The Molecular Basis for Na-dependent Phosphate Transport in Human Erythrocytes and K562 Cells

Richard T. Timmer and Robert B. Gunn

From the Department of Physiology, Emory University School of Medicine, Atlanta, Georgia 30322

Abstract: The kinetics of sodium-stimulated phosphate flux and phosphate-stimulated sodium flux in human red cells have been previously described (Shoemaker, D.G., C.A. Bender, and R.B. Gunn. 1988. J. Gen. Physiol. 92: 449–474). However, despite the identification of multiple isoforms in three gene families (Timmer, R.T., and R.B. Gunn. 1998. Am. J. Physiol. Cell Physiol. 274:C757–C769), the molecular basis for the sodium-phosphate cotransporter in erythrocytes is unknown. Most cells express multiple isoforms, thus disallowing explication of isoform-specific kinetics and function. We have found that erythrocyte membranes express one dominant isoform, hBNP-1, to which the kinetics can thus be ascribed. In addition, because the erythrocyte Na-Pi cotransporter can also mediate Li-Pi cotransport, it has been suggested that this transporter functions as the erythrocyte Na-Li exchanger whose activity is systematically altered in patients with bipolar disease and patients with essential hypertension. To determine the molecular basis for the sodium-phosphate cotransporter, we reasoned that if the kinetics of phosphate transport in a nucleated erythroid-like cell paralleled those of the Na-activated pathway in anucleated erythrocytes and yet were distinct from those known for other Na-Pi cotransporters, then the expressed genes may be the same in both cell types. In this study, we show that the kinetics of sodium phosphate cotransport were similar in anuclear human erythrocytes and K562 cells, a human erythroleukemic cell line. Although the erythrocyte fluxes were 750-fold smaller, the half-activation concentrations for phosphate and sodium and the relative cation specificities for activation of 32P influx were similar. Na-activation curves for both cell types showed cooperativity consistent with the reported stoichiometry of more than one Na cotransported per Pi. In K562 cells, external lithium activation of phosphate influx was also cooperative. Inhibition by arsename, K_i = 2.6–2.7 mM, and relative inhibition by amiloride, amiloride analogs, phosphonoformate, and phloretin were similar. These characteristics were different from those reported for hNaPi-3 and hPiT-1 in other systems. PCR analysis of sodium-phosphate cotransporter isoforms in K562 cells demonstrated the presence of mRNAs for hPiT-1, hPiT-2, and hBNP-1. The mRNAs for hNaPi-10 and hNaPi-3, the other two known isoforms, were absent. Western analysis of oc erythrocytes and K562 cells with isoform-specific antibodies detected the presence of only hBNP-1, an isoform expressed in brain neurons and glia. The similarities in the kinetics and the expression of only hBNP-1 protein in the two cell types is strong evidence that hBNP-1 is the erythrocyte and K562 cell sodium-phosphate cotransporter.

Key words: cotransport • phosphate • sodium • lithium • BNP-1

Introduction

The kinetics of sodium-stimulated phosphate flux and phosphate-stimulated sodium flux in human red cells were initially described by Shoemaker et al. (1988). Recently, we have shown that the Na-phosphate cotransporter can also mediate Li-phosphate cotransport with similar kinetics and pharmacology (S. Elmariah and R.B. Gunn, manuscript in preparation). It is known that the rabbit kidney Na-phosphate cotransporter (NaPi-2) can mediate Na-Na exchange (Forster et al., 1998) and no other examined isoform transports lithium. Thus, the erythrocyte Na-phosphate cotransporter may mediate both the ouabain-insensitive Na-Na exchange and Na-Li exchange activities. The molecular identification of the Na-Li exchanger in erythrocytes and neurons has important clinical implications for understanding the treatment of bipolar disease with lithium and the development of essential hypertension. Although more than 24 Na-phosphate cotransporters in three gene families (Fig. 1) have been cloned and some are expressed in erythrocytes (Werner et al., 1991; Magagnin et al., 1993) and cultured mammalian cells (Quabius et al., 1996; Timmer and Gunn, 1998), the molecular basis for the sodium-phosphate cotransporter in erythrocytes is unknown. Human representatives of each type have been cloned: hNaPi-10, a type Ia; hBNP-1, a type Ib; hNaPi-3, a type IIa; hPiT-1, a type IIa; and hPiT-2, a type IIb. Some of these isoforms show very restricted expression; e.g., type II cotransporters are principally found in the kidney and small intestine. In contrast, the type III isoforms are found in nearly every tissue in the body and thus are felt to be the constitutive housekeeping forms of Na-phosphate cotransporters that every cell seems to require to maintain intracellular phosphate above electrochemical...
equilibrium with respect to plasma phosphate. Because most cells express several isoforms of Na-phosphate cotransporters, the kinetics of individual isoforms have been evaluated principally in brush border vesicles, oocytes, and mammalian expression systems that may lack native regulatory mechanisms. The type Ia isoform was originally identified in proximal tubules of the kidney (Werner et al., 1991). A type Ib Na-phosphate cotransporter was recently cloned by subtractive hybridization of N-methyl-d-aspartate (NMDA)-treated primary cultures of cerebellar granule cells isolated from rat pups (Ni et al., 1994). This Na-phosphate cotransporter was originally reported to be a brain specific Na-PO₄-inorganic cotransporter (BNPi or BNP-1), but the human isoform was also detected by Northern analysis in intestine, colon, and testes (Ni et al., 1996). Expression of BNP-1 in oocytes increased Na-dependent ³²PO₄⁻₄ uptake (Ni et al., 1994). The amino acid sequences of hBNP-1 (Ni et al., 1996) and hNaPi-10 (Chong et al., 1993) share 22% identity, as determined using the ClustalX algorithm for sequence alignment (Higgins et al., 1996). Any of these or an unknown gene's product could be responsible for erythrocyte Na-PO₄ cotransport.

K562 cells were first isolated by Lozzio and Lozzio in 1971 from a patient with chronic myelogenous leukemia in blast crisis (Lozzio and Lozzio, 1975). The cells have many characteristics of a red cell precursor; e.g., they can be stimulated to produce embryonic and fetal hemoglobin after treatment with dimethylsulfoxide, hemin, butarate, thymidine, etc. In addition, they constitutively express many red cell proteins, including spectrin and glycophorin A (Yurchenco and Furthmayr, 1980) and L-type pyruvate kinase (Jansen et al., 1983). However, there are no previous reports regarding the existence of a Na-phosphate cotransporter system in these cells or the identity of specific isoforms that may be expressed. K562 cells may express any combination of Na-PO₄ cotransporter genes to feed their high metabolic demand for phosphate. It is known that they do not express AE1, which is the dominant phosphate pathway in mature erythrocytes (Horton et al., 1981; Law et al., 1983; Dissing et al., 1984), and thus the Na-PO₄ cotransporter present in erythrocytes (Shoemaker et al., 1988) may be overexpressed to meet these needs.

