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Hydraulic conductivity of polymer matrices

Wayne D. Comper and Oliver Zamparo

Biochemistry Department, Monash University, Clayton, Victoria 3168, Australia

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We demonstrate that the chondroitin sulfate proteoglycan exhibits enhanced sensitivity to the flow of water compared to other macromolecules which is in accord with their functional role in conferring compressive resistance to cartilage. In order to understand factors that may contribute to its low hydraulic conductivity, a comparative study of hydraulic conductivity, as measured by the sedimentation velocity technique is made of various macromolecules representing variations in charge density, chemical composition, thermodynamic nonideality, size and flexibility. The polymers examined were dextran, poly(ethylene glycol), poly(vinyl alcohol), albumin, and dextran sulfate. The differences in hydraulic conductivity between the various macromolecules could not be explained by conventional theories which included prediction of hydraulic conductivity related to the radius of the molecule regarded as a uniform cylinder, nor the absolute charge density of the molecule and nor to the steric hindrance offered by the macromolecule to the diffusion of tritiated water. A qualitative relationship is established, however, between the noncounterion polymer contribution to osmotic activity and the resistance to water flow for polymers with high osmotic activity.

1. Introduction

The process of hydraulic permeability of water through regions containing aqueous polymer solutions is of major importance in describing the function of certain tissues, such as the biomechanical properties of cartilage [1] and blood capillary – interstitial transport [2]. The central parameter describing hydraulic permeability is the hydrodynamic frictional coefficient, f_{12}, which represents the frictional interaction between the polymer (component 1) and solvent – water (component 2) [3]. The measurement of hydraulic permeability, or the hydrodynamic frictional coefficient, may be conveniently made through sedimentation velocity analysis [4]. Previous studies have shown that in semidilute solutions of polymers, namely dextrans [5] and chondroitin sulfate proteoglycans [1], the hydraulic permeability is molecular weight independent, i.e., the viscous dissipation of water over the surface of the polymer is governed by polymer segments rather than the whole molecule. Quantitative interpretation of the nature of this viscous dissipation has involved theories based on steric hindrance-obstruction effects [6] and electrolyte dissipation for charged macromolecules [7]. In any event, there is still a paucity of information concerning macromolecular parameters governing hydraulic permeability as in some cases specific resistance may arise through the primary structure of the macromolecule used. In this study, we demonstrate that the chondroitin sulfate proteoglycans appear to have enhanced resistivity to flow compared to other macromolecules and therefore would be particularly suitable to cartilage function in resisting compression [1]. The investigations presented here set out to establish further correlations of the factors that may influence hydraulic permeability. The various

Correspondence address: W.D. Comper, Biochemistry Department, Monash University, Clayton, Victoria 3168, Australia.

parameters studied include macromolecular composition, shape, charge substitution, osmotic pressure and tritiated water diffusion. The use of the Carmen-Kozeny equation in combination with the theory of Happel and Brenner [6] for flow-through beds of uniform cylindrical fibers was found to be inadequate to explain the data in semidilute solution. We do, however, establish a relationship between macromolecules with relatively high osmotic activity and their resistance to flow.

1.1. Sedimentation analysis

We have previously shown [5] that the sedimentation coefficient of a polymer in a volume-fixed frame of reference $(S_1)_v$ is directly related to f_{12} through the following equation

$$(S_1)_v = (1 - \rho v_1)(1 - \phi_1) M_1 / f_{12} \quad (1)$$

where ρ is the solution density, v_1 the partial specific volume, ϕ_1 the volume fraction and M_1 the molecular weight of 1. The molecular weight independence of $(S_1)_v$ in semidilute solution is reflected in the molecular weight independence of the M_1/f_{12} term. Previous studies have demonstrated that M_1/f_{12} from diffusion analysis is quantitively similar to that from sedimentation [5]. A direct relationship between specific hydraulic conductivity k and the sedimentation coefficient has been derived [4] as

$$k = \frac{\eta_2 (S_1)_v}{C_1 (1 - v_1/v_2)} \quad (2)$$

where η_2 is the solvent viscosity and C_1 the concentration of 1 in mass/volume units.

