Hyperpolarised xenon magnetic resonance spectroscopy for the longitudinal assessment of changes in gas diffusion in IPF

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ABSTRACT
Prognosticating idiopathic pulmonary fibrosis (IPF) is challenging, in part due to a lack of sensitive biomarkers. A recent article in Thorax described how hyperpolarised xenon magnetic resonance spectroscopy may quantify regional gas exchange in IPF lungs. In a population of patients with IPF, we find that the xenon signal from red blood cells diminishes relative to the tissue/plasma signal over a 12-month time period, even when the diffusion factor for carbon monoxide is static over the same time period. We conclude that hyperpolarised $^{129}$Xe MR spectroscopy may be sensitive to short-term changes in interstitial gas diffusion in IPF.

INTRODUCTION
Despite significant developments in our understanding of the pathogenesis of idiopathic pulmonary fibrosis (IPF) and the emergence of efficacious treatments, 1, 2 prognostication remains challenging. Pulmonary function tests (PFTs), including forced vital capacity (FVC) and diffusing capacity of the lungs for carbon monoxide ($D_{LCO}$), form the basis of assessing progression and treatment response, but are insensitive to longitudinal change. 3 An FVC decline of ≥10% is a validated primary endpoint for disease progression and is predictive of mortality, 4 but longitudinal data demonstrate substantial intrapatient variability. 5 New biomarkers may help to assess disease progression. MRI with hyperpolarised helium ($^3$He) or xenon ($^{129}$Xe) gas can reveal subtle changes in lung ventilation and microstructure. 6 Of particular interest for pulmonary gas exchange assessment is the solubility of xenon in lung parenchyma and blood. 6, 7 $^{129}$Xe shows distinct signals from the red blood cells (RBCs) and interstitial tissue/plasma (TP) compartments by virtue of its environment-dependent resonant frequency, which enables evaluation of gas exchange efficiency by MR spectroscopy (MRS). Wang et al recently used $^{129}$Xe MRS to identify regions of gas transfer deficit in IPF. 8 Herein, we describe preliminary findings evaluating the sensitivity of $^{129}$Xe MRS to longitudinal physiological changes in patients with IPF.

METHODS
In a study with National Health Service Research Ethics Committee approval, 18 participants with a multidisciplinary diagnosis of IPF were recruited and provided prospective informed written consent. Five patients were taking antifibrotic treatment on recruitment to the study (four on pirfenidone and one on nintedanib). During the study, a further three patients commenced pirfenidone and two patients commenced nintedanib. All underwent baseline imaging and 10 underwent repeated scans 1–3 hours later. Fourteen participants returned at 6 months (195±24 days) and 13 returned at 12 months (361±31 days). Each underwent pulmonary MRS with hyperpolarised $^{129}$Xe gas on a 1.5T whole-body MRI scanner. Scans were well tolerated and completed in all, except one participant at the 12-month visit, who completed neither $D_{LCO}$ nor the MR breath-hold manoeuvre.

$^{129}$Xe was polarised under regulatory licence and 600 mL of isotopically enriched xenon was balanced with nitrogen to a total inhaled dose of 1 L. Whole lung $^{129}$Xe MRS was performed during a 10–15 s breath-hold after inhaling the gas mixture from functional residual capacity. A pulse-acquire sequence was used to acquire whole-lung spectra of $^{129}$Xe in the TP and RBC compartments (bandwidth: 1.8 kHz; flip angle: 90°; repetition time: 1 s). Data analysis was performed using MATLAB. After discarding the first spectrum, spectra were averaged and zeroth-order phased, and integrals over the RBC and TP spectral peaks were evaluated to derive the ratio RBC:TP.

PFTs were performed on the same day as MR. Spearman’s r determined the strength of correlations. Friedman tests evaluated the significance of differences in baseline, 6 and 12-month metrics. Intraclass correlation coefficient and Bland-Altman analyses assessed reproducibility of RBC:TP.

RESULTS
Summary statistics of demographics, PFTs and RBC:TP measurements (median (IQR)) are as follows: age (years) 71.5 (67.8–74.3); FVC (%-predicted) 75.1 (64.3–95.1); $D_{LCO}$ (%-predicted) 42.0 (34.6–56.3); baseline RBC:TP 0.26 (0.18–0.34). Same-day repeat scanning yielded highly reproducible intrapatient RBC:TP ratios, (see Bland-Altman plot, figure 1; intraclass correlation 0.963). A statistically significant correlation (r; 95%CI) was observed between baseline RBC:TP and $D_{LCO}$ (r=0.677; 0.293 to 0.873), but not FVC (r=0.336; −0.170 to 0.702). Correlations with $D_{LCO}$ (%-predicted) remained significant at...
Figure 1  Bland–Altman plot of 129Xe RBC:TP at baseline. Bland–
Altman plot of intraparticipant, interscan RBC:TP ratio reproducibility in
10 participants, with the y-axis representing percentage error. Dashed
line represents bias, with dotted lines representing 95% CIs. RBC, red
blood cell; TP, tissue/plasma.

Figure 2  Longitudinal change in FVC, DLOCO and RBC:TP. (A–C): Box and whisker diagrams with associated Friedman’s test p values, representing
6-month and 12-month follow-up change in FVC, DLOCO and 129-xenon MR-derived RBC:TP ratio. Note that a statistically significant difference was
not demonstrated in DLOCO (B), whereas FVC (A) and RBC:TP (C) declined significantly over 12 months. Individual participants’ metrics of FVC, DLOCO,
and RBC:TP at baseline, 6 and 12 months are plotted in (D), (E) and (F), respectively. DLOCO, diffusing capacity of the lungs for carbon monoxide; FVC, forced
vital capacity; RBC:TP, red blood cell to tissue/plasma.

