Glucose Transport in Plasma Membrane Vesicles from Rat Adipose Tissue*

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SUMMARY

Plasma membranes of a high degree of purity have been prepared from isolated adipose cells of rat epididymal fat pads. \(^{3}H\)Glucose uptake by the membranes has been measured with a Millipore filtration technique, with \(L-[^{14}C]\)glucose serving as a marker for nonspecific uptake or trapping of the sugars. The plasma membrane preparation shows glucose transport as evidenced by the following: (a) \(n\)-glucose is both taken up and released more rapidly than \(L\)-glucose, (b) countertransport of \(D\)-glucose can be shown, (c) with prolonged incubations, \(D\) - and \(L\)-glucose uptake reach equilibrium at the same level.

The uptake of \(D\)-glucose is inhibited by a low concentration of phlorizin and higher concentrations of 2-deoxyglucose and 3-O-methyl glucose, but not by \(L\)-glucose or fructose. It is greatly inhibited by \(N\)-ethylmaleimide. Cyclic adenosine 3',5'-monophosphate and its dibutyryl derivative, ATP, AMP, glucose 6-phosphate, glucose 1-phosphate, fructose 1,6-di-phosphate have no appreciable effect. Glucose appears to be taken up or transported into a relatively impermeable intravesicular space. Exposure of the membranes to increasing sucrose concentrations leads to osmotic shrinkage and decreased glucose uptake.

We conclude that the glucose transport system remains intact in isolated plasma membranes and can be studied in the absence of other cell components.

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In recent years, major advances have been made in the study of transport on a subcellular level in bacteria (1). With the possible exception of the sodium-potassium-activated ATPase (2), similar progress has not been made in studies on mammalian tissues. A large number of mammalian transport systems have been examined in detail, but generally intact tissues and whole cells have been utilized, and knowledge of the molecular mechanisms involved has not been forthcoming.

Adipose tissue provides an excellent tool for the study of sugar transport on a subcellular level. Glucose transport has been well characterized in both intact tissue (3, 4) and isolated fat cells (5, 6); it appears to involve facilitated diffusion of the sugar without an "active" system for concentrating against a chemical gradient (3). Furthermore, glucose transport into adipose cells serves as the locus for one of the major actions of the hormone insulin (4).

Recently, Illiano and Cuatrecasas (7) have reported on the use of fat cell "ghosts" to measure glucose uptake directly. By using a rapid filtration technique and measuring uptake at early time points, they were able to measure initial rates of transport and avoid the problem of glucose metabolism, which in their preparations was negligible up to 4 min. With this technique they verified that glucose transport was a saturable process, independent of metabolic energy, temperature-dependent and insulin-sensitive.

We have previously reported (8) that a microsomal fraction prepared from isolated, disrupted adipose cells of the rat epididymal fat pad showed selective uptake of \(n\)-glucose. The sugar was not phosphorylated in the process. Uptake of glucose was inhibited by phlorizin. Release of \(n\)-glucose was more rapid than \(L\)-glucose. We were further able to demonstrate accelerated uptake in microsomes "previously loaded" with unlabeled \(n\)-glucose (counterflow). Insulin preliminary treatment of the isolated fat cells prior to rupture led to accelerated \(n\)-glucose uptake by the microsomes (9). Based on these facts, it was postulated that microsomal vesicles retained a functioning glucose transport system with many of the characteristics of sugar transport observed in intact cells.

The usual "microsomal" fractions prepared by differential centrifugation of tissue homogenates contain elements of both the plasma membrane and endoplasmic reticulum (10). The microsomal fraction used in our initial studies (8) had the further disadvantage of showing considerable variability from preparation to preparation. It seemed important, therefore, to find a means of preparing a more reproducible and more highly purified plasma membrane fraction, since this should contain the glucose transport system from the intact cell. The publication by McKeel and Jarett (11) of a rapid method for the preparation of relatively pure plasma membrane fractions from isolated adipose cells provided the means for doing this. We report here the re-

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sults of studies of glucose transport in plasma membrane vesicles prepared from adipose cells of the rat.

