Received:
16 October 2017

Revised:
27 February 2018

Accepted:
15 March 2018

<https://doi.org/10.1259/bjr.20170796>

Cite this article as:

Yoon SH, Lee C, Park J, Goo JM, Park J-Y. Gradient-echo-based 3D submillisecond echo time pulmonary MR imaging: a preliminary usability study on clinical and preclinical MR scanners. *Br J Radiol* 2018; **91**: 20170796.

SHORT COMMUNICATION

Gradient-echo-based 3D submillisecond echo time pulmonary MR imaging: a preliminary usability study on clinical and preclinical MR scanners

¹SOON HO YOON, MD, ²CHANHEE LEE, MSc, ²JINIL PARK, MSc, ^{1,3}JIN MO GOO, MD and ²JANG-YEON PARK, PhD

¹Department of Radiology, Seoul National University College of Medicine, Seoul National University Hospital, Seoul, South Korea

²Department of Biomedical Engineering, Center for Neuroscience Imaging Research, Institute for Basic Science, Sungkyunkwan University, Suwon-si, South Korea

³Institute of Radiation Medicine, Seoul National University Medical Research Center, Seoul, South Korea

Address correspondence to: Dr Jang-Yeon Park

E-mail: jyparu@skku.edu

†The authors Soon Ho Yoon and Chanhee Lee contributed equally to the work.

Objective: To preliminarily investigate a technical feasibility of a submillisecond echo time concurrent-dephasing-and-excitation (CODE) sequence for pulmonary MRI on clinical and preclinical MR scanners

Methods: CODE imaging (echo time, 0.14 ~ 0.18 ms) was performed with American College of Radiology phantom at 3 T, 7 healthy volunteers at 1.5 and 3 T, 10 rabbits at 3 T, and 2 rodents at 9.4 T. Signal-to-noise ratio was compared in phantom. Image quality of human MRI was visually assessed on a 5-point scale for comparison between CODE and conventional lung MRI sequences. Visibility of bronchi, subcentimeter nodules, and MR air-bronchogram were assessed in animal studies.

Results: In phantom study, signal-to-noise ratio was higher with CODE than with original three-dimensional

ultrashort-echo time sequence (106.71 ± 4.32 vs 91.66 ± 3.54 ; $p < 0.001$). Image quality of human MRI was better with CODE than with conventional MRI sequences ($p \leq 0.002$). Bronchi remained traceable up to the fifth bronchial generation in CODE images in rabbits and rodents. 95.2% of metastatic nodules (diameter, 1.5 ± 0.4 mm) and 93.8% of MR air-bronchogram (diameter, 0.9 ± 0.2 mm) in rabbits.

Conclusion: Submillisecond echo time pulmonary MRI was technically feasible by using CODE on various MR scanners.

Advances in knowledge: CODE can be a practical alternative for lung MRI on both clinical and pre-clinical scanners, without challenges of free-induction-decay-based ultrashort-echo time sequences.

INTRODUCTION

Lung MRI has been limited in its use mainly due to innate characteristics of the lung: a paucity of protons; shortened T_2^* due to large magnetic-susceptibility differences at the interface between airspace and bronchovascular structure; and cardiopulmonary motions. Such difficulties can be mitigated with ultrashort-echo time (UTE) MRI.¹ Several UTE imaging techniques such as original three-dimensional (3D) UTE,²⁻⁵ sweep imaging with Fourier transform,⁶ zero echo time,⁷ and pointwise-encoding time reduction with radial acquisition⁸ have been developed for imaging ultrashort T_2 species and tentatively introduced for lung MRI providing anatomical and functional (e.g. perfusion) information with a radiation-free diagnostic potential for pulmonary diseases. From a technical standpoint, some sophisticated but impressive improvements of original 3D UTE for lung MRI were recently made using

variable density gradients and limited field of view by slab selection.³ Appropriate k-space trajectories of 3D radial sampling were also suggested for free-breathing lung MRI with retrospective respiratory gating.⁹