6 months ($r=0.831; 0.525$ to $0.947$) and 12 months ($r=0.760; 0.312$ to $0.931$). Statistically significant changes (median change (95% CI); Friedman p value) were seen over 12 months in FVC ($−0.2\%$, $−7.8$ to $−0.2\%$; $p=0.048$) and RBC:TP ($−0.08$, $−0.04$ to $−0.14$; $p=0.001$), but not DLOCO ($−0.5\%$, $−5.6\%$ to $5.8\%$; $p=0.881$), see figure 2. Although the mean observed decline in FVC was small, five patients demonstrated a relative FVC decline $\geq 10\%$, defined as clinically significant.

DISCUSSION

Hyperpolarised 129Xe MRS is highly reproducible and sensitive
to longitudinal changes in pulmonary gas exchange efficiency in
IPF. The correlation between RBC:TP and DLOCO suggests the tech-
niques reflect similar underlying gas exchange pathophysiology,
although with gases that have different membrane diffusion
properties. While DLOCO showed no longitudinal change, RBC:TP
demonstrated a trend to decline over 6 months and a statistically
significant decline over 12 months. Our baseline RBC:TP and DLOCO correlation is slightly weaker than reported in\(^6\) possibly
due to differences in MRS parameters, reference equations for DLOCO,
or inclusion of healthy volunteer data in previous

DLOCO is calculated from exhaled gas concentrations measured
at the mouth, while MRS obtains 129Xe measurements directly
from the alveoli, alveolar-capillary membrane and RBCs. The
observed reduction in RBC:TP when DLOCO is stable may therefore
result from differing gas properties and measurement
procedure, reflecting different pathophysiology. These differ-
ences may be emphasised by the postures used when measuring
DLOCO (sitting) and 129Xe RBC:TP (supine). The supine posture
may cause a partial redistribution of ventilation and perfusion
to regions of the lung less affected by disease. Indeed, Wang et al demonstrated how TP signal increases and RBC signal falls
in lung tissue afflicted with IPF and how RBC signal is almost
absent in areas severely afflicted.\(^8\) The 129Xe signal from the
tissue and RBC compartments is weighted by a combination of
specific ventilation, interstitial thickening, delayed gas diffu-
sion and perfusion deficit. In future 129Xe spectroscopic studies,
additional measurement the 129Xe alveolar gas signal as a refer-
ence, alongside contrast enhanced perfusion MRI may provide
complementary physiological information to help understand
the observed RBC:TP decline. Additionally, acquisition of
longitudinal CT data could yield insight into the mechanism of

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RBC:TP change. We also note that inflation level may influence RBC:TP ratio in a non-negligible manner. Thus, future studies should consider varying the inhaled xenon gas dose with lung capacity.

Despite relatively limited participant numbers, we were able to identify a statistically significant decline in RBC:TP , indicating the power of this approach. The observed FVC decline is small, but consistent with treatment intervention studies1 2 and suggests a clinically significant decline in lung function and parallel gas exchange impairment. The decline observed in MRS-derived RBC:TP is underpinned by different pathophysiological mechanisms to that in FVC, and thus, RBC:TP may be additive to our current repertoire of physiological assessment tools. With further development, this technique may offer a sensitive endpoint for early-stage clinical trials.

Correction notice This article has been corrected since it was published Online First. The copyright licence was changed from CC BY-NC to CC-BY.

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REFERENCES
1. Noble PW, Albera C, Bradford WZ, et al. Pirfenidone in patients with idiopathic pulmonary fibrosis (CAPACITY): two randomised trials. Lancet 2011;377:1760–9.
2. Richeldi L, du Bois RM, Raghu G, et al. Efficacy and safety of nintedanib in idiopathic pulmonary fibrosis. N Engl J Med 2014;370:2071–82.
3. Nathan SD, Albera C, Bradford WZ, et al. Effect of continued treatment with pirfenidone following clinically meaningful declines in forced vital capacity: analysis of data from three phase 3 trials in patients with idiopathic pulmonary fibrosis. Thorax 2016;71:429–35.
4. King TE, Safiri S, Starko KM, et al. Analyses of efficacy end points in a controlled trial of interferon-gamma1b for idiopathic pulmonary fibrosis. Chest 2005;127:171–7.
5. Fain SB, Korosec FR, Holmes JH, et al. Functional lung imaging using hyperpolarized gas MRI. J Magn Reson Imaging 2007;25:910–23.
6. Stewart NJ, Leung G, Norquay G, et al. Experimental validation of the hyperpolarized 129Xe chemical shift saturation recovery technique in healthy volunteers and subjects with interstitial lung disease. Magn Reson Med 2015;74:196–207.
7. Qing K, Ruppert K, Jiang Y, et al. Regional mapping of gas uptake by blood and tissue in the human lung using hyperpolarized xenon-129 MRI. J Magn Reson Imaging 2014;39:346–59.
8. Wang JM, Robertson SH, Wang Z, et al. Using hyperpolarized 129Xe MRI to quantify regional gas transfer in idiopathic pulmonary fibrosis. Thorax 2018;73:21–8.
9. Qing K, Mugler JP, Alves TA, et al. Assessment of lung function in asthma and COPD using hyperpolarized 129Xe chemical shift saturation recovery spectroscopy and dissolved-phase MRI. NMR Biomed 2014;27:1490–501.