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Inhibition of transepithelial osmotic water flow by blockers of the glucose transporter

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On the basis of evidence derived mostly from human erythrocytes, it has been suggested that water traverses cell membranes through membrane-spanning proteins such as the anion channel or the glucose transporter acting as water pores. However, specific inhibitors of such permeation processes have not been found to block water transport, and hence a precise identification of the water route has not been possible so far. We have investigated this issue by characterizing the osmotic flows across a fluid-transporting epithelium, the rabbit corneal endothelium. The rate of such flows was monitored continuously as a function of time. We confirmed prior findings of (a) an inhibition by PCMBS on osmotic water flow, and (b) lack of inhibition by DTNB and DIDS. On the other hand, we have found for the first time that several blockers of glucose facilitated diffusion, namely, phloretin (2 mM), phloridzin (2 mM), diallyldiethylstilbestrol (0.1 mM), cytochalasin B (20 μg/ml), and ethylidene-D-glucose (200 mM), all clearly inhibit osmotic flow. Our evidence is consistent with the hypothesis that both water and glucose may traverse these cell membranes through the same channel-like pathway contained in the glucose transporter membrane-spanning protein.

Introduction

Corneal endothelial fluid transport. This work originates from our prior studies on water relations in the cornea of the eye. This organ is kept transparent by the activity of its posterior epithelial monocellular cell layer, the endothelium, which displays a high osmotic permeability [1,2] and transports significant amounts of electrolytes and water [3,4] across itself. In the course of our studies on the basic mechanism of this fluid transport [4], recent evidence has [2] led us to conclude that the transendothelial transport of water most probably takes place across the cell membranes, just as it appears to do in other water-transporting epithelia such as the gall bladder [5].

The route for water permeation through cell membranes. In order to explain fluid transport fully, one would need to know the basic mechanism of water movements through cells and tissues. Yet, although water movements across cell membranes are a most ubiquitous and important feature of living processes, the precise route for it remains unclear. Thus, it has been variously suggested [6] that water simply traverses the lipid bilayer in most membranes except for those most permeable, where it would in addition traverse a water pore [7], also called a water channel [8], which would constitute a polar route across the lipid bilayer.

The evidence in red blood cells: the anion chan-

Abbreviations: PCMBS, *p*-chloromercuribenzenesulfonate; DIDS, 4,4′-diisothiocyanatostilbene-2,2′-disulfonate; DTNB, 5,5′-dithiobis(2-nitrobenzoate); DADES, 3,3′-diallyldiethylstilbestrol.

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nel. Studies of this latter route in human erythrocyte membranes had led to the suggestion [9,10] that the transmembrane protein (band 3) containing the anion channel [11,12] is the route of the water transport. However, later evidence has cast doubts on such suggestion. For example, DTNB, which is a good blocker of and marker for the anion channel in red blood cells, has been variously reported to block osmotic water flow by 60% [13] and not to affect water osmotic permability [14]. This discrepancy is important, since the observed inhibitory effect of DTNB on osmotic flow was central for the argument that the anion channel is the water permeation route [10]. More recent evidence has pointed to either the anion channel or the glucose transporter or both (bands 3.0 and 4.5) as the water permeation site [15,16]; still, a more definite identification could not be done for lack of evidence that any specific inhibitor of those proteins would block water transport.

Our own results: the glucose transporter as water channel. Given this background, we have reexamined the effect on osmotic water flow of blockers of SH groups and of both anion and glucose permeation. Two of the approaches we have utilized appear to be novel for this area of work:

(a) we measured water flow across an epithelial preparation (the corneal endothelium) instead of red blood cells, and,

(b) rather than determining osmotically-induced cell volume changes (as done classically with red blood cells), we monitored continuously the rate of water flow as a function of time.

While we confirmed some prior results obtained with erythrocytes, we also found a crucial difference, namely, that in our preparation all glucose transport inhibitors blocked osmotic water flow. The conclusion that emerged from these experiments is consistent with the hypothesis that both water and glucose traverse cell membranes through the same channel-like pathway, that is, through the protein identified as the glucose transporter (band 4.5). An account of some of our early findings has appeared in Abstract form [17].

