Phase-Resolved Functional Lung MRI (PREFUL): A Signal Processing Perspective Grounded in Contemporary Literature

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1 Core Idea of PREFUL

PREFUL (Phase-Resolved Functional Lung MRI) is a non-contrast-enhanced method for extracting regional lung function from proton MRI acquired during free breathing [1, 2].

The defining principle is the reordering of dynamic MRI data according to respiratory or cardiac phase to reconstruct a representative physiological cycle [1].

This distinguishes PREFUL from purely frequency-based approaches by explicitly reconstructing the temporal structure of breathing rather than analyzing it only in the spectral domain.

Key properties:

- Free-breathing acquisition
- No contrast agent or inhaled gas required
- Simultaneous access to ventilation and perfusion information

2 Position Within Proton Lung MRI methods

Within proton-based lung MRI, PREFUL belongs to a broader class of techniques that extract functional information from intrinsic signal variations.

2.1 Related Methods

- Fourier Decomposition (FD-MRI)
- SElf-gated Non-Contrast-Enhanced Functional Lung Imaging (SENCEFUL)
- Oxygen-enhanced MRI
- UTE-based functional imaging

PREFUL can be interpreted as an evolution of Fourier decomposition approaches, combining temporal reordering with less restrictive filtering strategies.

PREFUL belongs to a broader class of non-contrast-enhanced functional lung MRI techniques, including Fourier decomposition and related approaches [2].

Recent developments extend PREFUL toward three-dimensional acquisitions and improved robustness in functional lung imaging [3].

3 Signal Model

Let $S(\mathbf{x}, t)$ denote the MRI signal at spatial position $\mathbf{x}$ and time t.

The observed signal can be modeled as a mixture of physiological components:

$$S(\mathbf{x}, t) = S_0(\mathbf{x}) + S_{\text{resp}}(\mathbf{x}, t) + S_{\text{card}}(\mathbf{x}, t) + \epsilon(\mathbf{x}, t) \tag{1}$$

where:

- S_{resp} : respiratory modulation (ventilation)
- S_{card} : cardiac modulation (perfusion)
- ϵ : noise and residual artifacts

PREFUL aims to isolate and reorganize S_{resp} and S_{card} through phase-resolved reconstruction.

4 Phase-Resolved Reconstruction

4.1 Phase Extraction

A surrogate respiratory signal $\phi(t)$ is derived either from:

- image intensity variations
- k-space center (self-navigation)

4.2 Binning

The continuous time axis is mapped to a phase domain:

$$t \longrightarrow \phi(t) \in [0, 2\pi] \tag{2}$$

Data are grouped into phase bins:

$$\mathcal{B}_k = \{S(\mathbf{x}, t) \mid \phi(t) \in \Delta_k\} \tag{3}$$

4.3 Cycle Reconstruction

A synthetic respiratory cycle is reconstructed:

$$S_{\text{cycle}}(\mathbf{x}, \phi_k) = \langle S(\mathbf{x}, t) \rangle_{t \in \mathcal{B}_k} \tag{4}$$

This produces a consistent temporal representation of breathing.

5 Ventilation Quantification

Ventilation is derived from signal changes across respiratory phases.

5.1 Basic Definition

A simple proxy for ventilation is:

$$V(\mathbf{x}) \propto \frac{S_{\text{insp}}(\mathbf{x}) - S_{\text{exp}}(\mathbf{x})}{S_{\text{exp}}(\mathbf{x})} \tag{5}$$

where:

- S_{insp} : signal at inspiration
- S_{exp} : signal at expiration

5.2 Interpretation

Signal differences reflect:

- changes in air fraction
- changes in tissue density

6 Perfusion Quantification

Perfusion is extracted from higher-frequency components linked to cardiac motion.

6.1 Concept

- Cardiac-induced signal oscillations modulate lung signal
- These variations correlate with blood flow

6.2 Separation Strategy

Two main strategies:

- temporal filtering
- phase-resolved separation

7 Relation to Fourier Decomposition

Fourier decomposition (FD-MRI) separates signals based on frequency:

$$S(\mathbf{x}, t) \xrightarrow{\mathcal{F}} S(\mathbf{x}, \omega) \tag{6}$$

7.1 Key Difference

- FD: frequency-domain separation
- PREFUL: phase-domain reconstruction

PREFUL introduces:

- improved temporal consistency
- reduced sensitivity to irregular breathing

8 Advantages and Limitations

8.1 Advantages

- No radiation
- No contrast agents
- Works in free breathing
- Provides regional functional maps

8.2 Limitations

- Indirect measurement of ventilation
- Sensitive to motion estimation errors
- Limited signal-to-noise ratio

9 Outlook: Toward 3D PREFUL

Recent developments extend PREFUL toward 3D acquisitions.

Key challenges:

- acquisition speed
- motion consistency
- reconstruction complexity

Emerging solutions include:

- spiral trajectories
- low-field MRI
- constrained reconstruction

10 Conclusion

PREFUL represents a conceptually elegant approach to functional lung imaging by transforming a time series into a phase-consistent physiological model.

From a signal processing standpoint, it can be interpreted as:

> *phase-aligned resampling and reconstruction of quasi-periodic physiological signals.*

Bibliography

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