Pulmonary Ultrashort Echo Time (UTE) MRI

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Highlights

- Very short T2* of the lungs (~1-2 ms) makes proton-based structural lung MRI very challenging
- Using ultra-short echo times (TE < 0.1 ms) can dramatically increase lung signal
- Robust 3D UTE acquisitions using commercially available 1.5T and 3T scanners are feasible
- Zero-TE (ZTE) variants of UTE offer both advantages and unique challenges

Target Audience: Thoracic radiologists and MRI physicists interested in lung MRI

Objectives

1. To provide an overview of the benefits and challenges of UTE lung MRI
2. To summarize the principal strategies for implementing UTE lung MRI, with an emphasis on the 3D radial approach
3. To describe the key differences and trade-offs between ZTE and UTE sequences
4. To describe the state-of-the-art of how UTE MRI has been applied to image lung disease

Background

MRI of the lungs has been limited by very low proton density and short T2* (~1-2 ms). As early as 1991, medical physicists recognized the potential of radial acquisition methods to decrease echo times and avoid some of this T2* signal decay(1). As clinical echo times have progressively decreased into the sub-millisecond range, many clinicians and researchers have begun to notice that lung disease becomes more apparent. Motivated by these observations and also by the results of research over the past decade in the field of microsecond echo time imaging of extremely short T2* tissues such as cartilage and cortical bone(2), several research groups have applied these ultra-short echo time (UTE) methods to the lungs, with promising results in both small animals(3-5) and in humans(6-8).

Methods

When used to image cartilage or cortical bone, most UTE work has focused on achieving echo times in the microsecond range. The T2* of the lungs, while very short, is significantly higher than the T2* of these musculoskeletal tissues. Thus UTE MRI of the lungs can overcome a majority of the lung T2* decay with echo times in the 10-100 μs range. This is possible on commercially available hardware.

A 3D radial pulse sequence allows data read-out to begin immediately after transmit-receive switching is complete, without the need for any preparatory phase-encode gradients. It is also inherently quite robust to the respiratory and cardiac motion artifacts that are commonly encountered in lung imaging. UTE approaches usually begin sampling data at the center of k-space immediately after the radiofrequency (RF) excitation, with data acquisition occurring while the read-out gradient is ramped up. The minimum switching time between transmit and receive allows the use of a slab selective RF and accommodates a small prewinder gradient to ensure that the beginning of the readout starts at the center of k-space. The use of a slab selective RF can decrease the amount of radial streak artifact arising from excited tissues outside of the imaged field of view (FOV). Use of variable density rather than trapezoidal gradients can improve signal-to-noise by virtue of the fact that the center of k-space is inherently oversampled using 3D radial trajectories.

A variant of this basic UTE sequence is the zero-TE (ZTE) method (9) whereby the read-out gradient is ramped up prior to the RF excitation, removing the necessity for a prewinder. This approach has the obvious theoretical advantage of further improving signal by moving to 0 ms echo time. An ancillary benefit that might be especially important when imaging young children is the potential for a near silent acquisition due to the very mild gradient ramping over the course of an acquisition. There are notable challenges, however. The fact that the center of k-space cannot be directly acquired because it occurs before transmit/receive switching can occur. The missing central k-space data must either be acquired using a supplemental approach such as single point imaging (1 TR for each k-space point) or estimated from the existing data, possibly using some prior knowledge of the object being imaged. Furthermore, to minimize the missing central k-space data, ZTE methods usually use a very short non-selective "hard pulse" that can contribute to radial streak artifact due to excited tissues outside of the FOV. Finally, if a near-silent approach is desired, then contiguous read-out trajectories must be near each other in k-space in order to avoid rapid gradient switching. This effectively rules out the use of retrospective respiratory gating methods for either freezing respiratory motion or for visualizing respiratory motion.

The 3D radial approach is inherently inefficient in its sampling of k-space, oversampling the center and undersampling the periphery. This can lead to relatively long scan times. However, with the use of respiratory gating (including the possibility of retrospective gating when pseudorandom trajectories are used), it is possible to obtain high-quality images with a 5-min free-breathing scan. In fact, being able to perform a free-breathing exam can be a practical advantage when imaging patients with lung disease who are more likely to have difficulty performing breath-holds.

Results

UTE and ZTE MRI of the lungs has been used successfully by several groups to directly image a variety of lung pathologies in both small animals as well as in humans. By increasing the baseline lung signal above the level of noise, UTE MRI also enables several other approaches, including direct lung T1 or T2* mapping, magnetization transfer to differentiate tissue types within the lungs, and the use non-traditional contrast agents. Furthermore, UTE approaches are now being used not only for structural lung image but also for functional imaging of lung perfusion and ventilation, enabling intrinsically coregistered assessment of lung structure and function. Some examples of recent research in these applications will be presented to provide some insight into the potential impact of the technique.

Discussion

UTE and ZTE MRI of the lungs offer the potential of providing a non-irradiating alternative to CT, especially in pediatric populations or those in whom repeated cross-sectional imaging is necessary to monitor disease progression or treatment effect. The strength of lung MRI has traditionally been in the realm of functional imaging using an extrinsic contrast mechanism to provide the signal (e.g. injected gadolinium for perfusion or inhaled hyperpolarized gases). A weakness of these approaches has been a relative lack of a structural correlate for these functional measures. Ultrashort echo time MRI of the lungs has demonstrated not only that it can provide this structural reference for use with functional lung MRI studies, but has shown that it can also further improve existing functional lung imaging methods themselves.

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