# Self-diffusion of poly(ethylene oxide) in aqueous dextran solutions measured using *FT*-pulsed field gradient n.m.r.

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Transport in ternary polymer<sub>1</sub>, polymer<sub>2</sub>, solvent systems has been investigated using an n.m.r. spin-echo technique. The dependence of the self-diffusion coefficient of poly(ethylene oxide) polymers on the concentration and molecular size of dextran in aqueous solution has been measured. Monodisperse poly(ethylene oxide) fractions ( $\bar{M}_w$ =7.3×10<sup>4</sup>, 2.8 · 10<sup>5</sup> and 1.2 · 10<sup>6</sup>) and dextrans ( $\bar{M}_w$ =2 · 10<sup>4</sup>, 1 · 10<sup>5</sup> and 5 · 10<sup>5</sup>) have been employed over a range of concentration up to the miscibility limit in each system. It is found that when the molecular size of the diffusant is commensurate with or exceeds that of the matrix polymer, a relationship of the form: ( $D/D_0$ )<sub>PEO</sub>=exp- $k(C[\eta])$  is applicable, where  $C[\eta]$  refers to the dextran component and is considered to describe the extent of coil overlap in concentrated solution. ( $D/D_0$ ) is independent of the molecular size of the poly(ethylene oxide), at least in the range studied ( $\bar{M}_w$ <300 000).

Keywords Self-diffusion; n.m.r.; poly(ethylene oxide); dextran; ternary system

# **INTRODUCTION**

Transport phenomena in polymeric multicomponent systems have attracted considerable attention in recent years. Interest has mainly been directed to elucidating the interactions between mixtures of polymers in a low molecular weight solvent (polymer<sub>1</sub>, polymer<sub>2</sub>, solvent). Dextran solutions have frequently been used partly because they constitute a suitable model for the extracellular matrix of connective tissue, (see the recent review of Preston et al.<sup>1</sup> for references), but also because of a number of attractive features: dextran is a neutral polymer, available as well-characterized fractions which are soluble in water up to concentrations in excess of 50%(w/w). The present communication deals with the selfdiffusion of monodisperse fractions of poly(ethylene oxide) (PEO) in dextran solutions. PEO is highly suitable as a model neutral polymer in n.m.r. spin-echo investigations owing to its favourable transverse relaxation time  $(T_2)$ . The concentration of PEO has been held at  $1 \text{ kg m}^{-3}$  in order to maximally extend the range of dextran concentration. The latter extends from the dilute to the semi-dilute regions, up to the limit of miscibility of the two polymers in aqueous solution.

Measurement of self-diffusion coefficients is uniquely important since it allows one to investigate the translational mobility of a molecule in the absence of concentration gradients, i.e. under essentially equilibrium conditions. This is invaluable in elucidating dynamic aspects of polymer solutions and especially those of ternary systems in which thermodynamic factors play a dominant role. Precise measurements of self-diffusion have only been possible on small molecules, but in recent years advances in pulsed field gradient n.m.r. have greatly extended the usefulness of the method to encompass polymer systems<sup>1-5</sup>. This technique monitors the

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Brownian displacement of individual molecules during a time  $\sim 300$  ms and for simple random walk behaviour yields the self-diffusion coefficient. This contrasts with, for example, quasi-elastic light scattering which measures the mutual diffusion of solute at finite concentrations. A new technique, also giving the self-diffusion coefficient, is forced Rayleigh light scattering (FRS)<sup>6</sup>. A valuable feature of these techniques is the possibility of exploring the frictional behaviour over extended ranges of molecular weight and concentration where conventional means of following diffusional processes have grave limitations. It may be noted that comparable information is, in principle, also obtainable from sedimentation studies in the ultracentrifuge. However, the experiments are difficult to perform with the required precision at high concentrations and the sedimentation of the matrix polymer is a complicating factor; see the discussion of Laurent et al.<sup>7</sup> and Langevin and Rondelez<sup>8</sup>.