Quantitative prediction of k has mainly been focused on neutral polymers. As far as we are aware there is no theory to describe electrolyte dissipation at finite concentrations. The Carmen-Kozeny equation is often used to describe hydraulic permeability in a random network of cylinders where

$$k = \frac{r_1^2 (1 - \phi_1)^3}{4G(\phi_1)^2} \quad (3)$$

where r_1 is the radius of the fiber and G is the Kozeny constant which varies with fiber concentration. The theoretical dependence of G on ϕ_1 has been analyzed by Happel and Brenner [6] for beds of neutral uniform cylindrical fibers.

1.2. Tritiated water exchange diffusion

For exchange diffusion or tracer diffusion, we designate the labelled component of 2 as 2*. From previous analysis, the exchange diffusion coefficient D_2 may be derived without assumption as

$$D_2^* = RT/(f_2^*{}_2 + f_2^*{}_1)$$

which reduces to [5]

$$D_2^* = RT/(f_2^*{}_2 + c_1 f_{12}/c_2) \quad (4)$$

where c_i are the molar concentrations of i. Therefore, measurement of the exchange diffusion coefficient should give an estimate of f_{12} as embodied in eq. 4.

2. Materials and methods

2.1. Materials

Bovine serum albumin (Cohn fraction V) and chondroitin sulfate (whale/shark) were purchased from Sigma (St Louis, MO). Dextran T500 ($\bar{M}_w \sim 500\,000$), and dextran sulfate T500 ($\bar{M}_w \sim 500\,000$) were from Pharmacia (Uppsala, Sweden). Poly(vinyl alcohol) (degree of polymerization $n = 1750 \pm 50$) (batch P469) was obtained from Tokyo Kasei Koyyo (Tokyo, Japan) and poly(ethylene glycol) ($\bar{M}_w \sim 40\,000$) from Serva (Heidelberg, F.R.G.). Chondroitin sulfate proteoglycan subunit (PGS) was prepared from Swarm rat chondrosarcoma as described previously [1]. Visking dialysis tubing was from Medicell International, U.K. Tritiated water (HTO) (lot no. 1275-133, 0.25 mCi g^{-1}) was from New England Nuclear (Boston). ^{22}Na was supplied as aqueous 20 mM NaCl (spec. act. 0.37 mCi/μg NaCl) by the Radiochemical Centre (Amersham, U.K.). Unless otherwise stated, all other reagents were of the highest grade commercially available.

2.2.1. Sedimentation

Sedimentation coefficients were measured at speeds ranging from 44 000 to 56 000 rpm at 20 °C in the analytical ultracentrifuge by use of the schlieren optical system and monitoring the movement of material sedimenting away from the meniscus. Normally, the solutions are so concentrated that the concentration gradient that develops refracts light completely out of the cell. The result is that a band develops that moves according to the sedimentation of the material. The sedimentation rate was recorded by monitoring the movement of the band median by a series of ten photographs taken over a time period of up to 48 h. Measurements of the movement of the front or back of the band yielded very similar sedimentation coefficients to the movement of the median. Preliminary experiments did demonstrate that sedimentation rate of poly(ethylene glycol), which had the lowest sedimentation coefficient, for a given concentration, at 9.7 and 16 kg m^{-3} was independent of rotor speed between 30 000 and 56 000 rpm.

2.2.2. Tritiated water exchange diffusion

A transport apparatus of similar design to that described by Linder et al. [8] and developed by Sundelöf [9] was used to measure HTO diffusion in polymer solutions. The analysis was similar to previous studies of water exchange diffusion in dextran polysaccharide solutions [10]. Each measurement of the HTO diffusion coefficient in the polymer solution was taken over a range of four different time points. All experiments were performed in duplicate. The probable error in the reduced diffusion coefficient ($D_2^*/D_2^{*\circ}$, where $D_2^{*\circ}$ is the diffusion coefficient of tritiated water in the absence of polymer) was equal to or less than 0.03.

2.2.3. Osmotic pressure

Osmotic pressures of various polymer samples at high concentration were obtained by equilibrium dialysis against dextran T500 solutions of known osmotic pressure [5] over a period of 2–3 weeks at 4 °C. Final concentrations were determined as described below.

2.2.4. Partition coefficients

The distribution of NaCl in dextran solutions was determined by dialysing dextran solutions of varying concentration against 100 vols. of 0.15 mol dm^{-3} NaCl containing ^{22}Na of known specific activity. The dialysis proceeded for 2 weeks and distribution of ^{22}Na in the dextran and dextran-free compartments was determined by radioactive counting.