Methods

The isolated rabbit corneal endothelium was mounted in a chamber so as to separate two compartments filled with the appropriate experimental solutions. The water flow across it was measured as previously [18] described (except that an infrared sensor was now used to detect water level). The solution on the aqueous side was bubbled with a 95% air/5% CO_2 mixture saturated with water vapor. The hydrostatic pressure difference across the tissue ($P_{aqueous} - P_{stroma}$) was 12 cm H_2O, and the temperature was kept at 36.8° C. Both sides of the preparation were bathed with basal salts plus 6.9 mM glucose (BSG solution). After mounting, the endothelial preparation typically developed its characteristic spontaneous rate of fluid transport towards the aqueous side (6 to 10 $\mu l \cdot h^{-1} \cdot cm^{-2}$). After monitoring this for about 30 min, a relatively large osmotic flow (12 to 20 $\mu l \cdot h^{-1} \cdot cm^{-2}$) was induced by making the aqueous side hypertonic by 200 mosmol/l above BSG tonicity. The compounds utilized as osmotic agents were either dimethyl sulfoxide (DMSO), propionamide, sucrose or glucose. After attaining a steady osmotic flow, a blocker was added while retaining the osmotic gradient. The blockers used were *p*-chloromercuribenzenesulfonate (PCMBS), 5,5′-dithiobis(2-nitrobenzoate) (DTNB), 4,4′-diisothiocyanatostilbene-2,2′-disulfonate (DIDS), phloridzin, phloretin, cytochalasin B and dihydrocytochalasin B (all obtained from Sigma, St. Louis, MO), 4,6-*O*-ethylidene-D-glucose (from Aldrich, Milwaukee, WI) and 3,3′-diallyldiethylstilbestrol (DADES), prepared by Lee's Bio-Organic Labs., Marcus Hook, PA.

Results

Sulfhydryl blocker

As in studies in human erythrocytes [19–21], the osmotic flow was inhibited by the sulfhydryl blocker PCMBS (Fig. 1B, 1C and Table I). After adding the inhibitor, there was a short delay, and then the rate of flow decreased exponentially. The same form of time dependence was seen with the other inhibitors (Fig. 1), so we determined the initial rates of inhibition (Table I) from the initial slopes of the exponentials in each case. For comparison, we also include in Table I results obtained in control experiments done by imposing an osmotic gradient without the subsequent use of inhibitors. As the example in Fig. 1A shows, in