**Materials and Methods**

L-[14C]Glucose and n-[3H]glucose were obtained from New England Nuclear and were routinely diluted with unlabeled sugars to final specific activities of 1 μCi per μmole and 4 μCi per μmole, respectively. Cyclic AMP, dibutyryl cyclic AMP, ATP, AMP, and NADH were obtained from Sigma Chemical Co. Phosphorylated sugar derivatives were obtained from Calbiochem. Crude bacterial collagenase was obtained from Worthington. NEM was obtained from Schwarz BioResearch.

Preparation of Membrane Fractions—Sprague-Dawley male rats maintained on ad libitum feeding were killed by a blow on the head and cervical dislocation. Isolated fat cells from the epididymal pads were prepared according to the method of Rodbell (5). Microsomes were prepared as previously described (8). Plasma membrane and endoplasmic reticulum fractions were prepared according to the method of McKee and Jarett (11). For initial characterization of the fractions, Ficoll gradients were used, as these appeared to give somewhat purer preparations. In subsequent experiments, the preparative method utilizing sucrose gradients was altered as follows: low speed centrifugation for the isolation of nuclei was omitted. The final pellet (P0 according to McKee and Jarett (11)) was resuspended, layered on top of the sucrose gradient (ρ1.1 to 1.2 in 10 mM Tris-Cl, pH 7.4, 0.1 mM EDTA), and centrifuged at 40,000 rpm for 45 min in a SW 41 rotor. A banding pattern similar to that seen with the original method was obtained. The zone of lower density, ρ1.10 to 1.15 (plasma membrane) was harvested and diluted 1:4 with 0.25 M sucrose, 10 mM Tris at pH 7.4. This was centrifuged at 10,000 × g for 15 min.

“Sonicated plasma membranes” were prepared by the following procedure. The final plasma membrane pellet prepared from the fat cells of an appropriate number of rats (in most cases 12 to 24) was suspended in 5 to 10 ml of ice-cold 0.25 M sucrose with 10 mM of Tris, pH 7.4. The suspension was sonicated for a few seconds in an ice bath with a Branson model 8 sonifier. The membranes were then resolated by centrifugation at 100,000 × g for 30 to 60 min and resuspended in a small volume of the same medium. In preparing “hypotonically lysed plasma membranes” the pellet was suspended in 5 to 10 ml of 1 mM Tris at pH 7.4 and incubated at 0°C for 30 min. The membranes were then resolated by centrifugation as noted above and resuspended in 0.25 M sucrose with 10 mM Tris, pH 7.4; incubations were carried out in this medium.

Assay for Uptake of Labeled Sugars—To a suspension of membrane particles a mixture of L-[14C]glucose and n-[3H]glucose (final concentration of 5 mM each except where specified otherwise) was added. The final volume of incubation was 0.25 to 0.5 ml. All incubations were carried out at 20°C, except where indicated. At various times, aliquots (50 to 100 μl) of the suspension were filtered rapidly over a previously chilled Millipore filter, pore size 0.45 μ. The pellet was then washed rapidly on the filter in a dropwise fashion with ice-cold Krebs-Ringer bicarbonate or Krebs-Ringer phosphate buffer with one-half the usual concentration of calcium (12). Initially 2 to 5 ml of wash solution were used, but it was subsequently found that after the first 10 drops of buffer, there was a selective washing out of n-glucose. Therefore, in later experiments only 5 to 10 drops of the wash solution were used. A buffer of high ionic strength gave the most reproducible results in the washing step and isotonic NaCl or MgSO4 solutions served as well as Krebs-Ringer buffers. Non-ionic solutions such as iso-osmotic sucrose led to a more extensive loss of labeled sugars from the pellets, and brief washes with distilled water removed all the radioactivity from the membranes. After washing, the filters were transferred directly to counting vials, the membranes dispersed in 0.2 ml of distilled water by vigorous agitation on a Vortex mixer and the radioactivity determined in 10 ml of Buher’s scintillation solution (13). Specific activities were determined by counting appropriate dilutions of the labeled sugars under similar conditions. “Net” n-glucose was determined as the difference between n- and L-glucose uptakes.