3D UTE pulse sequences usually offer the minimum echo time (or delay time) less than 0.01^{6,7} to 0.05–0.1 ms²⁻⁵ with strong hardware requirements, e.g. for quick transmit/receive switching, and/or intricate acquisition strategies including gradient-ramp sampling. Most of them adopt free-induction-decay (FID) acquisition schemes with radial sampling to minimize echo time, which may cause a trouble in preserving the true $k = 0$ by missing some samples nearby the k-space center.¹⁰

The concurrent-dephasing-and-excitation (CODE) pulse sequence, a recently developed 3D radial gradient-echo

submillisecond echo time sequence, can be implemented on pre-clinical and clinical MR scanners without demanding hardware or sequence modification.¹¹ Since it employs gradient-echo acquisition, CODE can avoid most of the challenges that other FID-based UTE imaging techniques encounter, still offering echo times of ~0.14 ms or longer.

The aim of this study was to preliminarily investigate a technical feasibility of the CODE sequence for submillisecond echo time pulmonary anatomic MRI on clinical and preclinical MR scanners.

METHODS AND MATERIALS

A human study was approved by the institutional review board of our hospital (IRB No. H- 1305-623-491), and informed consent was obtained from all participants. An animal experiment was approved by the Institutional Animal Care and Use Committee at Seoul National University Hospital (IACUC No. 13-0006-C2A0).

Pulse sequence

For submillisecond echo time imaging, a 3D radial gradient-echo-based CODE sequence was used,¹² where the pre-dephasing gradient applies during spin excitation to minimize echo time ([Supplementary Figure 1](#), [Supplementary Material](#) available online). Since asymmetric gradient echoes are produced in CODE, missing some sample points near the k-space center is not an issue *vis-a-vis* FID-based UTE imaging. Besides, non-uniform k-space sampling during gradient ramping is not needed because gradient-echo acquisition begins on a gradient plateau. A tailored sinc radiofrequency pulse was used ensuring a flat frequency-response profile.

Patients and animals

A summary of MR studies is shown in [Supplementary Figure 2](#). Seven healthy adult volunteers participated in human lung study. For animal study, we used 10 rabbits (New Zealand White, male, 3.0–3.5 kg) and 2 normal rats (Fischer 344, male, 8 weeks of age).

The 10 rabbits were divided into control ($n = 5$) and disease groups ($n = 5$). Among the disease group, hematogenous pulmonary metastasis was induced in three rabbits by intravenous injection of 0.5 ml of tumor suspension of VX2 carcinoma into the marginal ear vein using an 18-gauge needle. A lobar pneumonia model was induced in other two rabbits. After tracheal intubation, a Terumo guide wire and a 4Fr. Davis catheter were applied through the endotracheal tube on conventional fluoroscopy for selection of the right lower lobes, and subsequently, 1 ml of complete Freund's adjuvant was injected. The animals were allowed food and water *ad libitum*.

MR image acquisition

MRI was performed on two clinical and one pre-clinical scanners: 1.5 T clinical scanner (Siemens Avanto, Erlangen, Germany) for human study; 3 T clinical scanner (Magnetom Trio; Siemens, Erlangen, Germany) for phantom, human and rabbit studies; 9.4 T pre-clinical scanner (Agilent Technologies, Santa Clara, CA) for rat study.

CODE was optimized for pulmonary MRI including in terms of scan parameters, k-space trajectories, and optimal number of radial views ([Supplementary Material 1](#)). Particularly, the k-space trajectories were chosen to maintain k-space uniformity after retrospective respiratory gating, containing self-navigation for motion tracking.⁹ Detailed scan parameters for CODE imaging are shown in [Table 1](#). An original 3D-UTE (oUTE hereafter) sequence was also optimized in terms of scan parameters including number of radial views to acquire 3D FID-based UTE images. Three conventional lung MRI sequences were used for comparison of image quality in human volunteers.

Image analysis

CODE and oUTE image reconstruction was performed offline in MATLAB (Mathworks, R2011a, Natick, MA) using fast Fourier transform via gridding.