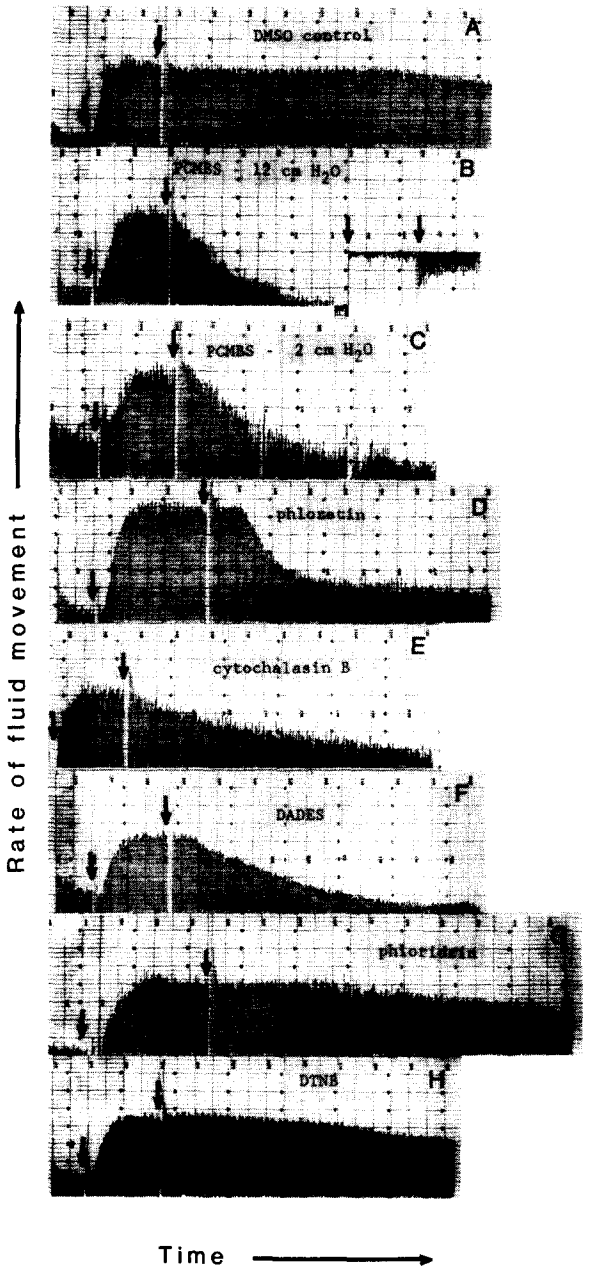

Fig. 1. Transendothelial water flow as a function of time in photographs of the original recorder charts. Scale of ordinate: 1 large division = 100 nl/min; scale of abscissa: 1 division = 15 min. The positive direction in the ordinate (positive flow) signifies movement of water from the stromal (basal) side to the aqueous (apical) side. Unless specified, a hydrostatic pressure head of 12 cm H_2O was applied to the aqueous side. Going from left to right in the panels, fluid transport normally ensued, after which the first arrow marks the establishment of an osmotic gradient of 200 mosM by substituting a hypertonic solution on the aqueous side. Unless specified, the osmotic agent was DMSO. The second arrow marks the second manipulation, usually the addition of a test compound (also by substitution of the solution on the aqueous side).

(A) Expt. No. 34; control experiment; at the second arrow, the solution on the aqueous side (BSG) was completely replaced by fresh BSG.

(B) Expt. No. 82; test compound: 2 mmol/l PCMBS; after some 4 h, when the flow reversed its direction, the baseline of the recording was repositioned (third arrow). At the fourth arrow, the hydrostatic pressure head was increased from 12 to 18 cm H_2O, and an increased leak ensued.

(C) Expt. No. 81; test compound: 2 mmol/l PCMBS; hydrostatic pressure head: 2 cm H_2O.

(D) Expt. No. 76; osmotic agent: sucrose; test compound: 2 mM phloretin.

(E) Expt. No. 48; test compound: 20 μg/ml cytochalasin B.

(F) Expt. No. 58; test compound: 0.1 mM DADES.

(G) Expt. No. 30; test compound: 2 mM phloridzin.

(H) Expt. No. 67; test compound: 2 mM DTNB.

such experiments the osmotic flow remained constant for a relatively long period, and then it declined very slowly.

Anion channel blockers

We also studied the effect of the anion channel blockers DTNB and DIDS on osmotic flow. Our results are consistent with those of Benga et al. [14] for both blockers, in spite of the difference in methods and preparation. They measured human erythrocyte H_2O diffusional permeability. In our hands, DTNB (2 mM) had only a modest effect, which was not statistically significant (Fig. 1H and Table I). Similarly, DIDS (50 μM) had no significant effect on osmotic flow (Table I). At this point, like Benga et al. [14] we decided to search for another transmembrane protein which could act as the water channel.

Inhibitors of the glucose transporter

The carrier for facilitated diffusion of glucose or glucose transporter [22,28] is a good candidate for the role of a water channel. It is a well studied membrane protein; recently, the transporters of two human cells have been sequenced [22]. It traverses the membrane entirely, it is present in most if not all animal cells [23], and, where the number of molecules per cell has been estimated as in human erythrocyte [24,25], it is present in the relatively large numbers that would be necessary to have it account for significant water permea-