2.2.5. Preparation of solutions

All polyelectrolyte solutions were dialysed extensively against 0.15 mol dm^{-3} NaCl solution or phosphate-buffered saline (PBS) which consisted of 0.14 mol dm^{-3} NaCl, 2.68×10^{-3} mol dm^{-3} KCl, 1.5×10^{-3} mol dm^{-3} KH_2PO_4, and 8.1×10^{-3} mol dm^{-3} Na_2HPO_4 (pH 7.5) before use.

2.2.6. Analytical procedures

The concentration of PGS was determined by an automated carbazole method [11]. Tritium radioactivity was determined using 1.0 ml aqueous samples with 8.0 ml of a scintillant mixture as described by Fox [12], and recorded on an LKB Wallac 1214 Rack beta scintillation counter. For ^{22}Na, the radiation was measured in an Ekco scintillator counter type N664A (Ekco Electronics, U.K.) using a thallium-activated sodium iodide crystal as scintillator. Dry weights of polymer samples were measured by heating the samples over P_2O_5 at 60 °C and 133 Pa pressure (under vacuum) until constant weight was obtained. Solution densities were measured on a DMA 55 density meter (Anton Paar, Graz, Austria). Estimates

Table 1

Partial specific volumes of macromolecular solutes

Sample	Partial specific volume (ml g^{-1})
Dextran T500	0.600 [a]
Dextran sulfate	0.457 [a]
Bovine serum albumin	0.730 [b]
Poly(vinyl alcohol)	0.760 [a]
Poly(ethylene glycol)	0.833 [a]
Chondroitin sulfate proteoglycan	0.490 [c]

[a] Measured in water with a density meter.
[b] From ref. 13.
[c] From ref. 1.

of the partial specific volume for each polymer were made from density measurements made on at least four solutions (made by weight with polymer samples of known moisture content) that covered the concentration range used in the study (table 1). The concentration of albumin was determined by absorbance at 280 nm and of the dextran fractions by optical rotation.

3. Results

The concentration dependence of the sedimentation coefficient (S_1) in the range of 0–2.2 S (S, Svedberg unit, 10^{-13} s) as a function of polymer volume fraction (ϕ_1) for the different polymer preparations is shown in fig. 1. In general, the sedimentation coefficient is seen to decrease with increasing volume fraction although the absolute magnitude of S_1 varies widely. Albumin exhibits the highest S_1 values, ranging from 0.7 to 2.05 S, corresponding to a volume fraction range of 0.05–0.18 S, whereas poly(ethylene glycol) exhibits the lowest S_1 values, namely, a range of 0.009–0.475 S for a volume fraction range of 0.01–0.03.

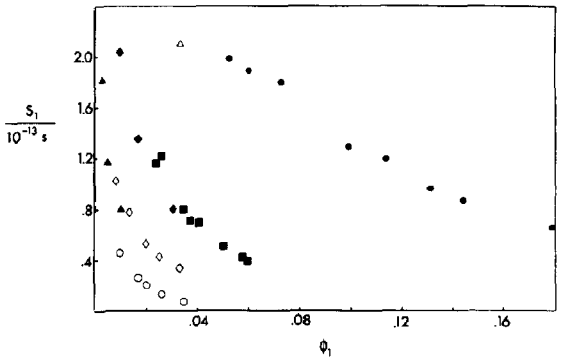

Fig. 1. Concentration dependence of sedimentation coefficient, S_1, as a function of polymer volume fraction, ϕ_1, for albumin in PBS (●), dextran T500 in PBS (■), dextran sulfate T500 in 1.0 ml dm^{-3} (△), 0.1 mol dm^{-3} NaCl (◆), 0.01 mol dm^{-3} NaCl (▲), poly(ethylene glycol) in water (○) and poly(vinyl alcohol) in water (◇). All polymer solutions were dialysed extensively against the appropriate solvent prior to the sedimentation velocity experiment.