For signal-to-noise ratio (SNR) comparison using an American College of Radiology phantom, 13 square regions of interest (size, $22 \times 22 \text{ mm}^2$) were selected all over the phantom. To properly evaluate the SNR of multichannel-coils data, SNR was calculated by the difference method, which utilizes a difference image of two repeated identical acquisitions, as specified by Dietrich et al.¹³

Qualitative visual analyses were performed on the CODE and conventional lung MRI human volunteer data acquired at 3 T in terms of image quality, noise and artifacts. It was rated on a 1–5 scale by consensus of two radiologists with more than 7 years of experience in chest MRI, applying a grading system for assessment of each item ([Table 2](#)).

In normal rabbits and rats, the radiologists traced bronchi on consecutive axial CODE images and assessed the last generation of traceable bronchi. Nodules in a lung metastasis model and MR air-bronchogram in a lobar pneumonia model were identified on CODE images and compared with those on CT images which were served as a reference standard. CT scan was taken within 2 days before MRI.

Statistical analysis

The paired *t*-test was used for SNR comparison between CODE and oUTE images of phantom at 3 T. Semi-quantitative grades of CODE and conventional lung MRI sequences were also compared using the Friedman test. The *post hoc* analysis was performed using a Wilcoxon's rank test between pairs of MRI sequences after Bonferroni correction by applying a *p*-value of 0.005 for 10 pairs of the 5 lung MRI sequences. A two-sided significance level of 5% was used for all analyses. Statistical analyses were performed using the SPSS package (SPSS 22.0, Inc., Chicago, IL).

RESULTS

SNR comparison: CODE vs original 3D UTE in phantom

CODE images showed about 16% higher SNR (106.71 ± 4.32) than oUTE images (91.66 ± 3.54) ($p < 0.001$) ([Supplementary Figure 3](#)).

Table 1. Acquisition parameters for pulmonary MRI

MR scanner	Target	Pulse sequence	Coil	Dim.	TR (ms)	TE (ms)	FA (°)	FOV (mm)	Matrix	Resolution (mm)	# of views	RF pulse	Acquisition time (sec)
Optimization: number of radial views and respiratory gating													
9.4 T (Agilent)	Water phantom (diameter, 3.5 cm)	CODE	Single-channel transceiver coil	3D	3.58	0.25	10	80 ³	128 ³	0.63 ³	Varying ^b	sinc	107.4 250.6
SNR Comparison: CODE vs conventional 3D UTE													
3T (Trio)	ACR phantom ^a	CODE	4-ch head coil	3D	3.43	0.14	5	384 ³	352 ³	1.10 ³	100,000	sinc+	343
3T (Trio)	ACR phantom ^a	UTE	4-ch head coil	3D	3.43	0.075	5	384 ³	352 ³	1.10 ³	100,000	square	343
<i>In vivo</i> anatomic imaging													
1.5 T (Avanto)	Human thorax	CODE	3-ch body and 2-ch chest coils	3D	3	0.14	2 ^d	384 ³	500 ³	0.77 ³	160,200	sinc	480.6
3T (Trio)	Human thorax	CODE	3-ch body and 2-ch chest coils	3D	3	0.14	2 ^d	384 ³	500 ³	0.77 ³	160,200	sinc	480.6
3T (Trio)	Human thorax	UTE	3-ch body and 2-ch chest coils	3D	3.35	0.05	5	320	400 ³	0.80 ³	160,200	rect	480.6
3T (Trio)	Rabbit thorax	CODE	8-ch knee coil	3D	8 ^c	0.17	5	250 ³	392 ³	0.64 ³	60,000	sinc	480
9.4 T (Agilent)	Rat thorax	CODE	Single-channel transceiver coil	3D	3.38	0.18	5	150 ³	600 ³	0.25 ³	100,000	sinc	338
3T (Trio)	Human thorax	T ₂ w TSE	3-ch body and 2-ch chest coils	2D	5,320	83	140	379 × 308	384 × 250	1.0 × 1.2 × 6.0			180
3T (Trio)	Human thorax	T ₁ w VIBE	3-ch body and 2-ch chest coils	2D	3.8	1.4	11	300 × 243	384 × 250	0.8 × 1.0 × 4.0			15
3T (Trio)	Human thorax	T ₁ w radial VIBE	3-ch body and 2-ch chest coils	2D	3.3	1.3	11	379 × 308	384 × 250	1.0 × 1.2 × 4.0			90

2D, two-dimensional; 3D, three-dimensional; ACR, American College of Radiology; CODE, concurrent dephasing and excitation; Dim., dimension; FA, flip angle; FOV, field of view; RF, radiofrequency; SNR, signal-to-noise ratio; TE, echo time; TR, repetition time; TSE, turbo spin echo; UTE, ultrashort-echo time; VIBE, volumetric interpolated breath-hold examination.