TABLE I

EFFECTS OF BLOCKERS ON TRANSENDOTHELIAL OSMOTIC FLOWS

Osmotic agent (mol/l) and blocker (mmol/l) [a]	Expt. No.	Osmotic flow (nl/min)	Delay (min) (Av. ± S.E.)	Rate of inhibition or decline (%/min) (Av. ± S.E.)
DMSO (0.2)	1	475	15	0.51
PCMBS (0.5)	21	490	22	1.10
	22	510	15	0.93
	26	375	78	0.57
			33 ± 13	0.78 ± 0.12
DMSO (0.2)	20	600	13	1.30
PCMBS (1.0)	23	545	11	1.19
	25	300	18	1.52
			14 ± 2	1.34 ± 0.08
DMSO (0.2)	19	440	11	1.16
PCMBS (2.0)	24	290	9	1.59
	82	404	6	1.67
	83	305	3	1.75
			7 ± 2	1.54 ± 0.11
DMSO (0.2)	79	385	16	1.61
PCMBS (2.0)	80	250	16	2.50
$\Delta P = 2$ cm H_2O	81	400	12	1.52
			15 ± 1	1.88 ± 0.26
DMSO (0.2)	30	375	108	0.48
Phloridzin	64	225	177	0.37
(2.0)	65	395	150	0.23
	68	325	119	0.35
	69	370	187	0.66
			148 ± 14	0.42 ± 0.06
DMSO (0.2)	31	345	8	0.39
Phloretin	32	315	9	0.47
(2.0)	36	305	12	0.80
	37	410	15	1.85
	38	350	12	0.78
			11 ± 1	0.86 ± 0.23
Sucrose (0.2)	73	555	33	1.85
Phloretin	74	600	40	1.61
(2.0)	75	690	47	1.25
	76	575	30	2.00
			38 ± 3	1.68 ± 0.14
Propionamide	43	125	27	0.85
(0.1)	44	175	24	0.95
Phloretin (2.0)	46	105	33	0.71
	70	120	26	0.61
			28 ± 2	0.78 ± 0.06
DMSO (0.2)	48	420	11	0.86
Cytochalasin B	49	330	10	0.60
(20 μg/ml)	50	385	8	1.96
	72	400	118	0.33
	92	300	54	0.79
			40 ± 19	0.91 ± 0.25

TABLE I (continued)

Osmotic agent (mol/l) and blocker (mmol/l) [a]	Expt. No.	Osmotic flow (nl/min)	Delay (min) (Av. ± S.E.)	Rate of inhibition or decline (%/min) (Av. ± S.E.)
DMSO (0.2)	56	357	51	0.66
DADES (0.1)	57	315	34	0.99
	58	305	19	0.79
	71	340	165	1.52
			67 ± 29	0.99 ± 0.16
D-Glucose (0.2)	97	315	42	0.65
	98	505	27	0.83
Ethylidene-	99	375	60	1.39
D-glucose (200)	100	420	39	1.14
	101	380	32	1.64
	102	395	33	1.02
			39 ± 4	1.11 ± 0.14
DMSO (0.2)	27	300	161	0.35
DTNB (2.0)	28	430	64	0.20
	66	225	192	0.30
	67	340	75	0.15
			123 ± 27	0.25 ± 0.04
DMSO (0.2)	88	250	52	0.19
DIDS (0.050)	89	400	184	0.28
	90	300	75	0.28
	91	375	143	0.23
			114 ± 26	0.25 ± 0.02
DMSO (0.2)	59	370	13	0.14
1% ethanol	60	330	150	0.25
(control)	86	250	68	0.50
	87	325	205	0.42
			109 ± 37	0.33 ± 0.07
DMSO (0.2)	34	385	205	0.19
no blocker	35	435	170	0.31
(control)	84	300	272	0.30
	85	295	300	0.29
			237 ± 26	0.27 ± 0.02

[a] Except where noted.

tion. In addition, recent work by Benga and his co-workers [15,16] strongly suggests that the water channels could only be either the anion channel or the glucose transporter or both. However, counter to this idea, previous work from several other laboratories using human erythrocytes [19,20,14, 26] has shown no effect on water permeation by phloretin, a well-known enzymatic inhibitor [27]

which is particularly effective in blocking the facilitated diffusion of glucose across the membranes of several types of cells [28,29].