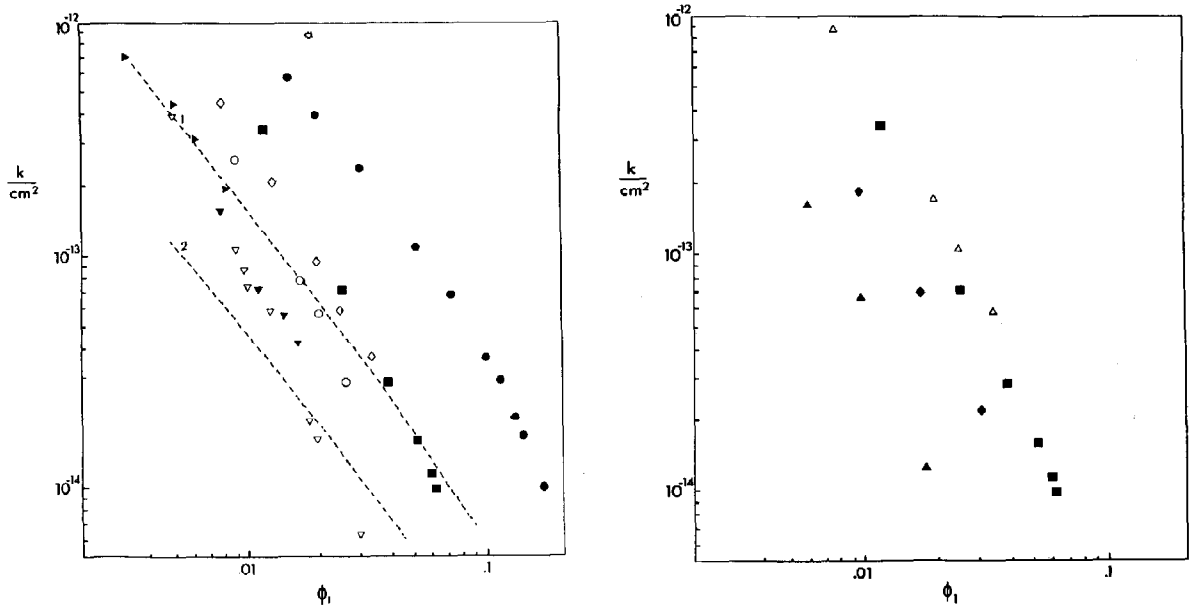

Fig. 2. Concentration dependence of specific hydraulic conductivity, k, as calculated from eq. 2, from the data given in fig. 1. Same symbols as in fig. 1 legend. Data for Swarm rat chondrosarcoma proteoglycan in PBS (▽) and in 1.0 mol dm^{-3} NaCl (▼) are combined with those of Comper and Williams [1] in panel a. Data for hyaluronate in 0.2 mol dm^{-3} NaCl were from Preston et al. [15] (▶). Theoretical values of k with $r_1 = 0.55$ nm (dashed curve 1) and $r_1 = 0.3$ nm (curve 2) are from eq. 3 using Happel-Brenner theory [6] to evaluate G.

There are a number of important qualitative features of the sedimentation data. We demonstrate that the polyelectrolyte fractions show evidence of electrolyte dissipation [7] or the 'primary charge effect' [14] in sedimentation in that the presence of charge on the polymer generally lowers the S_1 value. A considerable reduction in S_1 of dextran sulfate is observed by lowering the NaCl concentration to 0.01 mol dm^{-3}. A comparison of the uncharged polymers reveals a marked difference in S_1 values for a given ϕ_1, with the magnitude of S_1 being in the order of dextran > poly(vinyl alcohol) > poly(ethylene glycol).

When the sedimentation data are expressed in terms of specific hydraulic conductivity from eq. 2 some new comparative features emerge due to the influence of the $(1-v_1)$ term in eq. 2 (fig. 2). Clearly, the influence of shape of the macromolecule is significant in determining the magnitude of the specific hydraulic conductivity. Albumin, a globular protein with relatively densely packed chains, offers considerably less resistance to flow as compared to linear, random coil type structures. In this case, the k values for dextran are slightly greater than for poly(vinyl alcohol) but approximately the same as those for dextran sulfate in 1.0 mol dm^{-3} NaCl, the values for poly(ethylene glycol) and dextran sulfate in 0.1 mol dm^{-3} NaCl are similar and notably lower than those for poly(vinyl alcohol), and the values for chondroitin sulfate lie between those of dextran sulfate in 0.01 and 0.1 mol dm^{-3} NaCl. It is evident from these