#### **EXPERIMENTAL**

Polymers: Poly(ethylene oxide) (PEO)

- PEO 5.7:  $\bar{M}_w = 5.7 \cdot 10^3$ ;  $[\eta] = 0.012 \text{ m}^3 \text{ kg}^{-1}$  $(\bar{M}_w/\bar{M}_n = 1.10)$
- PEO 73: (SE-8)\*;  $\bar{M}_w = 0.73 \cdot 10^5$ ;  $[\eta] = 0.0930 \text{ m}^3 \text{ kg}^{-1}$  $(\bar{M}_w/\bar{M}_n = 1.02)$
- PEO 280: (SE-30)\*;  $\overline{M}_{w} = 2.78 \cdot 10^{5}$ ;  $[\eta] = 0.235 \text{ m}^{3} \text{ kg}^{-1}$  $(\overline{M}_{w}/\overline{M}_{w} = 1.05)$
- $(\bar{M}_w/\bar{M}_n = 1.05)$ PEO 1200: (SE-150)\*;  $\bar{M}_w = 1.2 \cdot 10^6$ ;  $[\eta] = 0.650 \text{ m}^3$ kg<sup>-1</sup> ( $\bar{M}_w/\bar{M}_n = 1.12$ )

(\* Denotes type according to Toya Soda Mfg. Co. Ltd., Tokyo, Japan.)

# Dextran

(a) DEX 10:  $\tilde{M}_w = 1.1 \cdot 10^4$ ;  $[\eta] = 0.012 \text{ m}^3 \text{ kg}^{-1}$ 



Figure 1 Self-diffusion coefficients for three PEO fractions in aqueous solutions of Dextran 110. (a) PEO 73 (b) PEO 280 (c) PEO 1200. The critical overlap concentration,  $C^{*}(=1/\{\eta\})$  is shown for Dextran 110; the critical miscibility concentration  $C_m$  is also shown



*Figure 2* Relationship between log  $(D/D_0)$  for PEO 73 and the concentration of dextran for three molecular weights of the latter polymer: (a) DEX 20 (b) DEX 110 (c) DEX 500

(b) DEX 20:  $\bar{M}_{w} = 1.9 \cdot 10^{4}$ ;  $[\eta] = 0.016 \text{ m}^{3} \text{ kg}^{-1}$ (c) DEX 110:  $\bar{M}_{w} = 1.00 \cdot 10^{5}$ ;  $[\eta] = 0.031 \text{ m}^{3} \text{ kg}^{-1}$ (d) DEX 500:  $\bar{M}_{w} = 5.1 \cdot 10^{5}$ ;  $[\eta] = 0.060 \text{ m}^{3} \text{ kg}^{-1}$ 

#### Solvents

D<sub>2</sub>O from Ciba Geigy, Switzerland.

Prior to preparation of solutions, the materials were dried in vacuum at 40°C. All solutions were prepared by weighing. Density information was taken from Roots *et* al.<sup>9</sup> for poly(ethylene oxide) and Brown *et al.*<sup>10</sup> for dextran and used for correcting concentrations to a volume basis.

#### Self-diffusion measurements

The pulsed field gradient nuclear spin-echo measurements were made at 99.6 MHz using improved versions of methods described previously<sup>3</sup>, the experiments now being made at a fixed  $\Delta$  for all  $\delta$ -values as described in ref, 4. Deuterium oxide was used as the solvent since it was required for lock purposes. The final concentration of PEO was 1 kg m<sup>-3</sup>. The solutions were made by adding an equal volume of a 2 kg m<sup>-3</sup> PEO solution (in D<sub>2</sub>O) to the solution of the appropriate dextran in D<sub>2</sub>O. All measurements were made at 25°C. The experimental uncertainty in the measured diffusion coefficients varied between  $\pm 0.1 \cdot 10^{-11}$  m<sup>2</sup> s<sup>-1</sup> which were the extreme values determined during the measurement series. The latter value was for PEO 1200 ( $\bar{M}_w = 1.2 \cdot 10^6$ ) in dextran 110 ( $\bar{M}_w = 100\,000$ ) at 3.5% and represents the limit at which self-diffusion coefficients can be attained using the present experimental arrangement.

The dextran signals were weak and characterized by very short  $T_2$ -values. By contrast, PEO has unusually favourable, long  $T_2$ -values and it was possible to extend  $\Delta$  to 240 ms. Under these conditions, both dextran and water proton signals were completely absent in the spectra. Furthermore, the lower range of accessible diffusion coefficients was extended considerably.

## **RESULTS AND DISCUSSION**

### Dependence of $D_{PEO}$ on dextran concentration

The experimental results are typified by those shown in *Figure 1* as plots of log  $D_{PEO}$  vs. C <sub>Dextran</sub>. The range of concentration over which it was possible to make measurements was limited by the compatibility of the two polymers in aqueous solution. The maximum dextran concentration at which a given PEO fraction could be dissolved at 1 kg m<sup>-3</sup> is indicated as  $C_m$  in the figure. In each case  $C_m$  substantially exceeds the critical overlap concentration coefficients for PEO 1200 ( $\overline{M}_w = 1.2 \cdot 10^6$ ). The experimental uncertainty is high for this fraction (see Experimental) and these data are only included to mark the limit of usefulness of the present experimental arrangement. The conclusions drawn below are based on the data for fractions PEO 73 and PEO 280.