Since mature human red blood cells are anucleated and have no DNA or RNA, the identification of the gene of origin of a given protein is not always straightforward. We reasoned that if the kinetics of phosphate transport in K562 cells paralleled those of the Na-activated pathway in erythrocytes and yet were distinct from those known for other Na-PO₄ cotransporters, then the expressed genes may be the same in K562 cells and mature erythrocytes. Furthermore, the identification of the mRNAs for Na-PO₄ cotransporters in K562 cells would restrict the likely gene candidates, and concordance of Western analysis on the two cell types could specifically identify the transporter, provided its known kinetic characteristics did not conflict with those of the two cell types. In this paper, we show that the transporter that mediates the Na-phosphate cotransporter in K562 cells has the same kinetic and pharmacological characteristics as the transporter responsible for Na-phosphate cotransport in mature human red cells. The characteristics of Na-dependent ³²PO₄⁻₄ influx into K562 cells and red blood cells are distinct from those of the renal sodium-phosphate cotransporter, hNaPi-3, or a widely expressed Na-PO₄ cotransporter, hPiT-1. We demonstrate by reverse transcription–PCR (RT-PCR) that the K562 cells contains mRNA for hPiT-1, hPiT-2, and hBNP-1, but not hPiT-10 or hNaPi-3. We show by Western analysis using specific antibodies to the individual cotransporters that hBNP-1 is the only Na-phosphate cotransporter polypeptide detectable in K562 cells and human red cells. We conclude that the K562 cells have a Na-phosphate cotransporters.

Figure 1. Dendrogram showing the three major families of Na-phosphate cotransporters identified in mammalian cells. The multiple sequence alignment was carried out using ClustalX on the derived amino acid sequences for the indicated isoforms (protein weight matrix used was Dayhoff PAM 250; gap penalty, 10; and floating gap penalty, 10; see Thompson et al., 1994). The dendrogram was constructed from the dendrogram output file of ClustalX. The commonly used designation for the given isoform is given in parentheses next to the species type from which the cDNA was isolated. The corresponding gene names for these isoforms as designated by the Human Gene Nomenclature Committee (HGNC) are as follows: (a) SLC17A1 for NaPi-10; (b) SLC20A1 for hPiT1; (c) SLC20A2 for hPiT2; and (d) SLC34A1 for NaPi-3. There is no name designated by HGNC for hBNP-1.

Abbreviations used in this paper: DNDS, 4,4'-dinitro-2,2'-stilbenedisulfonic acid; Hbg, hemoglobin; PCA, perchloric acid; pCMBS, p-chloromercuri phenylsulfonate; PFA, phosphonoformate; RT-PCR, reverse transcription–PCR.
porter that is the gene product of hBNP-1, and that this transporter protein is the same as, or closely related to, the one in mature human red cells.

No native cells have been used previously for the separate study of PiT-1, PiT-2, or BNP-1. The transport characteristics of these isoforms are wholly derived from their expression in Xenopus oocytes (Kavanaugh et al., 1994; Ni et al., 1994; Kavanaugh and Kabat, 1996), although the expression of one isoform may dominate, such as PiT-2 in rat fibroblasts (Kavanaugh et al., 1994). We propose here that erythrocytes and K562 cells are model systems for the behavior of BNP-1 which is also expressed in neuronal and glial cells, particularly the amygdala and hippocampus. Erythrocytes and K562 cells are the only cells known to express a single sodium-phosphate cotransporter isoform. The homologs of all three isoforms are widely expressed in rat brain, possibly in the same cells. The expression of rBNP-1 is selectively reduced in cerebellar granule neurons after subtoxic doses after ischemia (Ni et al., 1997) and significantly upregulated in CA1 pyramidal neurons of the hippocampus, the only Na-phosphate cotransporter isoform. The homologs of all three isoforms were not determined (Glinn et al., 1995).

Another possible reason for the importance of identifying hBNP-1 as the erythrocyte NaPO₄ cotransporter is that lithium can substitute for Na on the cotransporter. There are no other good molecular candidates for the Na-Li exchanger in erythrocytes. The strong arguments against the sodium-hydrogen exchanger isoform (NHE1-NHE4) as the Na/Li exchanger are summarized by West et al. (1998). It has been shown that the activity of the erythrocyte Na-Li exchanger correlates with the therapeutic responsiveness of patients with bipolar (manic depressive) disease to lithium therapy (Ostrow et al., 1978; Pandey et al., 1984; Zaremba and Rybakowski, 1986), but this remains controversial since it is not found in all patient populations (Werstuk et al., 1984). Similarly, the activity has been shown to correlate with the development of essential hypertension (Canessa et al., 1980; Adragna et al., 1982; Cooper et al., 1983; West et al., 1998). Consequently, the activity of BNP-1 in erythrocytes may be a marker for its activity in the brain and other tissues inaccessible to diagnostic assays.

**MATERIALS AND METHODS**

**Materials**

K562 cells (CCL 243) were obtained from American Type Culture Collection. Fetal calf serum was obtained from Atlanta Biologicals; RPMI 1640, l-glutamine, and other media components were obtained from Life Technologies, Inc. Disposable plastic culture flasks and dishes were obtained from Corning, Inc. All chemicals were reagent grade or better, and were obtained from either Fisher Scientific or Sigma-Aldrich. The sodium salt of 4,4'-dinitro-2,2'-stilbenedisulfonic acid (DNDS) was obtained from Pfaltz and Bauer, Inc. Reagents used in PCR and RT-PCR were obtained from CLONTECH Laboratories, Inc. or PE Biosystems. Isotopes were purchased from New England Nuclear. Optifluor scintillation fluid was obtained from Packard Instrument Co.

**K562 Cells**

Cells were maintained and grown in suspension in RPMI 1640 media supplemented with 10% heat-inactivated fetal calf serum containing penicillin (50 U/ml) and streptomycin (50 μg/ml). The cells were grown and incubated at 37°C in a 5% CO₂ atmosphere. The cells in all experiments were harvested and used from suspensions in logarithmic growth phase after being seeded at a density of 10⁶ cells/ml.

**Flux in K562 Cells**

Cells (6–7 × 10⁶) were harvested by decanting the cell suspension into several 50-ml tubes and centrifuging them at 3,000 g for 5 min at 4–10°C. The clear media was aspirated, and the cell pellets were resuspended in wash media to a total volume of ~100 ml, and the cell suspensions were combined. Wash media contained (mM): 0.81 MgCl₂, 5.55 d-glucose, 0.3 KH₂PO₄, 25 HEPES, pH 7.64 at 20ºC. The cell suspensions were centrifuged briefly at 3,000 g, the supernatant was aspirated, and the cell pellets were resuspended in wash media. This cell washing procedure was repeated three times. After the last centrifugation step, the cells were resuspended in a minimal volume of wash medium (8–10 ml) by gentle vortexing to form a markedly concentrated cell suspension (~7 × 10⁶ cells/ml) that was held at 20°C until use (~<15 min).