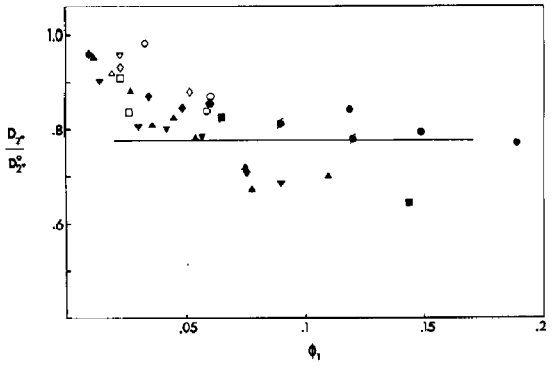

Fig. 3. Reduced diffusion coefficient $D_2^*/D_2^{*\circ}$, for tritiated water diffusion ($D_2^{*\circ}$, diffusion coefficient of tritiated water in the absence of polymer) as a function of polymer volume fraction, ϕ_1, for albumin (●) (data of Brown and Stilbs [16] for albumin shown by (◐)), dextran T500 (■), dextran T150 (M_w ~ 150000) (▲) and dextran T20 (M_w ~ 20000) (▼) (from Comper et al. [10]), poly(ethylene glycol) (○), poly(vinyl alcohol) (◇), chondroitin sulfate proteoglycan (▽) (from ref. 1), and chondroitin sulfate in PBS (□) and 1.0 mol dm^{-3} NaCl (△). The line represents the ordinate value for albumin $\phi_1 = 0.17$ which has a $k = 1.0 \times 10^{-14}$ cm^2 (fig. 2).

data that the chondroitin sulfate proteoglycan exhibits very low hydraulic conductivity as compared to the other macromolecules studied. The corresponding scaling relationships between k and ϕ_1, of the form $k = a\phi_1{}^b$, yield similar values for the constants a and b over the range of polymers studied where $-\log a$ may vary from 15.92 to 18.15 and b from -1.53 to -2.45 (table 2).

In an attempt to determine directly the steric obstruction offered by these various polymer frac-

Table 2

Scaling relationship of specific hydraulic conductivity k to volume fraction ϕ_1 of the form $k = a\phi_1{}^b$

The constants a and b ($\pm$S.E.) were obtained by linear regression analysis of data in fig. 2.

Material	Solvent	log a	b
Swarm rat chondrosarcoma	PBS	-17.13 ± 0.05	-2.36 ± 0.10
proteoglycan	1 mol dm^{-3} NaCl	-16.06 ± 0.04	-1.53 ± 0.16
Dextran sulfate	0.01 mol dm^{-3} NaCl	-18.15 ± 0.12	-2.45 ± 0.38
	0.1 mol dm^{-3} NaCl	-16.44 ± 0.01	-1.83 ± 0.03
	1.0 mol dm^{-3} NaCl	-15.92 ± 0.03	-1.85 ± 0.06
Dextran	PBS	-16.65 ± 0.02	-2.19 ± 0.04
Albumin ($\phi_1 > 0.1$)	PBS	-16.66 ± 0.02	-2.22 ± 0.09
Poly(vinyl alcohol)	H_2O	-16.09 ± 0.04	-1.80 ± 0.09
Poly(ethylene glycol)	H_2O	-16.73 ± 0.04	-2.03 ± 0.11

