.4 (13)	p = 0.013
At carina, transverse	181.8 (24.9)	185 (26.2)	p = 0.43
At xiphoid, AP	82.2 (17.1)	88.5 (16.2)	p = 0.044
At xiphoid, transverse	208.3 (25.4)	211.4 (25)	p = 0.27
Mean change in chest wall diameter in mm from inspiration to expiration, mm (SD)			
At carina, AP	39.2 (13.4)	23.8 (12.9)	p < 0.001
At carina, transverse	25.8 (12.3)	17.3 (9.2)	p < 0.001
At xiphoid, AP	22.6 (10.9)	12.9 (9.8)	p < 0.001
At xiphoid, transverse	10.7 (6.3)	7.6 (7.0)	p = 0.014

* Measured on axial images from the pleural surface at the sternum to the anterior vertebral body.

Table 3 –

Image quality measurements

Image Quality Comparison					
	Inspiration			Expiration	
	Case	Control		Case	Control
Excellent image quality	45	41		30	32
Good, slight artifact with no limitation of evaluation	5	8		13	16
Adequate, slight limitation in evaluation	0	1		6	2
Poor, limited evaluation	0	0		1	0
Very poor with unreliable evaluation	0	0		0	0

Table 4 –

Atelectasis comparison

Atelectasis Comparison					
Lobes with atelectasis	Inspiration			Expiration	
	Case	Control		Case	Control
0	42	41		41	40
1	7	3		7	6
2	0	3		1	1
3	0	1		0	1
4	1	2		1	2