The sodium-dependent ³²PO₄ influx was calculated as the difference between the influx measured in the presence and absence of sodium. The influx media contained (mM): 4.36 KCl, 0.81 MgCl₂, 5.55 d-glucose, 25 HEPES, and either 143.5 NaCl titrated with NaOH or 143.5 NMDG titrated with HCl to pH 7.64 at 20–21°C. Stopped Erlenmeyer flasks (50 ml) contained 10 or 15 ml of a medium with a prescribed composition and 1–2 μCi/ml of ³²PO₄. The flasks were placed in a shaking water bath at 37°C. After temperature equilibration of the media, the ³²PO₄ influx measurements were initiated by adding ~1 ml of the concentrated cell suspension prepared as described above. This addition dilutes the medium Na to ~130 mM during the flux measurement. Duplicate samples were taken at known times (~1, 2, 4, 7, 20, and 30 min) by removing 1 ml samples from the flasks and transferring them to labeled, 13-ml polystyrene test tubes containing 5 ml of ice-cold stop solution. Stop solution contained (mM): 144.5 NaCl, 6 KH₂AsO₄, 1 KH₂PO₄, and 20 HEPES, pH 7.64 at room temperature with KOH. These tubes were placed in a refrigerated centrifuge and spun at 2,000–3,000 g for 3–4 min. The supernatant was aspirated, and the pellets were immediately washed a further two times with 5 ml of ice-cold stop solution. The K562 cell pellets were lysed by addition of 250 μl of lysis solution A (1 mM MgCl₂, 20 HEPES, 0.5 Triton X-100, pH 7.6 at room temperature), followed by incubation overnight at room temperature or for 2 h at 37°C. Next, 500 μl of lysis solution B (1% sodium deoxycholate) was added, mixed by vortexing, and diluted by addition of 750 μl of glass distilled water to yield 1.5 ml lysate for each sample. After the last timed sample was taken, the remaining cell suspension in each Erlenmeyer flask was transferred to a test tube, centrifuged, and the clear supernatant was saved for analysis of ³¹PO₄ inorganic phosphate, and sodium. The lysed pellets of K562 cells were each analyzed for ³¹PO₄ and protein. The radioactivity of the lysate (0.5 ml) was counted in duplicate in Optifluor (3 ml). The protein was measured in duplicate using 100-μl samples in a standard BCA protein assay (Smith et al., 1985) using bovine serum albumin as the standard.
albumin as a standard. The reaction was performed in microtiter plates and measured in an MRX plate reader (Dynex Technologies) at 570 nm, as previously described (Timmer and Gunn, 1998). The radioactivity of the influx solution was measured by counting 10 μl of the flux suspension supernatant together with 490 μl of a mixture of the Triton X-100 and deoxycholate lysis solutions. The phosphate concentration of the influx solution was measured using a standard malachite green method (Henkel et al., 1988; Timmer and Gunn, 1998). The samples for influx solution-specific activity and cell lysates were counted contemporaneously and no correction (<0.5%) for radioactive decay was made.

Flux into Red Blood Cells

Human red blood cells were taken by venepuncture from one of us (R.B. Gunn) into a heparinized graduated cylinder. The whole blood was centrifuged in a 50-ml centrifuge tube at 12,000 g for 5 min at 4–10°C. The plasma and buffy coat were aspirated before the red cell pellet was dispersed with a glass rod into three volumes of ice-cold isotonic MgCl2 (110 mM) and again centrifuged briefly at 12,000 g. This wash procedure was repeated two to three more times and the mixed cells held on ice at 90% hematocrit until the flux measurement was initiated (<2 h).

The sodium-dependent 32PO4 flux into erythrocytes was measured in the same way as into K562 cells using the same flux medium with the following exceptions: (a) the influx media contained 0.25 mM DNDS, to block AE1-mediated phosphate influx; (b) samples were usually taken at ~15, 45, and 75 min; and (c) at the end of the washings, the red cells were lysed by adding 1 ml of glass-distilled H2O and vortexing. The lysed red blood cell pellets were each analyzed by: (a) transferring 50 μl into 5 ml test tubes with 2 ml of modified Drabkin’s solution, vortexing the test tube, and reading the extinction of cyanmethemoglobin at 540 nm in a Novaspec II spectrophotometer (Amersham Pharmacia Biotech) (the product of concentration of cyanmethemoglobin at 540 nM in a Novaspec II modified Drabkin’s solution, vortexing the test tube, and reading the OD); and (b) taking 500 μl of each lysate into a 2-ml microcentrifuge tube with 250 μl of 7% (vol/vol) perchloric acid (PCA). After vortexing and a brief centrifugation of the tubes, 350 μl of the clear supernatant was counted with 3 ml of Optifluor in a Tricarb-4000 liquid scintillation counter (Packard Instrument Co.). The radioactivity of the influx solution was measured by counting either 10 μl of the flux suspension supernatant together with 340 μl of 2% PCA or measuring 350 μl of a PCA extract of the supernatant prepared in the same way as the red cell lysate samples. In Na-free media, choline, DNDS was used. It was prepared by ion exchange of Na2-DNNS on a choline column of Rexyn 101 (H) (Fisher Scientific).

Flux Analysis

The values of picomoles per microgram protein for each of the six or more samples were plotted against the time elapsed between initiation of the influx and the time at which the samples were added to the ice-cold arsenate (K562 cells) or MgCl2 (red cells) solution to stop the influx reaction. The time course of 32PO4 content of K562 cells in a typical experiment is shown in Fig. 2. The 12–16 data points were fit to an exponential equation: y(t) = yinfinity *{1 − exp(−kt)}, where y is the cell content in picomoles per microgram protein at time t. The cell content of phosphate was determined from the ratio of the tracer content of the cells and the specific activity of the medium. The steady-state content of the cells was estimated by the best-fit value to yinfinity. The initial influx rate is given by the initial slope of the graph and is equal to the product of the two best-fit parameters yinfinity and k. In Fig. 2, the flux in a high sodium medium was 1,800 nmol/(g protein · min). The activation curves for phosphate were fit by minimization of the sum of squares for the Michaelis-Menten equation: v = Vmax PO4 / (K + PO4 + PO4), where V is the flux, PO4 is the extracellular total phosphate concentration (mM), and K is the concentration of total extracellular phosphate that causes half-maximal 32PO4 influx. The minimization algorithm used was the Solver module in the Excel spreadsheet (Microsoft Corp.). The activation curves for sodium were fit using the Hill equation: Flux = h[Na]1/2 / (1 + h[Na]1/2), where h is the Hill constant and N is the Hill coefficient.

Water Content

The water content of the red cells and K562 cells were measured. Red cells or K562 cells washed in appropriate media were loaded in nylon tubes at ~50–70% cytocrit and packed under standard centrifugation conditions (Gunn et al., 1973). The grams of cell water content was measured by drying to constant weight at 95°C, a known weight of wet packed cells and correcting for 2.5% (wt/wt) trapped extracellular space in red cells and 8–20% (wt/wt) trapped extracellular space between the K562 cells. The trapped space was measured using [14C]polyethylene glycol or H3-inulin under the same packing conditions.

Ion Content

The ion contents of K562 cells were determined by making extracts of known weights of wet packed cells in 7% (vol/vol) PCA and measuring the Na and K concentration by atomic emission spectroscopy, the chloride concentration by coulombometric titration, and the phosphate concentration as described above. The ion contents of K562 cells were measured after washing in either RPMI, 110 mM MgCl2, the NMDG-Cl or NaCl solutions given above.

Antibody Production

Peptides were synthesized and purified by reversed-phase HPLC (Emory University Microchemical Facility). The peptides that were synthesized are as follows: (a) the hPiT-1-specific peptide was CETERTSFKLGDLEAPER, (b) the hPiT-2-specific peptide was
CNAAEVIEAEAGGVMKLASE, and (c) the hBNP-1-specific peptide was CYESPALHPISEEERKYIED. The N-terminal cysteine residue is not present in the target isoform polypeptide sequence and was added to facilitate conjugation to keyhole limpet hemocyanin (KLH; Pierce Chemical Co.) with sulfosuccinimidyl 4[N-maleimidomethyl]cyclohexane-1-carboxylate (sulfo-SMCC; Pierce Chemical Co.). In brief, 2.0 ml KLH (10 mg/ml in water) was first activated by adding 1.0 ml of sulfo-SMCC (4.6 mM or 2 mg/ml) dissolved in conjugation buffer (83 mM Na₂HPO₄, 900 mM NaCl, and 100 mM EDTA). The activation reaction of KLH and sulfo-SMCC was allowed to proceed for 1 h at room temperature (18–22°C). The unreacted sulfo-SMCC is removed from KLH and sulfo-SMCC-activated KLH by gel filtration column chromatography. The reaction mixture was applied to a 10-ml column (EconoPac 10DG column; BioRad, Inc.) equilibrated with conjugation buffer (83 mM Na₂HPO₄, 900 mM NaCl, and NaPi-3, NM_003052. ‡IUPAC symbols are used for nucleotides and degenerate nucleotides.