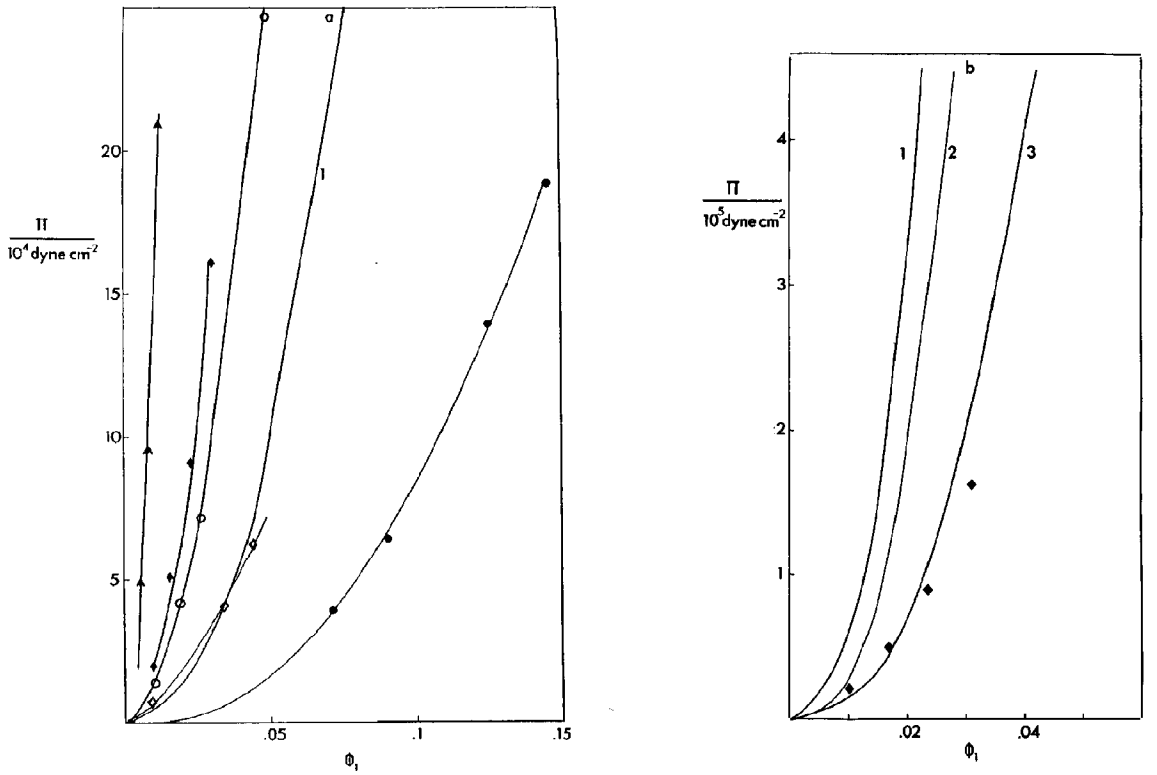

Fig. 4. (a) Osmotic pressure as a function of polymer volume fraction as determined by equilibrium dialysis against dextran (curve 1) of albumin in PBS (●), dextran sulfate in 0.1 mol dm^{-3} NaCl (◆) and in 0.01 mol dm^{-3} NaCl (▲), poly(ethylene glycol) in water (○) and poly(vinyl alcohol) in water (◇). (b) Osmotic pressure as a function of polymer volume fraction as determined by sedimentation-diffusion analysis [21] for chondroitin sulfate proteoglycan (curve 1), chondroitin sulfate in 1.0 mol dm^{-3} NaCl (curve 2) and dextran sulfate in 0.15 mol dm^{-3} NaCl (curve 3) [21]. Data on dextran sulfate in 0.1 mol dm^{-3} NaCl from equilibrium dialysis are also included (◆).

tions to water, we have measured the variation of the reduced diffusion coefficient of HTO as a function of polymer fraction (fig. 3). These results demonstrate that (i) the reduced diffusion coefficient of water decreases with increasing polymer volume fraction, (ii) the magnitude of the decrease is generally less for albumin, poly(ethylene glycol), and poly(vinyl alcohol) than it is for dextran and dextran sulfate, and (iii) differences between dextran and dextran sulfates are small. Values of $D_2^*/D_2^{*\circ}$ for albumin also appear to be in agreement with the data of Brown and Stilbs [16] (fig. 3).

It is of interest to compare the hydraulic conductivity of the various macromolecules with their osmotic pressure. The concentration dependence of osmotic pressure is shown in fig. 4. The osmotic pressures of dextran sulfate at various NaCl concentrations as determined by equilibrium dialysis

Table 3

Partitioning of ^{22}Na across Visking tubing separating solutions of dextran T500 and 0.15 mol dm^{-3} NaCl

Dextran T500 (kg m^{-3})	Partition coefficient
31.0	0.954
42.1	0.943
88.9	0.906
116.5	0.901
122.2	0.890
137.0	0.887

against dextran are shown in fig. 4a. The osmotic pressure for the dextran sulfates can only be regarded as approximate. This is apparently due to the effects of salt exclusion by the dextran (table 3) which appears to lower the effective osmotic pressure of the dextran sulfate as determined by equilibrium dialysis at least at relatively high concentrations as compared to that obtained by sedimentation diffusion (fig. 4b). The osmotic pressure of the chondroitin sulfate proteoglycan is higher than that of dextran sulfate although its linear charge density is lower (fig. 4b). The osmotic pressure for poly(ethylene glycol) is also higher than for other neutral molecules studied including poly(vinyl alcohol) which is similar to dextran (fig. 4a).