To measure the rate of release of bound sugar, membranes, and labeled n- and L-glucose were previously incubated in a total volume of 0.7 ml for 60 min at 20°C. At the end of this time two 0.1-ml aliquots were assayed as above and the remaining incubation mixture diluted with 4.5 ml of the same buffer. At the indicated times, 1.0-ml aliquots were filtered rapidly over a chilled membrane and washed as described above. The rate of release of sugars was determined as the difference between the amount taken up prior to dilution and that observed after dilution. All incubations were carried out in 0.25 M sucrose with 10 mM Tris of pH 7.4.

Replicate uptake assays showed a standard deviation of ±10% or less.

Analytical Techniques—5′-Nucleotidase and NADH oxidase were measured by methods previously described (14). Protein was measured by the procedure of Lowry et al. (15) with crystalline bovine serum albumin as standard. In addition, membrane protein was estimated by intrinsic protein fluorescence (16). Aliquots of membranes were suspended in 2 ml of 0.05% sodium dodecyl sulfate and excited at 286 nm in a Hitachi Perkin-Elmer spectrophotometer MFP 2A (slit width = 4 nm). Fluorescence emission was measured at 338 nm (slit width = 20 nm). Tryptophan was used as standard.

The value in milligrams of tryptophan was converted to milligrams of membrane protein by multiplying by 40.0. This conversion factor was obtained by assaying several samples both by native fluorescence and by the Lowry technique.

**Results**

Subcellular Localization of Glucose Uptake—Results of a typical preparation with the McKee and Jarett (11) technique are shown in Table I. AMPase was used as a marker for plasma membrane and NADH oxidase for endoplasmic reticulum (14). As judged by specific activities, the plasma membrane fraction showed a high degree of purity with less than 20% of the total protein representing endoplasmic reticulum. However, the other fraction was less pure; approximately 70% of the total protein represented endoplasmic reticulum, but as much as 40 to 60% of the total plasma membrane protein also appeared in this fraction.

Net or specific n-glucose uptake occurred primarily in the plasma membrane fraction (Table II), with much lower uptakes by the endoplasmic reticulum.
Modification of Preparatory Method—Plasma membranes isolated by the above method showed considerable variation in properties, particularly in the ratio of D- to L-glucose uptake, although D-glucose was always taken up more rapidly. Electron photomicrographs of the plasma membranes showed a mixture of various sized closed vesicles and open sheets of membranes. In an attempt to find a preparation with less "leakiness" to L-glucose, two procedures were tried. Plasma membranes were first isolated by the usual method, then subjected to either brief sonication in iso-osmotic sucrose-Tris or incubated in a hypotonic medium (1 mM Tris) before resolation and suspension in buffered isotonic sucrose. The two preparations showed a striking difference in sugar uptake (Fig. 1); the sonicated membranes showed a marked selectivity for D-glucose, whereas the hypotonically lysed preparation took up the two sugars in approximately equal amounts. Electron photomicrographs of the sonicated plasma membranes showed primarily small closed vesicles with none of the extended sheets observed in the original preparation.

The effect of sonication was also assessed by other parameters. After sonication, approximately half of the initial protein was recovered in the pellet of a 3 × 10^4 g min centrifugation, with a corresponding loss of total NADH oxidase activity. The recovery of 5'-nucleotidase was however 68 to 75%, with a resultant increase in the specific activity of this plasma membrane marker. Preliminary and postsonication plasma membrane fractions were examined by polyacrylamide gel electrophoresis in sodium dodecyl sulfate (17). The patterns obtained were virtually identical. By these criteria, no evidence was found that sonication resulted in selective loss of intrinsic plasma membrane components. Rather, it appeared that a representative fraction of the plasma membrane and contaminating endoplasmic reticulum, especially the latter, was sacrificed in this procedure. Sonication was used in all subsequent experiments.

Specific D-glucose uptake by sonicated plasma membranes showed a marked response to the osmolality of the suspending medium (Fig. 2). Progressively increasing sucrose concentrations above isotonic levels led to a striking decrease in net D-glucose uptake.