The reaction mixture was applied to a 10-ml column (EconoPac 10DG column; BioRad, Inc.) equilibrated with conjugation buffer (83 mM Na₂HPO₄, 900 mM NaCl, and NaPi-3, NM_003052. ‡IUPAC symbols are used for nucleotides and degenerate nucleotides.

The reaction mixture was applied to a 10-ml column (EconoPac 10DG column; BioRad, Inc.) equilibrated with conjugation buffer (83 mM Na₂HPO₄, 900 mM NaCl, and NaPi-3, NM_003052. ‡IUPAC symbols are used for nucleotides and degenerate nucleotides.

Published August 14, 2000

KH₂PO₄, 8.05 mM Na₂HPO₄, 136 mM NaCl, and 2.68 mM KCl, pH 7.2. The final solution contained the peptide-KLH in PBS (0.4 ml at 0.8–0.9 mg/ml in PBS) was emulsified with Titermax (250 μl; CytRx Corp.) using a syringe according to the manufacturer’s instructions. The emulsified conjugate adjuvant (50 μl) was injected in each hind quadricep of New Zealand White rabbits. At week five, a second injection of conjugate adjuvant was carried out as described above. Positive antisera were obtained from the same rabbits before the first injection.

Western Analysis

We followed the detailed protocol previously published (Timmer and Gunn, 1998), except that protein was transferred to PVDF (polyvinylidene difluoride) membranes instead of nitrocellulose membranes. The concentration of protein in the cell lysates was determined by the BCA method, as described above. Blots were probed with the primary antibody directed against the indicated NaPO₄ cotransporter protein isoforms, then developed using goat anti–rabbit immunoglobulin conjugated to horseradish peroxidase and chemiluminescence according to the manufacturer’s protocol (ECL Western Blot kit; Amersham Pharmacia Biotech). The primary antibodies used in these studies were prepared as described above (anti–PiT-1, anti–PiT-2, and anti–BNP-1) or as previously described (anti–NaPi-3; Timmer and Gunn, 1998).

T A B L E  I

<table>
<thead>
<tr>
<th>Target isoform*</th>
<th>Forward primer</th>
<th>Reverse primer</th>
<th>Forward primer sequence‡</th>
<th>Reverse primer sequence‡</th>
<th>Expected product bp</th>
</tr>
</thead>
<tbody>
<tr>
<td>hPIT-1</td>
<td>Pit1-1451F</td>
<td>Pit1-2275R</td>
<td>CAG TTC AGT CCA</td>
<td>CCA GCC AAC AGA</td>
<td>825</td>
</tr>
<tr>
<td></td>
<td>GCC GTC AG</td>
<td>GCC GCA AGA</td>
<td>CAC AAC AG</td>
<td>GGC AGA TGC CAG</td>
<td>310</td>
</tr>
<tr>
<td>hPIT-1</td>
<td>Pit1-1882F</td>
<td>Pit1-2191R</td>
<td>TCA GGA TAA</td>
<td>GCC AGA TGC CAG</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>GCC GCA AGA</td>
<td>GCC AGA TGC</td>
<td>CAC AAC AG</td>
<td>GGC AGA TGC CAG</td>
<td>310</td>
</tr>
<tr>
<td>hPIT-2</td>
<td>Pit2-482F</td>
<td>Pit2-1416R</td>
<td>ACG AGA CGG</td>
<td>GCC ACT CCT</td>
<td>935</td>
</tr>
<tr>
<td></td>
<td>TCG TCA TC</td>
<td>GCC TCA TC</td>
<td>CAC ACT CCT</td>
<td>GCC TCA TC</td>
<td>935</td>
</tr>
<tr>
<td>hBNP-1</td>
<td>BNP-1410F</td>
<td>BNP-1875R</td>
<td>CAG TCT ACC TGG</td>
<td>GCC TCA TC</td>
<td>466</td>
</tr>
<tr>
<td></td>
<td>TGG TCA TC</td>
<td>GCC TCA TC</td>
<td>CAC ACT CCT</td>
<td>GCC TCA TC</td>
<td>466</td>
</tr>
<tr>
<td>hBNP-1</td>
<td>BNP-1410F</td>
<td>BNP-1985R</td>
<td>TGC TCA TC</td>
<td>AAG ACG TAC TGG</td>
<td>576</td>
</tr>
<tr>
<td></td>
<td>TGG TCA TC</td>
<td>GCC TCA TC</td>
<td>CAC TCC T</td>
<td>GCC TCA TC</td>
<td>576</td>
</tr>
<tr>
<td>NaPi-10</td>
<td>NP10-512F</td>
<td>NP10-970R</td>
<td>GAG GCC GAC TTA</td>
<td>GAC CTT CTA GGT</td>
<td>459</td>
</tr>
<tr>
<td></td>
<td>CTT TCA TGG G</td>
<td>TAC CCA AGA</td>
<td>GAC CTT CTA GGT</td>
<td>TAC CCA AGA</td>
<td>459</td>
</tr>
<tr>
<td>NaPi-10</td>
<td>NP10-267F</td>
<td>NP10-971R</td>
<td>TTC CAC CTC TTA</td>
<td>TTA CCA AGA</td>
<td>705</td>
</tr>
<tr>
<td></td>
<td>TGG TGG CAT C</td>
<td>GGC CAG KG WGC</td>
<td>AGT CTC ATY CRG</td>
<td>GGC CAG KG WGC</td>
<td>379</td>
</tr>
<tr>
<td>NaPi-3</td>
<td>NPI0-952F</td>
<td>NPI0-1430R</td>
<td>ATY TGG TG</td>
<td>CAG GAT</td>
<td>479</td>
</tr>
</tbody>
</table>

The Genbank accession numbers for the target isoforms are as follows: hPIT-1, NM_005415; hPIT-2, NM_006749; hBNP-1, 173260; NaPi-10, NM_005074; and NaPi-3, NM_003052. ‡IUPAC symbols are used for nucleotides and degenerate nucleotides.

RESULTS

Phosphate Activation

The K₁/₂PO₄ for phosphate activation of 32PO₄ influx into K562 cells was determined from flux measure-
ments at several different total phosphate concentrations in sodium media at pH 7.4 at 37°C (Fig. 3). The \( K_{1/2} = 0.36 \text{ mM} \) when fit to the Michaelis-Menten equation by weighted least squares analysis. For comparison, we previously reported that the \( K_{1/2} \) for \( ^{32}\text{PO}_4^- \) flux into human erythrocytes was \( 0.30 \pm 0.02 \text{ mM} \) under similar conditions (Shoemaker et al., 1988).

**Sodium Activation**

The concentration dependence for external sodium activation of \( ^{32}\text{PO}_4^- \) influx in both K562 cells and human erythrocytes is shown in Fig. 5. In both cases, the sodium concentration was adjusted by isomolar substitution with NMDG. In both cell types, the cooperative activation by Na is evident by the sigmoidicity of the activation graph. This is consistent with more than one Na\(^+\) ion being required for phosphate influx. Although this cooperativity has not been previously reported in erythrocytes, it is consistent with previous measurements of the stoichiometry showing that more than one sodium is transported for each phosphate transported (Shoemaker et al., 1988). In K562 cells the \( K_{1/2} \) was 34 mM with Hill coefficient \( n = 1.5 \) and the constant \( h = 0.0047 \). However, these data can be equally well fit [nearby the same sum of squares of residuals: 886,797 (Hill) vs. 968,855 (M–M)] by a Michaelis-Menten equation (\( n = 1.0 \)) with best fit parameters for \( K_{1/2} = 80 \text{ mM} \) and \( V_{\text{max}} = 6,000 \text{ nmol/ (g protein · min)} \). In erythrocytes, the \( K_{1/2} \) was 46 mM, \( n = 1.9 \), and \( h = 0.0058 \).