4. Discussion

This study is concerned with delineating factors that control the movement of water through polymer matrices in semidilute solution. At present, there is no comprehensive theory to test our experimental analysis. For hydraulic conductivity governed by purely electrolyte dissipation, we would expect k to vary as $[NaCl]^{-0.5}$ [7], derived from the Debye-Hückel screening parameter, which corresponds to a 3-fold change in k for a change of NaCl concentration by an order of magnitude. This degree of change is seen for dextran sulfate (fig. 2); for example, at $\phi_1 = 0.01$ the value of k at NaCl concentrations of 0.01, 0.1 and 1 mol dm^{-3} is 5.5×10^{-14}, 1.8×10^{-13} and 6.5×10^{-13} cm^2, respectively. Electrolyte dissipation for the proteoglycan subunit as seen from its ionic strength dependence was much lower than predicted. At low proteoglycan concentrations there was no significant difference in k in PBS (ionic strength = 0.15) and 1 mol dm^{-3} NaCl whereas at $\phi_1 = 0.016$ there was a difference ratio of 1.56 as compared to the predicted value of 2.58. A further anomaly associated with electrolyte dissipation effects is that the proteoglycan has a significantly lower k value to dextran sulfate even though it has a lower charge density (~ 0.5 nm) as compared to dextran sulfate (~ 0.26 nm).

In terms of steric-obstruction models, a comparison of the HB (Happel-Brenner) theory of k for dextran (with $r_1 = 0.55$ nm) reveals a poor correlation with the experimental data particularly at low ϕ_1 (< 0.03) (fig. 2). Close agreement is obtained at higher ϕ_1 values although this may be fortuitous as the lines appear to intersect. Other estimates of r_1 for dextran from polymer-dextran interaction studies in ternary systems have yielded values of $r_1 \sim 1.0$ nm for dextran [17] which is probably a reflection of the branching with short chains that occurs in dextran. Polymer recognition by exclusion of the dextran fiber radius will therefore yield a higher value as compared to segments with which the water molecule interacts. These considerations lead us to suggest that the apparent agreement of the HB theory for hyaluronate with $r_1 = 0.55$ nm at low ϕ_1 (< 0.01) (fig. 2a) (ref. 18; see also ref. 19) may only be coincidental and further studies at higher concentration are required to confirm these conclusions with this polymer. The fact that poly(vinyl alcohol), with $r_1 = 0.47$ nm [17], has higher k values than hyaluronate, but lower values than dextran suggests that hyaluronate may be affected by electrolyte dissipation or some specific primary structural feature. The qualitative agreement with the HB theory is seen in terms of the influence of fiber radius. That is, it predicts that as the radius of the fiber is increased for a given ϕ_1 then k increases which is evident for dextran and poly(vinyl alcohol). However, in general, it is clear that the HB theory, whose variable parameters only include polymer concentration and fiber radius does not consistently account for the variation of k over a wide range of ϕ_1 (0–0.1).

There is now considerable evidence that water transport through polymer matrices is a polymer molecular weight independent process, i.e., it depends on water-polymer segment interaction which is the viscous dissipation of water movement over the surface of the polymer segment. Evidence has been established for molecular weight independence of S_1 in semidilute solutions of dextran [5] and HTO transport in dextran solutions [10]. The value of the reduced diffusion coefficient of HTO, namely, $D_2^*/D_2^{*\circ}$, is useful in the comparison of polymer matrices and their influence on the steric

exclusion of water as governed by the f_{12} term in eq. 4 provided that f_{22}^* does not change significantly over the range of ϕ_1 studied. It is the same process that determines f_{12} in $D_2^*/D_2^{*\circ}$ that governs k from eqs 1 and 2. A basis for comparison of the HTO transport data can be made from the stochastic model of Ogston et al. [17] which takes into account the molecular size of the interacting species on the basis of steric hindrance or the excluded volume concept. The reduced diffusion coefficient is given by