Properties of Sugar Uptake System—By "previously loading" the membranes with both D- and L-glucose, then diluting rapidly in buffer containing neither sugar, it was possible to measure the rate of release of both isomers (Fig. 3). In all cases, D-glucose exit was much more rapid than that of L-glucose.

Although the initial rate of entrance and exit of D-glucose exceeded that of L-glucose, in prolonged incubations uptake of the two isomers eventually reached equilibrium at the same level (Fig. 4). The rate of equilibration could be increased markedly by increasing the temperature of incubation.

Increasing the trans (i.e. intravesicular) concentration of glucose led to a marked increase in the rate of D-[3H]glucose uptake (Fig. 5). This was done by previously incubating the particles in a small volume containing a relatively high concentration of unlabeled D- or L-glucose, then rapidly diluting into buffer containing a low concentration of D-[3H]glucose. Uptake of the labeled sugar was more rapid in the membranes previously loaded with D-glucose than in the control previously loaded with L-glucose.

### Table I

<table>
<thead>
<tr>
<th>Fraction</th>
<th>NADH oxidase</th>
<th>AMPase</th>
<th>Protein (total)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μmoles NADH oxidized/mg membrane protein/min</td>
<td>μmoles P1 released/mg membrane protein/l</td>
<td>mg</td>
</tr>
<tr>
<td>Plasma membrane</td>
<td>0.99</td>
<td>1.55</td>
<td>0.32</td>
</tr>
<tr>
<td>Endoplasmic reticulum</td>
<td>5.35</td>
<td>0.50</td>
<td>1.60</td>
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### Table II

<table>
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<tr>
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<th>Net D-glucose uptake</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 min</td>
</tr>
<tr>
<td>Plasma membrane</td>
<td>6.88</td>
</tr>
<tr>
<td>Endoplasmic reticulum</td>
<td>1.08</td>
</tr>
</tbody>
</table>

**Fig. 1.** Effect of different treatments on D- and L-glucose uptake by plasma membranes. Plasma membranes prepared in the usual manner were treated by either brief sonication or incubation for 1 hour at 20° in 1 mM Tris, pH 7.4 (see "Materials and Methods"), resolated by centrifugation at 100,000 × g for 30 min, and suspended in 0.25 M sucrose containing 10 mM Tris at pH 7.4. D- and L-glucose uptake were assayed as described.

**Fig. 2.** Effect of increasing osmolarity on D-glucose uptake by sonicated plasma membranes. Sonicated plasma membranes were suspended in 100 mM sucrose with 10 mM Tris, pH 7.4. Aliquots, 0.25 ml, of the membrane suspension were placed in several tubes, then 0.25 ml of a sucrose solution added to each to give the final concentrations as indicated. The tubes were incubated at 20° for 15 min, then labeled D-glucose added, and uptake measured as described under "Materials and Methods."
Inhibition of Glucose Uptake—Phlorizin at a concentration of 1 mM proved to be a potent inhibitor of specific D-glucose uptake (Fig. 6). Other sugars inhibited uptake but only at higher concentrations. 2-Deoxyglucose and 3-O-methyl glucose were both potent inhibitors at 50 mM concentration, while at this level L-glucose had virtually no effect (Fig. 7). L-Arabinose and galactose showed less but definite inhibition at the same concentration (50 mM), while fructose had no effect (data not shown).

NEM, a relatively specific reagent for sulfhydryl groups (18), inhibited the uptake of D-glucose by plasma membrane vesicles (Fig. 8). Similar inhibition was observed when whole fat cells were exposed to NEM prior to disruption, then glucose uptake measured with plasma membranes prepared from NEM-treated and control cells.