**Lithium Activation**

The graph of the activation of \( ^{32}\text{PO}_4^- \) influx by external lithium was also cooperative in K562 cells (Fig. 6) and in erythrocytes (S. Elmariah and R.B. Gunn, manuscript in preparation). This suggests that there are at least two sites for lithium on the extracellular domain of the transporter that must be occupied by lithium for transport of phosphate in the absence of extracellular Na. Although the \( K_{1/2} \) was \( >140 \text{ mM} \), Li in sodium-free media (Fig. 6, \( K_{1/2} \sim 400-500 \text{ mM} \)), the extrapolated maximum flux was about the same for Li as for Na activation under the same conditions \( [3,900 \text{ nmol PO}_4^-/(g \text{ protein} \cdot \text{ min})] \). If the two cation binding sites for Na and Li are the same two sites, then the apparent affinity of the lower affinity site is greater for sodium than for lithium. This follows from using the reciprocal of the \( K_{1/2} \) values as a measure of the apparent affinity of the second (lower affinity) cation activation site. Namely, \( (34 \text{ mM}; \text{Na},K562)^{-1} \equiv (46 \text{ mM}; \text{Na},\text{RBC})^{-1} > > (\sim 450 \text{ mM}; \text{Li},K562)^{-1} \). This lower affinity for Li in the context of comparable \( V_{\text{max}} \) Values for the phosphate flux activated by either cation appears to be the sole reason why 143 mM Li only activates 19% as well as 143 mM Na\(^+\).

The activation of \( ^{32}\text{PO}_4^- \) influx at low concentrations (0–30 mM) of lithium (Fig. 6, bottom) did not appear to be cooperative upon careful inspection in two experiments, but rather could be fit with a Michaelis-Menten equation using \( K_{1/2} \equiv 7 \text{ mM} \) and \( V_{\text{max}} \equiv 90 \text{ nmol PO}_4^-/(g \text{ protein} \cdot \text{ min}) \). This component could be subtracted from the total flux to reveal the cooperative component as shown by the dotted curves in Fig. 6.

**Arsenate Inhibition**

Phosphate transport in the dog kidney (Ginsburg and Lotspeich, 1962), rat kidney brush border membrane vesicles (Hoffmann et al., 1976), and gut (Berner et al., 1976) is inhibited by arsenate, which behaves as a phos-
phate congener (Gmaj and Murer, 1986; Kenney and Kaplan, 1988). Arsenate inhibits sodium-activated $32\text{PO}_4$ influx into erythrocytes (S. Elmariah and R.B. Gunn, manuscript in preparation) with a $K_i = 2.6 \text{ mM}$ assuming complete competitive inhibition. Arsenate inhibits $32\text{PO}_4$ influx into K562 cells (Fig. 7) with a $K_i = 2.7 \text{ mM}$. These values are in contrast to the $K_i = 0.4 \text{ mM}$ reported for the inhibition of hNaPi-3 expressed in HEK-293 cells (Timmer and Gunn, 1998).

Pharmacology of Inhibition

In addition to the kinetics of activation, the pharmacology of inhibition, or lack thereof, is the same in mature erythrocytes and K562 cells measured under the same conditions. Shown in Fig. 8 is a comparison of the inhibition of $32\text{PO}_4$ influx by amiloride and six amiloride analogs in the two cell types. There are some minor variations between the two cell types, but, in general, amiloride and its analogs are poor inhibitors of the Na-dependent flux in these two cell types. Thus, the amiloride binding sites or its ability to inhibit this Na-Pi cotransporter are different from that on the Na/H and Na/Ca exchangers (Kleymen and Cragoe, 1988), epithelial Na channels of the principal cells of the distal nephron (Kleymen and Cragoe, 1988), the Na-hexose (Cook et al., 1987), or the Na-alanine (Harris et al., 1985) cotransporters, which are all amiloride sensitive and over 90% inhibited at these concentrations. Results in Fig. 9 show the percent of the control Na-phosphate flux into K562 cells and erythrocytes after treatment with p-chloromercuri phenylsulfonate (pCMBS), phosphonoformate (PFA), phloretin, vanadate, and DNDS. The effect of these drugs on NaPi-3-mediated Na-phosphate cotransport has been reported (Timmer and Gunn, 1998). There is only an apparent difference in the inhibition by pCMBS in erythrocytes and K562 cells. This is probably due to the high concentration of glutathione (1 mM) in red cells but not K562 cells since glutathione reacts with pCMBS and reduces the effective concentration in the erythrocyte experiments. In erythrocytes, the sensitivity of the cotransporter to DNDS cannot be directly determined since it was always present in the assays to block the AE1-mediated phosphate flux. However, since the Na-activated portion of the phosphate flux was always the same in the absence or presence of DNDS, the Na-phosphate cotransporter is not believed to be inhibited by DNDS. PFA has little effect on the Na-activated phosphate transport into K562 cells or erythrocytes, but is a strong inhibitor of NaPi-3 (Timmer and Gunn, 1998).
These data show that the kinetic and pharmacological characteristics of the Na- and Li-activated $^32$PO$_4$ influx is the same in K562 cells and mature erythrocytes. These kinetics are very different from the renal transport mechanisms mediated by hNaPi-3 (NaPi-2, rat). This is most easily explained by a common molecular mechanism in K562 cells and erythrocytes and one that is different from that in renal cells. We have, therefore, determined which genes of known sodium-phosphate cotransporter proteins are expressing mRNA in the K562 cells, and thus which protein was probably responsible for these flux characteristics.

**PCR Analysis of Sodium-Phosphate Cotransporter Isoforms**

We used primer design software to design several sets of primers specific for the human forms of the major known Na-dependent phosphate transporters shown in the dendrogram in Fig. 1. The primers used in these experiments are described in Table I. PCR reactions were carried out using cDNA templates (Fig. 10) derived from specific human tissues (brain, liver, and kidney) and K562 cells. The cDNA from human tissues was used as a positive control for these primer sets; e.g., liver cDNA was a positive control for the hPiT-1 and hPiT-2 primer sets, brain cDNA was a positive control for the BNP-1 primer sets, and kidney cDNA was a positive control for the NaPi-3 and NaPi-10 primer sets. It has been previously reported that PiT-1 and PiT-2 mRNAs are ubiquitously expressed as determined by Northern analysis (Kavanaugh et al., 1994). The expression of the two isoforms is approximately equal in liver (Kavanaugh and Kabat, 1996), where there is Na-dependent, arsenate-sensitive phosphate transport (Escoubet et al., 1993; Ghishan et al., 1993; Younus and Butterworth, 1993). The expression of BNP-1 mRNA was originally described as being restricted to the brain (Ni et al., 1994). The highest level of expression of BNP-1 in human is in brain, though there is low-level expression in intestine, colon, and testes (Ni et al., 1996). The expression of NaPi-3, a type IIa isofrom, is restricted to the renal proximal tubule (Magagnin et al., 1993). The principal tissue of expression for the type la isoform (e.g., NaPi-10) is also the kidney (Chong et al., 1993). PCR carried out using these...
primer sets specifically amplifies the predicted products from the cDNA prepared from tissues that are known to express these isoforms (compare predicted product sizes in Table I and the results in Fig. 10, left, A–H). When cDNA prepared from K562 cells is used as the template in the PCR reactions, only the primer sets for PiT-1, PiT-2, and BNP-1 yield the expected products (Fig. 10, right, D–H). In contrast, the primer sets for NaPi-3 and NaPi-10 do not yield any products from the same template cDNA. Thus, the mRNAs for PiT-1, PiT-2, and BNP-1 appear to be expressed in K562 cells. Similar results were obtained using total RNA isolated from the K562 cells used in these experiments and a single-tube RT–PCR system (data not shown). All experiments were carried out using a minus template negative control (water substitution for cDNA template). In these samples, there was no visible bands produced, indicating the absence of contaminating DNA in the PCR reagents (data not shown).