Given this background, we were somewhat surprised that in our preparation, phloretin (2 mmol/l) clearly inhibited osmotic flow (Table I and Fig. 1D). Furthermore, this inhibition by phloretin took place with either DMSO, propionamide, or sucrose as osmotic agents (Table I). Phloridzin (2 mmol/l) also inhibited water flow, although to a much smaller extent (Table I and Fig. 1G). This parallels the relative blocking effects of these two compounds on facilitated diffusion of glucose in some types of cells [29].

Subsequently, we utilized several other glucose transport inhibitors. We tested DADES, a compound in a group known to include some of the most potent blockers of facilitated diffusion of glucose (Ref. 28, 30; 50% inhibition is reached with less than 1 μM with this class of blockers). Its pronounced inhibitory effect on osmotic flow is shown in Fig. 1F and Table I. In keeping with this pattern, cytochalasin B, another known blocker [31,32] of facilitated diffusion, also markedly inhibited osmotic flow, as shown on Fig. 1E and Table I. This last result was firmed up by four control experiments done with dihydrocytochalasin B, which acts on cell mobility and morphology but does not affect the glucose transporter [33]. Dihydrocytochalasin B did not affect the osmotic flow. Lastly, we tested ethylidene-D-glucose, which is also known to inhibit glucose transport [34–36], and verified that it also blocked the osmotic flow (Table I).

The rates of inhibition in Table I give an idea of the relative potency of each of the inhibitors at the concentrations utilized. To be noted, cytochalasin B and DADES inhibit osmotic flow at lower concentrations than the other inhibitors, which is in line with their known behavior towards the glucose transporter. The rate of inhibition with phloretin was larger when sucrose was the osmotic agent than when either DMSO or propionamide were used. This may indicate some competition between phloretin, DMSO and propionamide for the blocking site. Still, the inhibitory effects were typically very large; thus, with the more potent inhibitors, after some 1–2 h the flow typically had fallen by 75 to 90% with respect to that during the control period (Fig. 1). On the other hand, experiments performed with the osmotic agents alone (such as DMSO) or in addition to the ethanol used as a vehicle for DADES * showed that the osmotic flow remained nearly constant for quite a long period of time (Fig. 1A, Table I).

Control experiments

Since the experiments must be carried out with a hydrostatic pressure gradient (ΔP) applied to the aqueous side [18], it might be argued that the decrease in positive flow observed with the different blockers (Fig. 1) might be due at least partially to an increased passive fluid leak across the paracellular pathway driven by the standard 12 cm H_2O ΔP utilized. However, at least three different lines of evidence lead us to reject this possibility.

(1) The actual rate of leak driven by ΔP was determined after the osmotic flow had been inhibited and was found to be relatively small. An example is shown in Fig. 1B.

(2) The tissue was exposed to an osmotic gradient, and then to Ca-free medium while maintaining the osmotic gradient. Since the apical intercellular junctions are known to open under these conditions [37], the positive flow decreased, reflecting an increased leak. However, the residual positive flow was still inhibited by the subsequent addition of 2 mM PCMBS.

(3) Perhaps most definitively of all, when these experiments were done with a reduced hydrostatic pressure gradient of only 2 cm H_2O, the inhibitory effects observed (Table I and Fig. 1C) were the same as with the larger ΔP.

Discussion

Significance of the present findings

The idea that the glucose transporter might be the 'pore' or channel sought for water permeation is not new in itself. It appeared in, among others, papers by Macey and Farmer [19], Owens and Solomon [26] and Benga et al. [14], but since in those cases phloretin was found not to affect water osmosis (or diffusion) in human erythrocytes, the notion remained questionable. It was also mentioned in a similar light in a recent paper

* Phloretin, which is insoluble in water at ambient temperature dissolved at the 36.8°C utilized here.

by Solomon et al. [10] and in a review by Macey [8]. Very recently, however, the view acquired new viability with the results of Benga and his coworkers [15,16]. From the patterns of PCMBS binding to cell proteins and water diffusion inhibition, they concluded that either or both the anion channel or the glucose transporter could be associated with water channels, although they cautioned that 'to date, there is no evidence that a specific inhibitor of one of these processes will inhibit water transport'.

