Finite-Difference Simulations of Xenon Diffusion in Lung Tissue

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Introduction: The ADC of noble gases, such as Xenon-129 and Helium-3, is an important tool for probing the dimensions of the lung microstructure. However, restricted diffusion is still not entirely understood. Hence, a quantitative understanding of this process is key to interpreting the ADC and extracting useful information such as alveolar dimensions. The only analytical theory proposed so far is the *Cylinder Model* [1], which (as the name suggests) makes quite basic assumptions about the geometry of alveolar ducts. In recent work, Helium-3 diffusion was simulated numerically and compared to the *Cylinder Model* [2]. In this work we have extended those simulations to Xenon-129, which has a significantly smaller self-diffusion coefficient [3].

The *Cylinder Model* treats each alveolar duct as an independent cylinder. This reveals two ADCs; one transverse, D_T, and the other longitudinal, D_L, to the main axis. The value of D_T, as a function of b-value, can be used to determine the diameter of the cylinder from diffusion theory. Hence it is possible to estimate the average diameter of the alveolar ducts in vivo.

Methods: We simulated xenon diffusion in 3D alveolar structures and compared the results with the *Cylinder Model*. The finite-difference methodology can be found in reference [2]. A total of two alveolar *groups* were studied, with R_A fixed at 0.14 μm, a = 300 μm and b = 600 μm, see Figure 1. The first *group* comprised: N = 4, and R = 210 μm; and the second comprised: N = 5, and R = 252 μm. For each *group*, a range of structures were generated with R_D varied between (R–R_A) and (R+R_A). Diffusion was then simulated in each of these structures using a simple PGSE gradient scheme; the duration of each lobe was fixed at 3.0 ms, and there was no delay between lobes. Simulations were then ran for 30 orientations, each using 12 b-values, where the gradient was stepped equally from 2 mTm-1 to 24 mTm^{-1}. The data was then summed, according to the *Cylinder Model*, and fitted with a least-squares routine, yielding values for D_L and D_T, which could be was used to find the average radius of the structure, *Rfit*. This **fitted** value was then compared to the **actual** *Effective Radius* of the structure, which was calculated as $Reff = \sqrt{\text{Volume}/(2\pi b)}$.

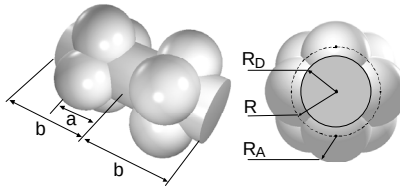
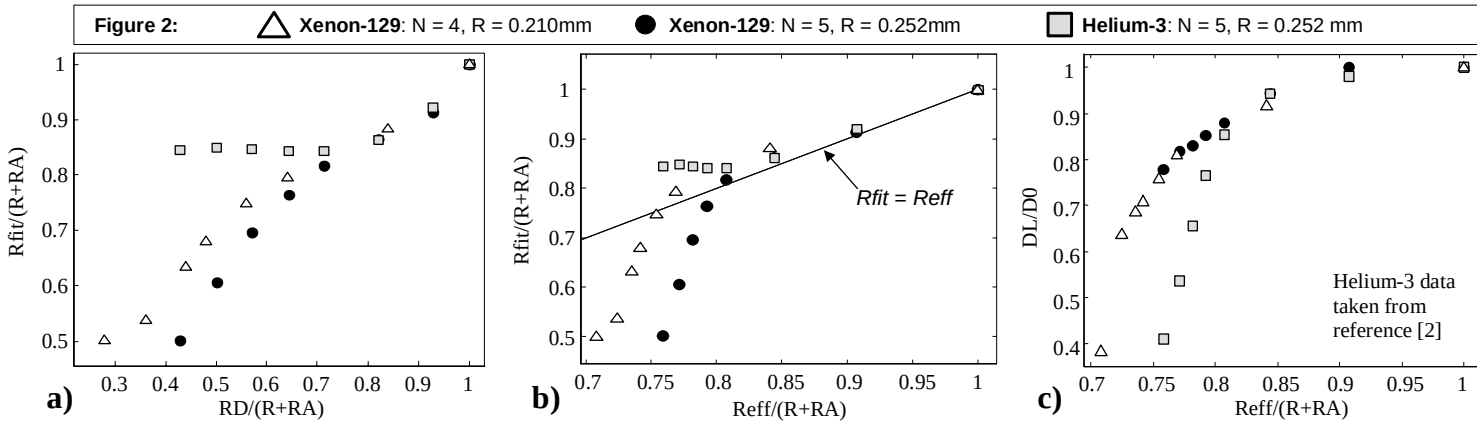


Figure 1: A 3D model for the alveolar duct, generated from a cylinder and 2N spheres. Here N = 4.



Results: The xenon simulation results are summarised in Figure 2. A subset of Helium-3 results are also shown for comparison. The *Rfit* data was found to vary *almost* linearly with the inner-diameter of the alveolar ducts, R_D, which was unexpected. However, on the other hand the *Rfit* data was found to greatly under estimate the average radii, *Reff*, which was in contrast to the Helium-3 results which tend to be an over estimate. The D_L values, for both xenon and helium, seem to follow a similar trend when plotted against *Reff*.

Discussion: The results suggest that the *Cylinder Model* breaks down for xenon in lung like structures, since the value of *Rfit* greatly under estimates the actual effective radius of the structure, *Reff*. This is somewhat expected since normal lung tissue deviates quite strongly from a cylindrical geometry. However, the measured *Rfit* data actually correlates quite strongly with the inner diameter of alveolar ducts, which could be a useful property for assessing early emphysematous changes (Fig 2c). The measured values of D_L, for both xenon and helium, follow a similar trend, and correlate quite well with the effective radius of the alveolar duct. In addition, the xenon data for both structures appear to be located on the same underlying curve (Fig. 2c). This feature could be exploited as a measurement of early emphysema-like changes in lung tissue, which has also been suggested for Helium-3 [1-2]. The ADC values (not shown) were found to be comparable to the work found in [3], however more investigation is required with different alveolar structures, and crucially, with different PGSE sequence parameters.

References

[1] Yablonskiy DA, Sukstanskii AL, Leawoods JC, Gierada DS, Bretthorst GL, Lefrak SS, Cooper JD, Conradi MS, Quantitative in vivo Assessment of Lung Microstructure at the Alveolar Level with Hyperpolarized 3He Diffusion MRI. Proc. Natl. Acad. Sci. USA, 2002. **99**: pp. 3111-3116.
[2] Fichele S, Paley MNJ, Woodhouse N, Griffiths PD, van Beek EJR, Wild JM, Finite-Difference Simulations of 3He Diffusion in 3D Alveolar Ducts: A Comparison with the "Cylinder Model". Magn. Reson. Med, 2004. **52**: pp. 917-20.
[3] Mugler III JP, Mata JF, Wang HTJ, Tobias WA, Cates GD, Christopher JM, Missel JL, Reish AG, Ruppert K, Brookeman JR, Hagspiel KD. The Apparent Diffusion Coefficient of Xe-129 in the Lung: Preliminary Human Results. In proc. ISMRM 2004, pp769