^aPhantom diameter, 190 mm, filled with a solution of 10-mM NiCl₂ and 75-mM NaCl.

^b30,000 and 70,000.

^cLonger than others due to dual-echo acquisition.

^dDue to the hardware limitation of the RF peak amplitude for the spatial resolution of ~0.8 mm, the flip angle was not allowed to exceed 2°.

Table 2. Qualitative grading system for the assessment of image quality and noise

Overall image quality
(1) Non-diagnostic; (2) poor; (3) fair; (4) good; and (5) excellent.
Depiction of the intrapulmonary vessels and lobar fissure
(1) Unacceptable (invisible central pulmonary vessels);
(2) Poor (barely visible central pulmonary vessels);
(3) Fair (visible peripheral pulmonary vessels with blurred margin);
(4) Good (visible peripheral pulmonary vessels with clear margin);
(5) Excellent (visible peripheral pulmonary vessels with clear margin and lobar fissures).
Depiction of the mediastinal structures
(1) Unacceptable (indistinguishable great vessels);
(2) Poor (only visible great vessels with clear margin);
(3) Fair (partially visible part of azygos vein and esophagus with indistinct margin);
(4) Good (partially visible part of azygos vein and esophagus with clear margin);
(5) Excellent (visible entire azygos vein and esophagus with clear margin).
Depiction of the bronchial structure
(1) Unacceptable (indistinguishable bronchial wall of lobar bronchi);
(2) Poor (clearly visible bronchial wall of lobar bronchi with few visible segmental bronchial walls);
(3) Fair (visible most of segmental bronchial walls with indistinct margin);
(4) Good (clearly visible most of segmental bronchial walls);
(5) Excellent (clearly visible some subsegmental bronchial walls).
Image noise
(1) Unacceptable; (2) above average increase; (3) average and acceptable; (4) less than average; and (5) minimum or nothing.
Respiratory motion, cardiovascular, and streak artifacts
(1) Unreadable because of severe artifacts; (2) substantial artifacts; (3) moderate artifacts; (4) minor artefacts; and (5) no artifacts.

In vivo anatomic imaging of human lung

Qualitative assessment of image quality showed a superiority of CODE to conventional lung MRI sequences in all items ($p \leq 0.002$), although the *post hoc* analysis failed to prove statistical significance due to the small number of subjects (Table 3). When retrospective respiratory gating was applied to CODE imaging, overall score was slightly improved (4.6→4.9): visibilities of intrapulmonary vessels and fissures (4.1→4.6), bronchial structures (4.3→4.7), image quality (3.7→4.1), and

artifacts (3.8→4.2) were improved, while visibility of mediastinal structures maintained. CODE image quality at 1.5 T (Figure 1) and oUTE image quality at 3 T fairly competed with CODE image quality at 3 T (Figure 2).

In vivo anatomic rabbit imaging

In normal rabbits, main, lobar and proximal segmental bronchi were clearly identifiable with thin bronchial walls. Thin bronchial walls were rarely visualized in the fourth

Table 3. Semi-quantitative comparison of image quality and noise between CODE and conventional lung MRI sequences

	T_2 W TSE	T_1 W VIBE	T_1 W radial VIBE	CODE		<i>p</i> -value
				Free breathing	Respiratory gated	
Overall image quality	3.1 ± 0.4	3.7 ± 0.5	3.9 ± 0.4	4.6 ± 0.5	4.9 ± 0.4	<0.001
Intrapulmonary vessels and fissures	2.7 ± 0.8	3.7 ± 0.5	4.0 ± 0.0	4.1 ± 0.7	4.6 ± 0.5	0.001
Mediastinal structure	3.7 ± 0.5	4.0 ± 0.6	4.1 ± 0.4	4.9 ± 0.4	4.9 ± 0.4	0.001
Bronchial structure	3.3 ± 0.5	3.1 ± 0.4	3.7 ± 0.5	4.3 ± 0.5	4.7 ± 0.5	0.001
Image noise	3.1 ± 0.4	3.0 ± 0.8	3.4 ± 0.5	3.7 ± 0.5	4.1 ± 0.4	0.002
Artifacts	3.7 ± 0.5	4.1 ± 0.3	4.2 ± 0.3	3.8 ± 0.3	4.2 ± 0.2	0.002

CODE, concurrent dephasing and excitation; TSE, turbo spin echo; VIBE, volumetric interpolated breath-hold examination.