The present results bring forward precisely that evidence, and point squarely to the glucose transporter as the site of water permeation in this preparation. To summarize, we have found, apparently for the first time in any system, that several known blockers of facilitated diffusion of glucose, namely, phloridzin, phloretin, DADES, cytochalasin B, and ethylidene-D-glucose, all inhibit transendothelial osmotic flow. The degree of specificity of each one of them separately for the glucose transporter can, of course, be argued about; for instance, phloretin and phloridzin also block Cl^- [38] and SO_4^{2-} [39] permeation in erythrocytes. However, the relevance of such observations for our case is dubious, since DIDS, which blocks the anion channel in erythrocytes [8], did not affect the osmotic flow in our preparation. Certainly, no such reservations can be voiced for two other inhibitors utilized (DADES and ethylidene-D-glucose), which seem quite specific for the glucose transporter (Refs. 28, 30 for DADES; Refs. 34–36 for ethylidene-D-glucose). As for cytochalasin B, a popular and potent blocker of the glucose transporter, the possibility of indirect effects via its parallel effect on actin filaments was discarded by verifying that dihydrocytochalasin B, which has the same morphological effects as its parent compound but does not affect glucose transport, did not block the osmotic flow.

For emphasis, it may be noted that 'success', defined as blockage by glucose transport inhibitors and non-blockage by non-glucose transport inhibitors, was achieved all 55 times in the 55 pertinent experiments in Table I.

Estimates of the number of permeation sites in corneal endothelium

The endothelium is the site of a sizable glucose facilitated diffusion mechanism [3], which is a requisite for the present reasoning. The number of sites of interest can be estimated in two ways: (a) from glucose flux measurements, and (b) from osmotic permeability values. In the first case, using a published value of $5.56 \cdot 10^{-6}$ $mM \cdot cm^{-2} \cdot min^{-1}$ for the V_{max} of the methyl-D-glucose transport mechanism [40], we arrive at a transfer rate of $1.75 \cdot 10^8$ molecules/s per cell. Using an estimate for the turnover of 1000 molecules/s per site (derived from erythrocyte data), the site density is $1.8 \cdot 10^5$ sites/cell. In the second case, we calculate (see below) a hydraulic conductance of $8.2 \cdot 10^{-13}$ cm/s per site ($\times 1$ cm^2 of area) based on Poseuille's law. Given an apical hydraulic conductance of 0.14 cm/s [2], we reach a value of $5.3 \cdot 10^5$ sites/cell, which agrees with the order of magnitude of the other estimate above. Granted that these order-of-magnitude estimates are not to be overemphasized, the agreement nevertheless appears interesting and is consistent with our reasoning.

Present and prior results

Discrepancies between prior and present results exist, but could be accounted for. The difference between the effects of phloretin on human erythrocytes and on our preparation may be due to a difference in tissue properties, or in the experimental conditions. The slow time-course for the inhibition currently observed is at variance with inhibitory effects on the transporter, which are much faster. However, under the present conditions, the large concomitant osmotic flow, the presence of ambient glucose, and cellular activity all (especially the first) might interfere with inhibition.

Prior implicit evidence for water permeation through the glucose channel

It seems interesting that, although conclusions as definite as the present ones have not apparently been drawn, evidence consistent with this notion has appeared in the literature. Some examples:

(1) Blocking effects of SH reagents. Inhibition by such agents as PCMBS on both glucose facilitated diffusion [29] and osmotic water flow [19–21] are well known, but a firm connection between these two lines of findings apparently has not been made until now.

(2) Water molecules permeating together with sugars. Arguments have been advanced for the presence of randomized water molecules inside a polar channel through which sugars are transported [41].