The data are summarized for PEO fractions PEO 73 and PEO 280 in *Figures 2* and 3 as plots of  $\log(D/D_0)_{PEO}$ vs. concentration of dextran where  $D_0$  is the self-diffusion coefficient for the PEO in the absence of dextran.

The exponential decrease of the self-diffusion coefficient has been noted previously by Tanner *et al.*<sup>16</sup> and Brown and Stilbs<sup>11</sup> for monodisperse, low molar mass PEO polymers in both binary and ternary systems up to concentrations well in excess of the critical concentration  $C^*$ . The present data also straddle the dilute and semi-



Figure 3 Plot of log  $(D/D_0)$  for PEO 280 versus concentration of dextran polymer: (a) DEX 20 (b) DEX 110 (c) DEX 500



Figure 4 Relationship between log  $(D/D_0)$  for PEO and the overlap parameter  $C[\eta]^{19-21}$ , where the latter refers to the dextran matrix:

	PEO 5.7	PEO 73	PEO 280
in:	DEX 10 (X) DEX 110 (O)	DEX 20 (□) DEX 110 (△) DEX 500 (▽)	DEX 20 (■) DEX 110 (●)

dilute domains where the critical concentration separating these regions is defined here, following Weissberg et al.<sup>12</sup>, as  $C^* = \frac{1}{[\eta]}$ . At C\* the macromolecules begin to touch (incipient overlap). The slopes in Figures 2 and 3 increase with increasing molecular weight of the dextran. As observed by Laurent et al.<sup>1</sup> for the diffusion of human serum albumin in dextran solutions of various molar mass, this dependence does not increase in direct proportion to the molar mass of the matrix polymer. As the molecular size of the matrix polymer increases with a given diffusant, the dependence becomes less marked. Tanner<sup>2</sup> made a similar finding for the diffusion of PEO in polydimethyl siloxane.

Exponential decay of  $D/D_0$  is also in keeping with 'obstruction' concepts and the semi-empirical expressions derived for them; see, for example, Ogston *et al.*<sup>13,14</sup>, who deduced a relationship of the general form:

$$D/D_0 \propto \exp(-B \cdot C^{1/2}) \tag{1}$$

where B is proportional to the radius of the diffusing spherical particle and C is the concentration of matrix polymer. Equation (1) was derived for compact solutes, such as globular proteins. However, hydrodynamic expressions applicable to such particles are frequently adequate for chain molecules in a Gaussian segment distribution, which are solvent-impermeable, and for which the intrinsic viscosity follows the Flory-Fox relationship, see, for example, the discussion in ref. 28.

This is possibly a good approximation for the highly flexible PEO chains. An example of the application of equation (1) to extended rod-like chains (Na deoxyribonucleate) is provided in the work of Laurent *et*  $al.^{17}$  who investigated the diffusion of some u.v.absorbing polymers in dilute aqueous hyaluronate solutions in the ultracentrifuge. These authors concluded that a relationship of the form of (1) was valid. Their data can, however, in fact be seen to more closely follow an exponential equation of the type:

$$\frac{D}{D_0} = \exp(-k \cdot C) \tag{2}$$

as found for the present data. It was also noted by these workers that the hydrodynamic radius calculated from equation (1) was apparently *smaller* than the hydrodynamic radius calculated from the diffusion coefficient in pure solvent. This led them to conclude<sup>17,18</sup> that there was end-on movement of the asymmetric particles in the polymer matrix. This result, however, does not necessarily support a reptation mechanism<sup>31</sup> for the transport of chain molecules in a ternary system. Rather it suggests that, while equation (1) may be valid for solid spheres (globular proteins), this relationship is inadequate for describing the diffusion of a rod-like polymer in a solution of a second linear polymer and does not allow evaluation of the radius of the diffusing equivalent hydrodynamic coil. This should not be expected since the theory<sup>14</sup> underlying equation (1) takes no account of the hydrodynamic interaction between diffusant and the matrix polymer which is unusually large in this case.