Figure 1. Representative axial free-breathing CODE images on 1.5 T (a, b) and 3 T clinical MR scanners (c, d), retrospectively respiratory-gated images on a 3 T clinical MR scanner (e, f) in a 30-year-old male volunteer. Bilateral major fissures (white arrow heads) and subsegmental bronchi (white arrows) in apical and posterior segment of both upper lobes are visible (a, c). Segmental bronchi and divisions of subsegmental bronchi (white arrows) are identifiable in both lower lobes with minute overlying streak artifacts (b, d). Note the difference of contrast between 1.5 and 3 T MR images. Image contrast obtained on a 1.5 T scanner was closer to a T_1 weighted image at the flip angle of 2° , while that obtained on 3 T machine was closer to a proton density-weighted image at the same flip angle, since the T_1 values of tissues at 1.5 T are relatively shorter than those at 3 T. Retrospectively respiratory-gated images on a 3 T scanner improved the visibility of bronchi in the lower lobes where respiratory movement was large, but not in the upper lobes where respiratory movement was negligible (e, f). CODE, concurrent-dephasing-and-excitation; UTE, ultrashort-echo time.

to fifth bronchial generation. Bronchi remained consecutively traceable up to the fifth bronchial generation in CODE images.

In three rabbits with pulmonary metastasis, a total of 21 subcentimeter-sized nodules were identified on CT images in lung parenchyma. Mean diameter and standard deviation of the nodules were 1.5 ± 0.4 mm. Of the 21 nodules, 20 nodules [95.2%; 95 CI (75.6–99.9%)] were found on CODE images (Figure 3). One nodule in the left lung base was missed on CODE images as the nodule was masked by the opacity induced from a diaphragmatic motion artifact. On CODE images, a 1 mm-sized nodule was additionally found in the left upper lobe, which was not identified on CT images, and this nodule was proven to be metastasis on follow-up CT scan after 10 days.

Figure 2. Representative axial free-breathing conventional UTE images (a, c, e) and CODE images (b, d, e) on 3 T clinical scanners in a 25-year-old male volunteer. Multiple segmental bronchi and divisions of subsegmental bronchi are identifiable in both lungs in original UTE and CODE images. Image contrast of UTE image was closer to T_1 weighting at the flip angle of 5° , while CODE image was relatively proton-density weighted, since CODE image was obtained at the less flip angle of 2° than UTE image. CODE, concurrent-dephasing-and-excitation; UTE, ultrashort-echo time.

In 2 rabbits with lobar pneumonia, a total of 16 air-bronchograms were identified on CT images. Mean diameter and standard deviation of orifice of air-bronchogram were 0.9 ± 0.2 mm. Among them, 15 [93.8%; 95 CI (69.6–99.9%)] were identically found on CODE images (Figure 3).

In vivo anatomic rat imaging

Main, lobar and segmental bronchi were clearly identifiable and thin bronchial walls were well depicted up to the third bronchial generation and partly visualized in the fourth to fifth bronchial generation (Figure 4). Bronchi were continuously traceable up to the fifth bronchial generation in CODE images.