(3) Molecular radii. Using CPK models and Stokes law, others have estimated the molecular radii of glucose and sucrose. The averages of the published values are 0.40 nm and 0.49 nm, respectively. Turning now to the glucose transporter, the membrane-spanning domains in the model suggested by Mueckler et al. [22] can be arranged so as to generate a structure with a central channel. Since the glucose transporter exhibits great specificity for D-glucose and other monosaccharides but excludes disaccharides [28,29,42], it may be assumed that the transporter channel radius lies somewhere between that of a monosaccharide and that of a disaccharide (0.40 to 0.49 nm). Such channel would admit the water molecules (radius approx. 0.15 nm) [43] readily. Conformation changes in the transporter would not change this basic picture, since at some point the channel would have to admit monosaccharides.

(4) Solomon's hypothesis and our results. As another interesting aspect of this reasoning, the range of 0.40 to 0.49 nm theorized just above for the radius of the glucose transporter channel brackets the 0.42–0.46 nm range for the radius of equivalent water pores calculated by Solomon and his co-workers [7,44]. There has been considerable discussion [45–49] of the validity of Solomon's and similar calculations. Such discussion may now be fueled by the fact that, from the arguments above, so far, our own results appear consistent with their thesis. At the same time, as mentioned above, the present results do not support the more recent view (as expounded in Solomon et al. [10]) that the band 3 anion channel is the predominant site of water permeation. True, there is some residual osmotic flow after treatment with some of the glucose transporter blockers, and DTNB had a slight but not statistically significant inhibitory effect, so that minor alternative pathways for water permeation such as the anion channel cannot be excluded.

(5) Polar transmembrane route. Molecular models of water and glucose [50] suggest that the O and H atoms in the glucopyranose form may interact with the glucose transporter channel sites just as water might. In fact, it has been suggested [22] that hydroxyl and amide side chains may line the transporter transmembrane channel and provide a polar and uncharged environment. Obviously such an environment would be quite suitable for the binding and migration of water molecules.

(6) Erythrocyte osmotic permeability and the hydrodynamic pore theory. It does not seem clear at present whether the permeation of water through transmembrane channels can be described in terms of the hydrodynamics of solvent flow across right cylinders of uniform cross section (see, for example, Ref. 7). Galey and Brahm [49] have pointed out that such assumption leads to inconsistencies when attempting to account for both osmotic and diffusional water permeation across erythrocyte membranes; they favor the view that such permeation takes place in single-file mode. Still, given our current results, the possibility that water may indeed be traversing an open channel some 0.45 nm in radius is too appealing to be discarded out of hand. Strictly for argument, then, we will assume that such is the case for human erythrocyte. We verify that, curiously, the osmotic permeability calculated for the putative channels in band 4.5 results in values of the order of published ones. Assuming cylindrical channels 0.45 nm in radius and 4.0 nm long, and using values of $1.3 \cdot 10^5$ [24] to $5.5 \cdot 10^5$ [25] for the total number NT of glucose transporter molecules per cell, and a cell area of $1.35 \cdot 10^{-6}$ cm^2 [51,52,10], the erythrocyte's hydraulic conductance based on Poiseuille's law [53] would be

$$LpRT/Vw = [(\pi r^4)/(8\, l\eta)] \times [\mathrm{NT}/A_{\mathrm{cell}}] = 790 \text{ to } 3500\ \mu\mathrm{m/s}$$

while representative published values are 110–340 μm/s [54]. Thus, the RBS osmotic permeability could be confortably accounted for by the minimum value calculated for its glucose transporters. We presume that these issues are bound to receive renewed attention.

Conclusion

The present initial report includes evidence only for osmotic flows. For more detailed support of our hypothesis one might want to have more

extensive information on the glucose transporter characteristics than there is in the literature for this tissue. Yet, barring an exceedingly implausible coincidence, the mere fact that all glucose transport inhibitors we have tested so far do inhibit osmotic flow in our preparation strongly suggests that water and glucose traverse the same path across these cell membranes. This in turn raises the tantalizing possibility that future work might show that the glucose transporter channels might constitute the main route for water permeation across the membranes of all animal cells.

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