Western Analysis of Sodium-Phosphate Cotransporter Isoforms

The expression of a particular mRNA does not always mean that the corresponding protein is also expressed. To determine whether the polypeptides for PiT-1, PiT-2, and BNP-1 were expressed in K562 cells, it was necessary to carry out Western analysis on total cell lysates. We had previously prepared antibodies specific for NaPi-3, which is a type II sodium-phosphate cotransporter (Fig. 1) that is localized exclusively to the kidney (Timmer and Gunn, 1998). The other known human sodium-phosphate cotransporters are: (a) NaPi-10, the human type I sodium-phosphate cotransporter, which is found predominantly in the kidney; (b) hBNP-1, the human type Ib cotransporter that was originally localized to brain tissue; (c) the hPiT-1 cotransporter; and (d) hPiT-2, which is homologous to hPiT-1, but is a distinct isoform.

Based on the isoforms detected by RT-PCR, we prepared isoform-specific antipeptide polyclonal antibodies to the hBNP-1, hPiT-1, and hPiT-2 cotransporter isoforms. To prepare these polyclonal antibodies, we followed a five-step procedure to construct the peptide antigens for the several sodium-phosphate cotransporters. First, the sequence for each isoform was analyzed using three different algorithms for prediction of membrane protein topology (Kyte and Doolittle, 1982; Eisenberg et al., 1984; Mohana Rao and Argos, 1986) to develop an approximate picture of the number and location of membrane-spanning segments for each. Second, the sequence for each isoform was analyzed using three different algorithms for prediction of membrane protein topology (Kyte and Doolittle, 1982; Eisenberg et al., 1984; Mohana Rao and Argos, 1986) to develop an approximate picture of the number and location of membrane-spanning segments for each.
were aligned using the Clustal algorithm (Higgins et al., 1992) to define regions of homology between several species to maximize the utility of the antisera. Fourth, the sequences for hNaPi-10, hBNP-1, hPiT-1, and hPiT-2 using the Clustal algorithm (Higgins et al., 1992) to define regions that are distinct for each of these cotransporters. Finally, we analyzed the sequence using the algorithm of Hopp and Woods (1981) to identify regions with a high probability for eliciting an immune response. The peptides that we used to make polyclonal antibodies based upon these analyses are given in Table II. Each immunizing peptide has a unique sequence with minimal potential for post-translational modification; e.g., glycosylation or phosphorylation. We were unable to identify a single peptide sequence for either hBNP-1 or hPiT-2 that would both be highly antigenic and recognize human and rat isoforms. Therefore, we used a peptide sequence that had lower predicted antigenicity but was common to both rat and human.

The antigens were prepared by conjugating the isoform-specific peptide to KLH, and the resulting antisera assayed in Western analysis using the isoform-specific peptide conjugated to BSA. None of the antisera had any reactivity to BSA at the dilutions used (data not shown). The specificity of the antibodies for the target peptide sequence is shown in Fig. 11 A. The antisera prepared using the Pit-1 peptide does not cross-react with the peptide sequences used for Pit-2 or BNPI-1. This lack of cross-reactivity is also true for the other antisera. We used the antisera to assay the expression of the three isoforms in rat brain and liver; these isoforms have been previously demonstrated in these tissues by Northern analysis (Kavanaugh et al., 1994) or RT-PCR (see above). The antisera for Pit-1 detects an ~70-kD polypeptide in rat brain and liver (Fig. 11, B). However, the antisera fails to detect the appropriate polypeptide in either human erythrocytes or K562 cells. The predicted molecular weight of this protein is 74 kD. Competition with the immunizing peptide shows that the band detected is specific (data not shown). The antisera for Pit-2 detects an ~40-kD polypeptide in rat liver (Fig. 11, B) and the reactivity for this polypeptide is specifically blocked with immunizing peptide (data not shown). However, the Pit-2 antisera does not detect any proteins in either K562 cells or human erythrocytes. The predicted molecular weight for Pit-2 is 70 kD, which is significantly larger than the protein detected in liver. We believe that this may be due to Pit-2 sensitivity to proteolysis, despite the inclusion of protease inhibitors in the extraction buffer used in these experiments. The discrepancy in molecular weight remains to be resolved. Finally, the antisera for BNPI-1 detects an ~116-kD polypeptide in brain, liver, human erythrocytes, and K562 cells. This apparent molecular weight exceeds the predicted 61 kD without glycosylation. Similarly, NaPi-3 has an apparent molecular weight of 125 kD by SDS-PAGE that exceeds the predicted 69 kD without glycosylation (Timmer and Gunn, 1998). Of the three isoforms that were detected at the mRNA level by RT-PCR, we can only detect the expression of the BNPI-1 polypeptide. We tentatively conclude that the Na-dependent phosphate activity measured in K562 cells arises principally from the BNPI-1 isoform of the sodium-phosphate cotransporter, despite the apparent expression of the mRNA for Pit-1, Pit-2, and BNPI-1. Whether or not the Pit-1 or Pit-2 polypeptides can be expressed in K562 cells remains to be explored. It is possible that the polypeptides for these proteins are synthesized in response to certain environmental conditions (low or high phosphate) or upon induction to the erythrocyte or leucocyte phenotype.
### TABLE II

<table>
<thead>
<tr>
<th>Target isoform</th>
<th>Genbank accession No.</th>
<th>Peptide sequence*</th>
<th>Position in human protein</th>
<th>Predicted to cross-react with rat isoform†</th>
</tr>
</thead>
<tbody>
<tr>
<td>hPiT-1</td>
<td>4885601</td>
<td>CEERTVSFLGDLXPERER</td>
<td>E313-R332</td>
<td>yes</td>
</tr>
<tr>
<td>hPiT-2</td>
<td>5830173</td>
<td>CNAVAEIEAEVEMKLASE</td>
<td>N438-E459</td>
<td>yes§</td>
</tr>
<tr>
<td>hBNP-1</td>
<td>159302</td>
<td>CYSEPALHPSISEERKYIED</td>
<td>Y257-D276</td>
<td>yes</td>
</tr>
<tr>
<td>hNaPi-3</td>
<td>4506985</td>
<td>CKLAAEEQKPSRLVPK</td>
<td>K77-K93</td>
<td>yes¶</td>
</tr>
</tbody>
</table>

*The amino-terminal cysteine is not part of the native protein sequence and is added to the peptide only for conjugation to the carrier protein. †Unless otherwise noted, the sequence is identical in rat or mouse. §The sequence “MKL” in the human sequence is "MRL" in the rat sequence. Preparation of this antibody was previously described (Timmer and Gunn, 1998). ¶ The comparable sequence in rat is (bold indicates mismatches): KLAQEEEQKPEPRLSPK. We have previously shown that this antibody specifically detects the appropriate polypeptide in rat kidney (Timmer and Gunn, 1998).