DISCUSSION

High-resolution 3D MR images of the lung at submillisecond echo times were achieved with a gradient-echo-based CODE pulse sequence after ready implementation on pre-clinical and clinical scanners in varying subjects without demanding hardware and/or software requirements. Due to the gradient-echo acquisition, minimum echo time of CODE was slightly longer than that of original 3D UTE by ~ 0.1 ms. It is unknown how the difference in the minimum echo time affects the visualization of fine structures in the lung. However, CODE was enough to visualize fissures and some subsegmental bronchi in consecutive slices. Visibility of these fine structures in CODE also competed with that of oUTE. SNR of CODE images was about 16% higher in phantom than that of oUTE images. It is also noteworthy that

Figure 3. Representative axial CT (a, b, d) images and 3 T CODE images (c, e) of lung metastasis and axial CT (f) image and 3 T CODE images (g) of lobar pneumonia in rabbits. Same day CT and CODE images in a rabbit with lung metastasis show 1.2 mm metastatic nodule in the right lower lobe (a, black arrow; c, white arrows). Another 0.8 mm nodule in the left lower lobe is depicted only in the CODE image (c, white arrows), but not in the CT image (b, black arrow). A 0.7 mm nodule in the left basal lung is noted in CT image but missed in CODE image due to the averaging respiratory motion artifact. In a rabbit with lobar pneumonia, three fine air-bronchograms are shown in the right lower lobar consolidation in CT image (f, black arrows). Among them, two air-bronchograms are identifiable in CODE image (g, white arrows). CODE, concurrent-dephasing-and-excitation.

CODE is less vulnerable to image artifacts caused by gradient imperfections including eddy currents than FID-based UTE with ramp sampling. Though further investigation is needed, optimizing SNR and respiratory gating look more desirable than shortening echo time in lung MRI for better visualization of fine anatomic structures.

We did not evaluate that CODE was sufficient for imaging patients with irregular breathing. It is uncertain whether lucent lung pathology such as emphysema, air-trapping or mosaic attenuation can be visualized properly in CODE imaging. However, CODE showed better image quality with less noises than conventional lung MRI sequences. CODE with submillisecond echo times may overcome the limitations of current pulmonary MRI and improve the detectability of tiny pulmonary metastases of 5 mm or less, one of the major obstacles in substitution for CT in cancer patients.⁴

High-resolution pulmonary MRI resistant to motion artifacts is most beneficial in a pediatric population when considering

Figure 4. Representative coronal and axial 9.4 T CODE images (a–d) in a normal Fisher 344 rat at 9.4 T pre-clinical MR scanner with respiratory gating. Coronal (a) and axial (b) MR images obtained in a rat show that thin proximal bronchial walls are identifiable (a, b; white arrows) but partly limited by motion artifact in lower lobes (b; white arrow head). When bronchi are traced in axial CODE images (c, d), bronchi are identifiable up to the fifth generation in CODE images (arrows; bronchi at each generation). CODE, concurrent-dephasing-and-excitation.

the risk of radiation exposure of CT scan.¹² The scan time of CODE imaging presented here may be longer than practical in infants or children, who need sedation for undergoing MRI.¹⁴ However, the acquisition time can be shortened at the expense of some image-quality loss with fewer radial views, or without any loss of image quality either by respiratory gating or by introducing compressed-sensing techniques.¹⁵ Although a prospective clinical study is needed for validation, pulmonary CODE imaging may be a potential radiation-free imaging substitute for chest CT scan in pediatric population.

There are some limitations in this study: the small number of human volunteers is one limitation, though it may be enough for reporting early feasibility on MR scanners at various field strengths; Patients were not examined with lung disease or respiratory distress; qualitative image analysis could have been performed better by the independent evaluation of two experienced radiologists.

CONCLUSIONS

The 3D radial gradient-echo-based CODE sequence showed usability with easy implementation on 3/1.5 T clinical and 9.4 T preclinical scanners in varying subjects. Without challenges of

other FID-based UTE sequences, it is expected that CODE can be a good alternative for standardized lung MRI on both clinical and preclinical scanners, providing desirable image quality with high SNR in a stable manner.

FUNDING

This study was supported by National Research Foundation of Korea, 2013R1A1A2063746 (JMG), and 2017R1A2B2004944 (J-YP).