The effects of several additional parameters on glucose uptake were explored. Replacement of sucrose buffer by isotonic NaCl or KCl led to a reduction in the rate of D-glucose uptake (Fig. 9). Glucose 6-phosphate, glucose 1-phosphate, fructose 1-phosphate, and fructose 1,6-diphosphate at a concentration of 5 mM had no effect on specific D-glucose uptake; this was true whether the sugar phosphates were present during the sonication step (to allow their incorporation into the intravesicular space) or simply added to the final incubation mixture. Similarly, ATP, AMP, cyclic AMP, and dibutyryl cyclic AMP, all at concentrations of 5 mM, had no effect on the net rate of D-glucose uptake.
Previous studies of glucose transport in adipose tissue have utilized either intact fat pads (4, 19, 20) isolated fat cells, (5, 20, 21) partially lysed but metabolically active ghosts (7, 22, 23). These methods, with one exception (see below) all have the disadvantage that the end point measured (CO2 production, 20, 21) or partially lysed but metabolically active ghosts (7, 22, 23) are not simply bound to a site on the membrane. Several observations suggest that this is in fact the case. With L-glucose as a marker for nonspecific trapping or "leakage" into the vesicles, we observed that D-glucose was both taken up and released more rapidly than L-glucose. The rapid release argues for a specific system facilitating both the inward and outward passage of glucose. If D-glucose were bound a high affinity site on the membrane, it should be released less rapidly than L-glucose, but the contrary was observed.

The ability to stimulate D-[14C]glucose uptake by previously loading the plasma membranes with D-glucose is an example of accelerated exchange diffusion. This phenomenon has been shown in a variety of tissues (26-29). In particular, Crofford and Renold (19) have demonstrated accelerated uptake of glucose into adipose cells previously loaded with the glucose analog 3-O-methyl glucose, and Crofford (30) has demonstrated 3-O-methyl glucose countertransport as a function of the trans-membrane glucose concentration. Although different interpretations of the "counterflow" phenomenon (26, 29) have been offered, it appears to be demonstrable only in the presence of a bidirectionally functioning system for facilitated diffusion (31). In contrast, if the uptake observed in our experiments were due to binding of D-glucose to the membranes, previously loading with unlabeled sugar should competitively inhibit the rate of uptake observed. Demonstration of accelerated exchange diffusion argues strongly that the glucose is being "transported" from the external medium into a separate "space."

Two other observations confirm that the glucose is moving into an intravesicular space which is bound by a semipermeable mem-

**DISCUSSION**

Previous studies of glucose transport in adipose tissue have utilized either intact fat pads (4, 19, 20) isolated fat cells, (5, 20, 21) or partially lysed but metabolically active ghosts (7, 22, 23). These methods, with one exception (see below) all have the disadvantage that the end point measured (CO2 production, glucone synthesis, or presence of the indicated concentration of NEM, then D-[3H]glucose and L-[4C]glucose added and uptake measured as described ("Materials and Methods"). Only net D-glucose uptake is shown.

![FIG. 8. Effect of NEM on net D-glucose uptake. Plasma membrane suspensions were incubated for 2 hours at 20°C in the absence (Control) or presence of the indicated concentration of NEM, then D-[3H]glucose and L-[4C]glucose added and uptake measured as described ("Materials and Methods"). Only net D-glucose uptake is shown.](image)

![FIG. 9. Effect of various cations on net D-glucose uptake. A suspension of plasma membranes in 0.25 M sucrose-10 mM Tris, pH 7.4, was divided into four equal aliquots which were centrifuged at 100,000 X g for 60 min. The supernatant medium was decanted and the tubes wiped carefully dry. The pellets were then suspended in one of the following media. (a) 0.25 M sucrose-5 mM sodium phosphate, pH 7.4; (b) 150 mM choline chloride per 5 mM Tris-HCl, pH 7.4; (c) 150 mM KCl-5 mM potassium phosphate, pH 7.4; (d) 150 mM NaCl-5 mM sodium phosphate, pH 7.4. Uptake of D- and L-glucose was determined on an equal aliquot of each suspension.](image)
brane barrier. First, L-glucose uptake is much slower than that of D-glucose, but eventually the two sugars reach identical concentrations (Fig. 4). This is compatible with the hypothesis that L-glucose enters by simple diffusion through the membrane or “leaks” in through holes in the membrane-bound vesicles. D-Glucose enters by a combination of specific transport and non-specific leaks. The absence of a mechanism for concentrating the sugars against a gradient (7) leads to simple equilibration with the medium concentration; since both isomers are present at the same initial external concentration, they both reach the same final intravesicular concentration. At equilibrium, the D- and L-glucose “spaces” are identical. The difference in the rate at which they reach equilibrium is a measure of D-glucose transport.