---

Figure 11. Expression of sodium-phosphate cotransporter isoforms in human tissues and K562 cells as determined by Western analysis. (A) The specificity of the antibodies for the antigenic peptides was tested by Western analysis of BSA-peptide conjugates. The lanes are labeled as follows: P1 (BSA-PiT-1 peptide conjugate), P2 (BSA-PiT-2 peptide conjugate), and P3 (BSA-BNP-1 peptide conjugate). Each lane was loaded with 1 ng of total BSA-peptide conjugate. The blot in α PiT-1 shows reactivity of these BSA-peptide conjugates with the anti–PiT-1 polyclonal antibody prepared using a KLH-PiT-1 peptide conjugate. The other blots were developed using the anti-PiT-2 polyclonal antibody (α PiT-2) or the anti–BNP-1 polyclonal antibody (α BNP-1). The antibody dilution of the primary antibody used in all cases was 1/1,000 of the crude sera. (B) Whole cell lysates were prepared from rat tissues, K562 cells and human erythrocytes as described in materials and methods. Total cell protein from these samples were used for Western analysis. The samples are indicated at the top and are as follows (left to right): K562, which is K562 total cell protein (10 μg); RBC, which is total human erythrocyte protein (10 μg); liver, which is total rat liver protein (10 μg); and brain, which is total rat brain protein (10 μg). The blots were developed using the indicated polyclonal antibodies: α PiT-1, the anti–PiT-1 polyclonal antibody; α PiT-2, the anti–PiT-2 polyclonal antibody; and α BNP-1, the anti–BNP-1 polyclonal antibody.
Ion Composition

The ion composition of erythrocytes is well known (Funder and Wieth, 1966a,b). Although K562 cells have been the subject of many papers, there are no measurements of ionic composition reported. In Table III, there are three experiments showing the composition of the supernatants and cells after being washed in different media, packed by centrifugation, and separately analyzed. K562 cells were washed in their culture medium (RPMI) with fetal calf serum, isotonic MgCl₂ (110 mM), the NaCl flux medium, or the N-methyl-glucamine Cl− prefix wash medium. After washing in the RPMI culture medium, the contents should reflect the steady state values. However, the supernatant includes both the composition of the wash medium and any ions lost by the cells between the last wash and separating the supernatant and packed cells. The loss of K from the cells is apparent in the values measured in the supernatants after the NaCl wash medium, where the supernatant K all comes from the cells and was variable (Table III, 4.5 mM in experiment 2 and 23 mM in experiment 3) due to different lengths of time between the last wash and centrifugation. This variability is reciprocally displayed in the cell K contents from these experiments (690 mmol/kg dry cell solid in experiment 2 and 650 in experiment 3). Some of the variability between experiments may arise from differences in the time of harvest relative to the last split of the cultured cells (i.e., whether they were in log or stationary phase of growth).

In general, K562 cells are high K, low Na cells with intracellular chloride at 50–60 mM, which is above electrochemical equilibrium if the membrane potential is −15 mV. The apparent water fraction (O₂H₂O) was constant (0.796–0.833), though after correction for the concurrently measured ¹⁴C-inulin or ¹⁴C-polyethylene trapped space, the water content, D gram of intracellular water/(gram dry cell solids), varied by 28%. The prefix wash reduced intracellular sodium content and concentration by half, but intracellular K, Cl, and PO₄ remained relatively constant. This reduction would increase the initial driving for Na-phosphate influx measured in NaCl medium.

Discussion

All cells of the body, except erythrocytes, maintain intracellular phosphate above electrochemical equilibrium using the inward sodium flux down its gradient to actively transport phosphate against its electrochemical potential gradient. The influx of ³²P₀₄ into red cells is normally by three pathways and, in plasma-like media at 37°C, the contributions of these three pathways are as follows: (a) 70% is mediated by anion exchanger AE1 (band 3) and can be blocked by DNDS or other stilbene disulfonates; (b) 25% is sodium-dependent Na-phosphate cotransport; and (c) 5% is by a pathway linear in extracellular phosphate concentration (up to 1 mM) (Gunn et al., 1989). In erythrocytes, only the monovalent phosphate species is transported by AE1. The phosphate is passively transported 2.8× faster by AE1 than by the NaPO₄ cotransporter under physiological conditions (Gunn et al., 1989). Thus, in erythrocytes, the steady state intracellular phosphate is close to equilibrium with the plasma phosphate.

The molecular basis for the sodium-dependent phosphate flux in erythrocytes has heretofore been unknown and provided the rationale for this study. For better or worse, erythrocytes are anucleated and thus do not have RNA or DNA. This attribute helps to make them ideally suited for detailed tracer transport measurements, but poorly suited for many molecular biological manipulations. Although reticulocytes are a commonly used nucleated model for erythrocytes, it is possible that the cotransport in reticulocytes is not mediated by the same molecule as cotransport in mature erythrocytes. However, to determine whether a cotransport activity in reticulocytes is the same as mature erythrocytes requires tracer influx experiments, and it is difficult to obtain large numbers of pure reticulocyte nuclei because of such studies. Thus, we chose to examine a model cell that has similar cotransporter kinetics and selectivity, is nucleated, and is easily obtained as a homogeneous population. The model cell used in these studies is the erythroleukemic cell line K562.

The results described above show that this cell line has the kinetics of NaPO₄ cotransport that are the same as in mature erythrocytes. We found, in K562 cells, that the Na activation kinetics were sigmoidal (Fig. 5, bottom), which led us to the careful reexamination of the Na activation kinetics in erythrocytes (Fig. 5, top). The clear sigmoidal Na-activation kinetics in erythrocytes now supports a mechanism with two (or more) Na sites and agrees with the previously observed stoichiometry of >1 Na per phosphate transported. There is no conflict between the data presented here and our previously reported data (Shoemaker et al., 1988). In the previous erythrocyte studies we reported that the ratio of the [PO₄]₀-activated ²²Na influx and the [Na]₀-activated ³²P₀₄ influx was 1.72 ± 0.02 at three different pH values and consequently a majority of the NaPO₄ cotransport coupled 2 Na per phosphate (Shoemaker et al., 1988). However, we also reported that Na-activation kinetics were described by the Michaelis-Menten equation for a single Na site. If the earlier data (Figure 4 in Shoemaker et al., 1988) were graphed after being corrected for the phosphate concentration used in the experiments shown in Fig. 5, top, the data points would scatter along the curve drawn in this figure. The sigmoidicity was not previously noticed because there were too few data points at low Na concentrations.
We show above that phosphate transport in both K562 cells is activated not only by sodium, but also by lithium (Fig. 4). There is no significant activation of phosphate transport by any other cation tested (Fig. 4). This pattern of cation activation is identical to that observed for erythrocytes (S. Elmariah and R.B. Gunn, manuscript in preparation). The lithium activation of $^{32}$PO$_4$ influx in K562 cells appears to have two separable components: a cooperative component similar to the Na-activated $^{32}$PO$_4$ influx and a hyperbolic, saturating component. This second component of lithium activation may arise either from a 1:1 cotransport mode of the normally 2:1 cotransporter or from a different cotransporter isoform. Alternatively, K562 cells may have an additional lithium-phosphate cotransporter besides hBNP-1, but it must be lithium specific since the evidence is against any 1:1 Na-phosphate cotransport (Fig. 5, bottom, inset). This additional cotransporter must not be in erythrocytes since 1:1 cotransport of Li or Na with phosphate is not apparent in the phosphate kinetics measured in erythrocytes (Fig. 5, top, inset).

The pharmacological properties of the Na-dependent phosphate transport activity in K562 cells and erythrocytes are strikingly similar (Figs. 8, and 9). Previously, we reported that arsenate had a variable inhibitory effect on erythrocyte Na-PO$_4$ cotransport (Shoemaker et al., 1988), but this may have been due to uncompensated pH changes in those experiments. It was the marked arsenate inhibition of phosphate transport by K562 cells (Fig. 7) that motivated a more careful study in erythrocytes that confirmed the similarity of arsenate inhibition in these two systems (S. Elmariah and R.B. Gunn, manuscript in preparation). In erythrocytes, the Na-activated $^{32}$PO$_4$ influx is the same in the absence and presence of 0.25 mM DNDS (Shoemaker et al., 1988) thus the cotransporter is not blocked by this compound, although 99% of the chloride and phosphate transport on AE1 is blocked. Other compounds tested (pCMBS at 0.1 mM, phloretin at 0.1 mM, vanadate at 1 mM, and PFA at 1 mM; Fig. 9) showed very similar effects on the Na-dependent phosphate transport in both K562 cells and erythrocytes.