REFERENCES

1. Bergin CJ, Pauly JM, Macovski A. Lung parenchyma: projection reconstruction MR imaging. *Radiology* 1991; **179**: 777–81. doi: <https://doi.org/10.1148/radiology.179.3.2027991>
2. Takahashi M, Togao O, Obara M, van Cauteren M, Ohno Y, Doi S, et al. Ultra-short echo time (UTE) MR imaging of the lung: comparison between normal and emphysematous lungs in mutant mice. *J Magn Reson Imaging* 2010; **32**: 326–33. doi: <https://doi.org/10.1002/jmri.22267>
3. Johnson KM, Fain SB, Schiebler ML, Nagle S. Optimized 3D ultrashort echo time pulmonary MRI. *Magn Reson Med* 2013; **70**: 1241–50. doi: <https://doi.org/10.1002/mrm.24570>
4. Burris NS, Johnson KM, Larson PE, Hope MD, Nagle SK, Behr SC, et al. Detection of small pulmonary nodules with ultrashort echo time sequences in oncology patients by using a PET/MR system. *Radiology* 2016; **278**: 239–46. doi: <https://doi.org/10.1148/radiol.2015150489>
5. Ohno Y, Koyama H, Yoshikawa T, Seki S, Takenaka D, Yui M, et al. Pulmonary high-resolution ultrashort TE MR imaging: comparison with thin-section standard- and low-dose computed tomography for the assessment of pulmonary parenchyma diseases. *J Magn Reson Imaging* 2016; **43**: 512–32. doi: <https://doi.org/10.1002/jmri.25008>
6. Kobayashi N, Idiyatullin D, Corum C, Weber J, Garwood M, Sachdev D. SWIFT MRI enhances detection of breast cancer metastasis to the lung. *Magn Reson Med* 2015; **73**: 1812–9. doi: <https://doi.org/10.1002/mrm.25301>
7. Gibiino F, Sacolick L, Menini A, Landini L, Wiesinger F. Free-breathing, zero-TE MR lung imaging. *MAGMA* 2015; **28**: 207–15. doi: <https://doi.org/10.1007/s10334-014-0459-y>
8. Dournes G, Grodzki D, Macey J, Girodet PO, Fayon M, Chateil JF, et al. Quiet submillimeter MR imaging of the lung is feasible with a PETRA sequence at 1.5 T. *Radiology* 2015; **276**: 258–65. doi: <https://doi.org/10.1148/radiol.15141655>
9. Park J, Shin T, Yoon SH, Goo JM, Park JY. A radial sampling strategy for uniform k-space coverage with retrospective respiratory gating in 3D ultrashort-echo-time lung imaging. *NMR Biomed* 2016; **29**: 576–87. doi: <https://doi.org/10.1002/nbm.3494>
10. Robson MD, Gatehouse PD, Bydder M, Bydder GM. Magnetic resonance: an introduction to ultrashort TE (UTE) imaging. *J Comput Assist Tomogr* 2003; **27**: 825–46. doi: <https://doi.org/10.1097/00004728-200310000-00001>
11. Park JY, Moeller S, Goerke U, Auerbach E, Chamberlain R, Ellermann J, et al. Short echo-time 3D radial gradient-echo MRI using concurrent dephasing and excitation. *Magn Reson Med* 2012; **67**: 428–36. doi: <https://doi.org/10.1002/mrm.23026>
12. Miglioretti DL, Johnson E, Williams A, Greenlee RT, Weinmann S, Solberg LI, et al. The use of computed tomography in pediatrics and the associated radiation exposure and estimated cancer risk. *JAMA Pediatr* 2013; **167**: 700–7. doi: <https://doi.org/10.1001/jamapediatrics.2013.311>
13. Dietrich O, Raya JG, Reeder SB, Reiser MF, Schoenberg SO. Measurement of signal-to-noise ratios in MR images: influence of multichannel coils, parallel imaging, and reconstruction filters. *J Magn Reson Imaging* 2007; **26**: 375–85. doi: <https://doi.org/10.1002/jmri.20969>
14. Schulte-Uentrop L, Goepfert MS. Anaesthesia or sedation for MRI in children. *Curr Opin Anaesthesiol* 2010; **23**: 513–7. doi: <https://doi.org/10.1097/ACO.0b013e32833bb524>
15. Gamper U, Boesiger P, Kozerke S. Compressed sensing in dynamic MRI. *Magn Reson Med* 2008; **59**: 365–73. doi: <https://doi.org/10.1002/mrm.21477>