$$\frac{D_2^*}{D_2^{*o}} = A \exp\left[-B\phi_1^{1/2}\right] \tag{5}$$

where $B = 1 + (r_2/r_1)$ and where A is a constant close to unity. This equation predicts that as r_1 increases so does the value of $D_2^*/D_2^{*\circ}$. This qualitative prediction is clearly evident with the high values of k for albumin as compared to the linear polymers. No major differences in $D_2^*/D_2^{*\circ}$ could be detected for the linear polymers for $\phi_1 < 0.05$ whereas significant changes are registered in the corresponding k values. This is probably best represented in terms of the corresponding ϕ_1 values for a given k value which should also give an identical $D_2^*/D_2^{*\circ}$ (as both parameters are essentially governed by the frictional term M_1/f_{12}). A k value of 1.0×10^{-14} cm^2 corresponds to ϕ_1 for PGS, poly(ethylene glycol), dextran sulfate in 0.1 mol dm^{-3} NaCl, poly(vinyl alcohol), dextran and albumin of 0.024, 0.046, 0.047, 0.062, 0.062 and 0.17, respectively. The ordinate of the reduced diffusion coefficient corresponding to $\phi_1 = 0.17$ for albumin has been drawn in fig. 3 to facilitate comparisons. The fact that it passes through $\phi_1 \sim 0.06$ for dextran and dextran sulfate would demonstrate that there is reasonable agreement with the obstruction effects of water in hydraulic flow as compared to diffusional exchange. An anomalous situation occurs with poly(ethylene glycol) and particularly chondroitin-sulfate-containing macromolecules whose corresponding reduced HTO diffusion coefficient values appear to lie well above the line at the corresponding k value. This demonstrates that other factors may be contributing to the enhanced resistance to hydraulic flow exhibited by these polymers. A related anomaly arises when it is evident that neither the HB theory nor steric hindrance based concepts can explain differences associated with k values of poly(ethylene glycol) as compared to poly(vinyl alcohol) which has essentially the same fiber radius.

A possible contributing factor associated with the anomalously low hydraulic conductivity of poly(ethylene glycol) as compared to other neutral molecules and of PGS as compared to dextran sulfate at different NaCl concentrations may be through the influence of osmotic activity of the macromolecule. Both chondroitin sulfate proteoglycan and poly(ethylene glycol) show relatively high osmotic pressures (fig. 4) as compared to the other polymers. In the case of the proteoglycan, however, it is not the osmotic activity of the constituent counterion as the discrepancy between HTO diffusion and k data is seen for chondroitin sulfate chains in 1.0 mol dm^{-3} NaCl where ionic effects would be screened out (fig. 3). The osmotic pressure of chondroitin sulfate in 1.0 mol dm^{-3} NaCl is still substantial, however, in relation to the other polymers (fig. 4b). The osmotic term would be derived from the properties of the polymer chain itself. The fact that albumin registered a relatively low $D_2^*/D_2^{*\circ}$ value for a given k value as compared to poly(ethylene glycol) would also suggest that osmotic environment is important, since albumin has a relatively low osmotic pressure (fig. 4). Osmotic effects in hydraulic conductivity in sedimentation experiments have also been reported elsewhere [4,22] where it was demonstrated that specific hydraulic conductivity is generally higher at theta conditions as compared to the behaviour of macromolecules in good solvents where the osmotic pressure is relatively high.

These results then may indicate a situation that, while the overall macroscopic osmotic pressures are approx. 10^5 dyne cm^{-2}, which are small in relation to the centripetal force on the polymer, approx. 10^7 dyne cm^{-2}, the osmotic environment at microscopic dimensions around the polymer chain may be influential in determining viscous dissipation of water. This osmotic environment would not be detected by HTO exchange as the exchange process does not recognise chemical potential gradients of water. This may imply that

osmotic gradients may extend from the polymer chain which will be determined, in part, by the intrinsic segmental mobility contribution to translational motion of the polymer as a whole. It is known that neutral polymers vary widely in their osmotic activity and interaction with solvent. We speculate that local chain-solvent interactions governed by segmental mobility may play an important role in viscous dissipation of water through regions containing the polymer.

Acknowledgements

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