Measurement of Pressure from the Diffusion Coefficient of 3He Gas

J. M. Wild[1], and S. R. Parnell[1]
[1]University of Sheffield, Sheffield, Yorkshire, United Kingdom

Introduction

Non-invasive measurement of pressure with NMR could have a variety of applications in-vivo (e.g. measurement of blood pressure) and in non-medical applications (e.g. pressure jets in fluid dynamics). In this work an inverse relation between the pressure of ^{3}He inside a closed syringe and the measured (apparent) diffusion coefficient (*D*) was observed using intermediate diffusion time pulsed gradient spin echo (PGSE) methods. Extension of the technique for measuring pressure in-vivo in micro bubbles is proposed using different gas mixtures and short time scale diffusion sequences.

Methods

All work was performed on a 1.5T Philips Eclipse system - 27mTm^{-1} peak gradients, max. slew 72Tm^{-1}s^{-1}. A custom built TR birdcage coil was used tuned to ^{3}He at 48.6 MHz. ^{3}He gas was polarised to 24% with spin exchange apparatus (GE). To investigate the diffusion dependence with pressure of ^{3}He, a phantom was constructed from a 50 ml plastic syringe. ^{3}He gas (D≈2x10^{-4} m^{2}s^{-1}) was decanted from the optical pumping cell (cell pressure ≈ 10 atm, temperature 30^{o}c) into the evacuated syringe. The original volume of gas in the syringe was measured from the graduations as V_1=60 ml. The original pressure in the syringe (P_1) was estimated as being slightly over 1 atm since the incoming gas pushed the syringe plunger out against friction.

NMR: The diffusion coefficient of the ^{3}He in the syringe was then measured using a Stejskal-Tanner PGSE sequence consisting of a pulse acquisition (S_1) with a bipolar trapezoidal waveform with b-value of 2.89 s/cm^2 (strength 26.2 mTm^{-1} duration 460 ms, 500 ms ramp time, direction along axis) [1], this was interleaved with a second pulse-acquisition (S_2) with b=0 (reference scan) at the same echo time. A flip angle of α=10^o was used and the contribution from the decay of the longitudinal magnetisation between pulses was normalised in the calculation of the diffusion coefficient D: $\exp(-bD) = (S_1/S_2)\cos\alpha$

The gas in the syringe was then compressed in stages from V_1 = 60 ml to V_2 = 56, 46, 35, 26 and 15 ml respectively and for each compression, *D* was measured 8 times and the mean calculated. The pressure in the syringe was then estimated from the ideal gas laws assuming constant temperature : $P_1V_1 = P_2V_2$.

Results

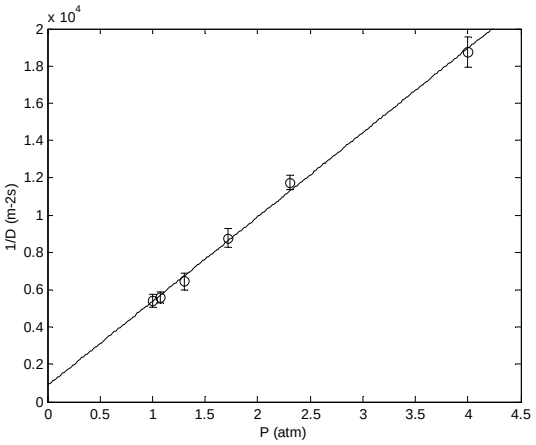
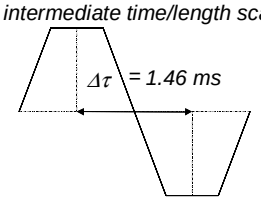


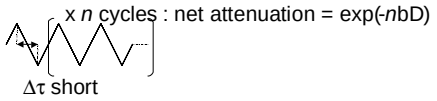
Fig. 1 *Plot of the inverse of the diffusion coefficient (1/D) as measured with PGSE NMR versus the pressure (P) as estimated from the gas volume. The error bars are the s.d. in the 8 measurements of D. The predicted linear behaviour from kinetic theory of an ideal gas is evident. The offset indicates that the original pressure in the syringe was P_1 = 1.2 atm which is consistent with the pressure gradient pushing the gas against the syringe plunger.*

Fig. 2

Bipolar gradient pair used for intermediate time/length scale measurements



Sawtooth gradient cycles of bipolar impulses for shorter time/length scale measurements



Discussion

The results with ^{3}He in this model confirm that the diffusion coefficient as measured with PGSE NMR is inversely proprotional to pressure as has been shown for ^{129}Xe/O_2 mixtures in glass cells [2]. The duration of the bipolar diffusion gradient pair used here, gives a characteristic diffusion time of t = Δτ = 1.46 ms. From the diffusion equation, the mean free path (characteristic length scale) of diffusion is given by λ= √(2Dt) = 0.76 mm. This confirms a regime, where the boundaries of the container (*d* ~ 2cm across) impose little constraint on the measured bulk diffusion coefficient (λ<< *d*) on this intermediate time scale of gradient sensitization and thus the narrow pulse approximation of Stejskal and Tanner [3] is reasonable. Hence the measured diffusion coefficient is a valid estimate of inter-atomic mean free path and thus gas pressure. The applications for pressure measurement in such a regime are manifold but are limited by the spatial length scale and so would generally be non-medical e.g. pressure measurement in gas flow rigs and inside optical pumping cells knowledge of the gas temperature and pressure in-situ would be useful in optimizing the spin-exchange process. For pressure measurement inside microscopic vessels, such as intra-vascular micro-bubbles, a gas mixture with a lower self diffusion coefficient would be needed to ensure the (λ< *d*) condition e.g. slower diffusing gases: ^{3}He-N_2 mix, D=0.9x10^{-4} m^{2}s^{-1} at 1 atm or ^{129}Xe, D=0.06x10^{-4} m^{2}s^{-1} at 1 atm. The ultimate aim is non-invasive localised measurement of systemic blood pressure with diffusion measurement in elastic walled gas filled micro-bubbles [4] in the blood. Under high hydrostatic pressure the bubble compresses and the diameter will decrease. For a bubble of diameter d = 10 μm, the characteristic diffusion time for slowly diffusing 129Xe, t = 8μs. This would require exceptionally short timescale NMR diffusion sensitisation [3] (Δτ ~μs). A move toward such short diffusion times could be made with very short gradient impulses swept out at the slew rate limits. The *b*-value of such a pair would be small and thus provide little attenuation. A solution would be to concatenate bipolar pairs in a train of *n* pulses to amplify the net *b*-value to *nb* –see Figure. Such an approach has very recently been proposed for short length scale diffusion measurement with gases [5] and is under investigation in this application of enacpsulated gas pressure measurement.

References [1] J Magn. Reson. 2004; 167(1):1-11 [2] J Magn Reson. 1998;135(2):478-86 [3] J. Chem. Phys., 1965. 42: 288-292. [4] Magn Reson Med. 2001;46(3):535-40. [5] In press doi:10.1016/j.jmr.2007.09.006

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