The above data suggests that the Na-dependent phosphate transport activities in K562 cells and erythrocytes are kinetically similar, thus supporting a common molecular identity for the cotransporter in these two cell types. We then determined which specific cotransporter isoforms were expressed in K562 cells and found that these cells express mRNA for three human Na-phosphate cotransporters: hBNP-1, hPiT-1, and hPiT-2 (Fig. 10). It may also express the mRNA from an unknown Na-PO$_4$ cotransporter gene. Antibodies to hBNP-1, hPiT-1, and hPiT-2 react only with BSA conjugated to the peptide sequence used as the antigen in their preparation (Fig.
brush border membranes (PFA: Gunn, 1998) and NaPi-3 (or the rat homolog) in cortical
itors of NaPi-3 expressed in HEK 293 cells (Timmer and
ther erythrocytes or K562 cells, but are significant inhib-
ificant Li-activated 32PO4 influx, whereas the (Type II)
erthrocytes; (b) K562 cells and erythrocytes have sig-
ificant 32PO4 influx, whereas the (Type II)
K562 cells: (a) the kinetics and pharmacology of Na-
pi-3 share some similar pharmacology (e.g., both are
in K562 cells (Fig. 10) and in HEK 293 cells expressing
cotransport in these cells. Although Na-PO4 cotransport
in these cells are the same as in mature
K562 cells to have only Na-Pi-3 protein by Western analysis and the two cell
types have similar transport kinetics, it seems likely that
these similarities are caused by the presence of hBNP-
1-mediated transport kinetics. Thus, we tentatively con-
clude that the erythrocyte sodium-phosphate cotrans-
porter is the same as hBNP-1. But this conclusion re-
quires additional experiments; e.g., heterologous ex-
pression and kinetic characterization of hBNP-1.
The other supportive evidence for this conclusion is the
exclusion of both hNaPi-3 and hPiT-1 based upon
their previously reported functional properties. For ex-
ample, the expression of hPiT-1 in oocytes induces ex-
ternal Na-activated inward current in the presence of ex-
ternal phosphate but no external Li-activated inward
(Eolah et al., 1994). This suggests that Li is not a
substrate for hPiT-1, unlike the cotransporter in erythro-
cytes and K562 cells. Therefore, although mRNA for
hPiT-1 was found in K562 cells, the apparent absence of
hPiT-1 protein in K562 cells and erythrocytes is consis-
tent with some other isoform mediating the Li-PO4
cotransport in these cells. Although Na-PO4 cotransport
in K562 cells (Fig. 10) and in HEK 293 cells expressing
NaPi-3 share some similar pharmacology (e.g., both are
not inhibited by DNDS, equally inhibited by phloretin
(50% at 0.1 mM) and are equally inhibited by pCMBS
(>90% at 1 mM) (Timmer and Gunn, 1998), these
cotransport activities have some distinct pharmacology. For example, PFA and vanadate had little effect on ei-
ther erythrocytes or K562 cells, but are significant inhib-
iteurs of NaPi-3 expressed in HEK 293 cells (Timmer and
Gunn, 1998) and NaPi-3 (or the rat homolog) in cortical
brush border membranes (PFA: K(\text{rat}) = 4.6 \times 10^{-4} \text{ M},
SzczechanskaKonkel et al., 1986; K(\text{rat}) = 2.1 \times 10^{-4} \text{ M}
and K(\text{human}) = 3.1 \times 10^{-5} \text{ M}, Yusufi et al., 1986). These
differences rule out NaPi-3 as a candidate for the K562
and erythrocyte cotransporter. As shown in Table IV, the
characteristics of the different isoforms when expressed in
different systems do not always agree. The differences
between hNaPi-3 and the form in erythrocytes as
described above are apparent. But the kinetic differences
between hPiT-1 and rPiT-2 expressed in oocytes and that
of erythrocytes are probably insufficient to exclude
them as candidates in those cells, except the apparent
absence of Li as a substrate in hPiT-1. Unfortunately,
there are no kinetic or pharmacological studies of native
or expressed hPiT-2 or hBNP-1. A side-by-side study of
their kinetics and pharmacology in a common expres-
sion system could strengthen the identification of hBNP-1
as the K562 and erythrocyte Na2PO4 cotransporter.
The results of this study are significant for two reasons.
First, the apparent expression of a single Na2PO4 cotrans-
porter, hBNP-1, in erythrocytes and K562 cells provides
a native cell system in which to characterize the
isoform-specific kinetics as reported here. In addition,
this suggests a native cell system to study the isoform-spe-
cific regulation of phosphate transport in future studies.
The predominance of PiT-2 expression in rat fibroblasts
provides another system for the study of isoform-specific
characteristics (Kavanaugh et al., 1994). However, many
cells express multiple isoforms of Na-phosphate cotrans-
porters. The mechanisms by which cells control their
intracellular phosphate concentration are poorly under-
stood, though changes in plasma phosphate concentra-
tion alter cell metabolism, presumably through altering
cytoplasmic phosphate activity and cytoplasmic phos-
phoryl potential. Since the Na-phosphate cotransport
mechanisms use the energy in the Na gradient, they are
probably closely regulated. Second, there is the sugges-
tion that the erythrocyte Na-phosphate cotransporter is
the molecular basis for Na-Li exchange in red cells. This
suggestion is based in part upon the observation that the
Na-phosphate cotransporter mediates Li-phosphate co-
transport (Fig. 4). In addition, a Na-dependent cotrans-
porter can mediate cation–cation exchange through a
slippage mechanism when only a cation, but no phos-
phate, is bound. For example, the rat homolog of NaPi-3
can mediate Na-Na exchange (Forster et al., 1998), and
the Na2PO4 cotransporter (hBNP-1) in erythrocytes can
mediate Na-Li exchange (S. Elmahia and R.B. Gunn,
manuscript in preparation). Thus, hBNP-1 function may
extend beyond the transport of phosphate to include
lithium transport and its therapeutic efficacy in neurons
and glia that express this Na-phosphate cotransporter.
Proof that hBNP-1 is also the molecular mechanism of
Na-Li exchange in red cells is beyond the scope of this
paper and is the subject of current studies in progress.

We thank P.M. Smith for maintaining the K562 cells, B. Stock-
man for performing SDS-PAGE and Western analysis, and B.M.
Medley for preparing the manuscript.
Azzarolo, A.M., G. Ritchie, and G. Quamme. 1991. Inhibition of so-
PFA inhibition
Arsenate, [32P]O4
Hill coefficient (Na) 1.5
Arsenate, K (mM) 1.1
V, /V, NaN
PFA inhibition
Stilbene disulfonate inhibition

The functional properties of hNaPi-3 in brush border vesicles (B-B vesicles) and expressed in Xenopus oocytes or cultured mammalian cells (HEK-293) are different from those found in erythrocytes and K562 cells in this report. There are no reports of functional parameters of expressed hPiT-2 or hBNP-1 or any other known native cells that express only these isoforms. The presence or absence of inhibition of transport is indicated by + or −, respectively.


This work was supported in part by the National Heart, Lung, and Blood Institute grant R37-HL-28674 to R.B. Gunn.