Second, the observed decrease in both D- and L-glucose uptake in the presence of concentrated sucrose solutions (Fig. 2) indicates that the vesicles are relatively impermeable to small molecules and shrink in the presence of a hypertonic external medium, thus decreasing the intravesicular volume. Binding to a specific membrane site would not be expected to show this graded response to increasing osmolarity.

The observation that the majority of specific D-glucose uptake is seen in a highly purified preparation of plasma membranes (Table II) is compatible with the accepted location of the glucose transport system in intact cells. The smaller uptake observed in the endoplasmic reticulum fraction could reflect an intrinsic transport system in these intracellular membranes. However, since with the present preparative procedure considerable amounts of plasma membrane are recovered in this fraction, the specific glucose uptake may be only a reflection of this contamination. The present experiments do not provide a conclusive answer to this point.

Although there are many advantages to the use of purified membranes in the study of sugar transport, there are certain problems inherent in this preparation. It is not clear, for example, how homogenous the population of vesicles is in its properties; there is no way of telling whether uptake occurs in all or a portion of the membranes, and whether the “leaking” of L-glucose is similarly uniform. It is possible, for example, that some of the vesicles are tightly closed and account for a large portion of the “specific” uptake of D-glucose while others have multiple breaks in the membranes and account for most of the L-glucose uptake. Furthermore, in the absence of a specific marker for the external surface, it is impossible to tell the orientation of the vesicles, that is, whether the external or internal cell surface is on the outside of the vesicle. At least in the case of red cells, it has been shown (32) that either “right-side-out” or “inside-out” vesicles can form during cell disruption according to the medium used, and that the two surfaces show considerable differences in properties. It is possible that both glucose “uptake” and “release” as we measure it could reflect movement of sugar from outer to inner cell surface but in vesicles of opposite orientation. However, the demonstration of acceleration of exchange “leaks” in through holes in the membrane-bound vesicles.

The role of sulfhydryl groups in glucose transport in adipose tissue has been unclear, since it is possible to show either stimulation or inhibition of sugar uptake by sulfhydryl-binding agents according to the conditions used (33, 34). In the present studies, with pure membranes, only inhibition is seen. This suggests that one or more sulfhydryl groups are a part of the “carrier” molecule itself or are in some way involved in maintaining the conformation of the carrier. However, at the relatively high NEM concentrations used in the present experiments (10 to 20 mM) it is not possible to rule out nonspecific effects on membrane structure as the cause of the observed inhibition of glucose uptake. The “insulin-like” effect seen in whole cells exposed to low concentrations of NEM (33) may reflect some direct interaction with the insulin-binding site or some less specific change in membrane structure not directly involving the site of glucose transport.

The role of cations in glucose transport is difficult to assess in the present experiments. In intact cells it has been reported that replacement of Na+ by other cations (35) or K+ lack (36) lead to accelerated glucose transport in the absence of insulin. We observe that replacement of sucrose by either isotonic NaCl or KCl leads to a decrease in the rate of glucose entry. However, in view of the known propensity for spontaneous aggregation of membranes in high ionic strength buffer (37), this is probably in part a nonspecific effect of ionic strength; this is further indicated by the depression of uptake observed in particles suspended in choline chloride. It appears that purified plasma membranes do not provide an appropriate preparation for studying the effects of ions on glucose transport.

Glucose uptake as measured in the present studies is similar in at least two important respects to glucose transport into intact adipose cells. First, as shown above, it is depressed by known competitive inhibitors of glucose transport such as phlorizin and 3-O-methyl glucose (38). Secondly, D-glucose uptake into plasma membrane vesicles can be specifically stimulated by prior exposure of the whole cells to physiological concentrations of insulin.

It appears clear that isolated, purified plasma membrane vesicles prepared from adipose cells retain an intact and functioning glucose transport system. This represents a first step toward the identification and purification of the molecular species involved in glucose transport.

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**REFERENCES**


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1 Manuscript in preparation.
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