The present results are consistent with a somewhat different interpretation. There is a good correlation of log  $(D/D_0)$  for PEO polymers with the product  $C[\eta]$  for the dextran matrix. The latter parameter is frequently used in unifying data for different concentrations and molecular weights in the same polymer system<sup>19-21</sup>. Frisch and Simha<sup>22</sup> postulated that the dimensionless quantity  $C[\eta]$ measures the degree of coil overlap (incipient coil overlap,  $C[\eta] \sim 1$ ) in solution if one neglects changes in coil dimensions with concentration. Since the retarding effect of the matrix polymer on the mobility of the first polymer will depend on some function of the molecular weight and contentration of matrix polymer, it is not surprising that the parameter  $C[\eta]$  is a useful one. Figure 4c shows that when the molecular size of the diffusing polymer approaches or is substantially greater than that of the matrix polymer, there is an excellent correlation between log  $(D/D_0)$  and  $C[\eta]$ . The relationship has the form:

$$D/D_0 = \exp(-0.56 C[\eta])$$
(3)

for the present systems. This contrasts with the behaviour predicted by equation (1) which describes proportionality to the radius of the diffusing globular particle. The present results thus show that, for a randomly coiling polymer which is commensurate in size with the molecules of the second linear polymer within which it is diffusing, the diffusional retardation  $(D/D_0)$  is determined only by the frictional interactions imposed by the matrix polymer, i.e. there is a relationship to the macroscopic viscosity of the system. It is of course well known that in the limit of very small diffusing molecules (e.g. solvent) diffusing in a polymer solution there is a correlation only with the concentration of matrix polymer according to first-order expressions, such as that of Wang<sup>23</sup>, and no dependence on matrix polymer molecular size<sup>11</sup>. Thus the divergent cases shown in Figures 4a and b apparently indicate intermediate situations where the size of the diffusant is significantly smaller than that of the matrix polymer. As the diffusant size increases relative to the matrix polymer, a correlation with the macroscopic viscosity of the system is observed (Figure 4c). Similar observations have been



Figure 5 Plot of log  $(D/D_0)$  versus segment – segment contact parameter  $(C \cdot \overline{M}_W)$  according to Bueche<sup>24</sup>. Data are for PEO 73 as a diffusant in solutions of DEX 20, DEX 110 and DEX 500, (compare Figure 2)



Figure 6 Comparison of diffusion data for binary and ternary systems. (a) PEO 280 in D<sub>2</sub>O where  $C[\eta]$  refers to the PEO component. (b) PEO 280 in DEX 110/D<sub>2</sub>O where  $C[\eta]$  refers to the DEX 110 component. Insert: log (D · 10<sup>11</sup>/m<sup>2</sup> s<sup>-1</sup>) vs. concentration for (c) PEO 280 in D<sub>2</sub>O and (d) PEO 280 in DEX 110/D<sub>2</sub>O

made by Preston et al.<sup>1</sup> for the diffusion of various proteins in dextran solutions and by Turner and Hallett<sup>29</sup> and Hallett and Gray<sup>30</sup> who investigated the diffusion of polystyrene latex particles in hyaluronate and dextran solutions.

Bueche<sup>24</sup> has proposed the product  $(C \cdot M_w)$  as an alternative correlation parameter which expresses segment-segment contacts in systems of uniform segment density. The product  $C M_w$ , however, considerably overestimates the dependence of  $(D/D_0)$ —see Figure 5.

There is some justification for a comparison between binary and ternary systems. Figure 6 shows data for PEO in D<sub>2</sub>O and also in the presence of DEX 110. The insert shows that the frictional interactions are much greater in the binary  $PEO/D_2O$  system than when the same polymer is diffusing in a dextran solution of the same mass concentration. Normalization hydrodynamically using the parameter  $C[\eta]$  (main diagram) somewhat overcompensates for the disparate diffusion rates but serves to indicate the dominant part played by the macroscopic viscosity.

It may be noted that scaling theory<sup>25</sup> predicts linear plots of  $\log D$  vs.  $\log c$  in the semi-dilute region with a value of slope  $\alpha = -1.75$ .

The present data, however, only extend into the lower part of the semi-dilute region, as shown in Figure 7, owing



Figure 7 Double logarithmic plot of self-diffusion data for three fractions of PEO in DEX 110. The broken lines have a slope of  $\alpha = -1.75$  in accordance with ref. 25

to the limitations of polymer compatibility. Hadgraft et al.27 have described QELS measurements of the diffusion of poly(-methyl methacrylate) solutions in benzene over a similar concentration interval and experienced the same problem. Their results have the same qualitative character although these authors give a limiting slope of  $\alpha = -0.6$ . In Figure 7 the broken lines have been given a slope of  $\alpha = -1.75$  as for binary systems<sup>25</sup>; it is not an implausible limiting value. The same qualitative picture is provided by the results of Koñák et al.26 who measured the diffusion of block copolymer micelles in solutions of polystyrene, also using QELS. These authors also concluded that the diffusion of micelles is governed by the macroscopic viscosity of the system.

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