Oxidative Damage and Erythrocyte Membrane Transport Abnormalities in Thalassemias

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Oxidative damage induced by free globin chains has been implicated in the pathogenesis of the membrane abnormalities observed in α and β thalassemia. We have evaluated transport of Na^+ and K^+ in erythrocytes of patients with thalassemias as well as in two experimental models that use normal human red blood cells, one for α thalassemia (methylhydrazine treatment, α thalassemia like) and one for β thalassemia (phenylhydrazine treatment, β thalassemia like). With the exception of the Na-K pump, similar alterations in membrane transport were observed in thalassemia and thalassemia-like erythrocytes. These were: increased K-Cl cotransport, Na-Li countertransport and reduced Na-K-Cl cotransport. The Na-K pump was reduced in thalassemia-like cells, whereas it was increased in severe α thalassemia and in β thalassemia cells. The increased K-Cl cotransport activity could be observed in light and dense fractions of β-thalassemic cells. K-Cl cotransport in thalassemic and thalassemia-like erythrocytes was partially inhibited by [(dihydro-indenyl) oxy] alkanoic acid and completely abolished by dithiothreitol. Thus, oxidative damage represents an important factor in the increased activity of the K-Cl cotransport observed in thalassemias, and of the K^+ loss observed in β-thalassemia erythrocytes.

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WHEREAS MOLECULAR DEFECTS responsible for decreased globin chain synthesis in thalassemias have been described in great detail, the membrane damage imposed by the presence of free α or β chains is complex and less well characterized. Morphologic, biochemical, and metabolic changes of the erythrocyte membrane contribute to the premature destruction of thalassemic erythrocytes. Thus, membrane damage represents an important mechanism leading to anemia in thalassemias.[1-4]

Previous studies in thalassemic erythrocytes have shown several alterations in membrane lipids and proteins,[2-4] an increase in globin binding to membrane skeleton[5] and a decrease in membrane thiols.[3,4] α and β thalassemias are characterized by different membrane skeleton protein abnormalities and different cell deformability features.[6,7] Many of these alterations are suggestive of an increased cell oxidative damage.[6-8]

One of the features that distinguishes severe β from α thalassemia is the presence of erythrocyte dehydration.[6] β thalassemia minor red blood cells (RBCs) were shown to lose potassium (K^+) after incubation in serum[9] or in autologous plasma,[10] probably as a consequence of the activation of the Gardos pathway induced by adenosine triphosphate (ATP) depletion and increased Ca influx.[11] Studies by Nathan et al[12] suggested a relationship between this abnormal K^+ leak and hemoglobin (Hb) precipitation on the membrane. Studies in sickle cell anemia, where cellular dehydration is prominent, have shown a marked activation of the K-Cl cotransport.[13-15] This system induces K^+ loss and cell shrinkage when the cells are swollen or exposed to acid pH.[13,15] [(Dihydro-indenyl) oxy] Alkanoic acid (DIOA), a specific inhibitor for this system,[16] is effective in reducing K^+ loss induced by K-Cl cotransport both in normal[17] and in oxygenated[17] or deoxygenated sickle cells.[18] K-Cl cotransport is also found in reticulocyte-rich but not in mature fractions of normal human RBCs.[19] The activation of K-Cl cotransport observed in SS and CC RBCs cannot be explained exclusively on the basis of an increased number of reticulocytes. Increased K-Cl cotransport has been reported in β-thalassemia RBCs[20] and in erythrocytes containing positively charged Hb variants in $\beta6$ and $\beta7$.[20] Oxidation leads to activation of K-Cl cotransport in normal human RBCs[21] and rabbit erythrocytes.[22]

Some of the features of the membrane damage observed in thalassemic RBCs can be reproduced by incorporating free α chains into normal RBCs, with the dialysis exchange hemolysis technique.[23,24] An excess of denatured α or β Hb chains with associated iron, heme, or hemichromes[8] is responsible for the generation of free radicals leading to the oxidative damage of the cell membrane in thalassemic RBCs.[1,8] Schrier and Mohandas have shown that the membrane protein abnormalities observed in severe β or α thalassemia can be reproduced in normal RBCs by exposure to the oxidants phenylhydrazine (PHZ) and methylhydrazine (MHZ), respectively (β- and α-thalassemia–like cells[8]).

In this paper, we examined the principal RBC cation transport pathways in α- and β-thalassemic RBCs. The effects on membrane transport of PHZ and MHZ treatment of normal human RBCs were also studied as well as those of DIOA and dithiothreitol (DTT) treatment.

MATERIALS AND METHODS

Drugs and chemicals. NaCl and KCl were purchased from Mallinckrodt, Inc, St Louis, MO. NaNO$_3$, albumin (bovine fraction V), TRIS(hydroxymethyl)aminomethane (TRIS), 3 (N-morpholino) propanesulfonic acid (MOPS), 2 (N-morpholino) ethanesulfonic acid, ouabain, sucrose, nystatin, bumetanide, DTT, PHZ, and MHZ were purchased from Sigma Chemical Co, St Louis, MO. MgCl$_2$, Mg(NO$_3$)$_2$ and dimethylsulfoxide were purchased from Fisher Scientific Co, Fair Lawn, NJ. DIOA was purchased from Research Bio-

chemicals Inc, Natick, MA. Okadaic acid (OKA) was purchased from Kamiya Biomedicals (Thousand Oaks, CA). All solutions were prepared using double-distilled water.

Patients. Informed consent was obtained from control subjects and patients. Blood was drawn after overnight fasting into heparinized tubes and processed within 24 hours. Sixteen heterozygous β-thalassemic (β-thalassemia minor or β-thalassemia trait) were studied. Six severe β-thalassemia patients were studied; they included two patients with Cooley's anemia (IVS-1 n.6/IVS-1 n.6; one 9 months old, Hb 7.3 g/dL, mean corpuscular volume [MCV] 60 fL; the other 12 years old, untransfused because of multiple RBC alloantibodies, Hb 7.5 g/dL, MCV 64 fL), and four patients with β-thalassemia intermedia (β°39/β°39; Hb: 8.3, 8.5, 8.4, 9.1 g/dL; MCV 62, 73, 60, 67 fL, respectively; two of these patients had been splenectomized). Three patients with α-thalassemia trait were studied (α-thal-1; -α$^{3.7}$; Hb: 15.1, 12.4, 10.2 g/dL; MCV: 73, 80, 82 fL, respectively). Three patients with Hb H disease (α αTh/--; Hb: 9.4, 9.9, 9.2 g/dL; MCV: 61, 62, 66 fL, respectively) were studied. None of the patients had received blood transfusions in the preceding 2 months.

Cation transport measurements. Plasma and buffy coat were removed after centrifugation at 1,200g for 10 minutes and the cells washed four times with a choline wash solution (CWS) containing 152 mmol/L choline chloride, 1 mmol/L MgCl$_2$, 10 mmol/L TRIS-MOPS), pH 7.40 at 4°C. An aliquot of cells was then suspended in approximately equal volume of CWS, and determinations of hematocrit, cell Na (1:50 dilution), and K (1:500 dilution) were performed. Erythrocyte Na$^+$ and K$^+$ contents were quantified by atomic absorption spectrophotometry with standards made in double-distilled water.

The maximal rates of Na-K pump and Na-K-Cl cotransport activity were measured in cells containing equal amounts of Na and K (50 mmol/L of cells, obtained with nystatin technique). With this procedure the internal sites for both transport system are saturated.[15] The nystatin-loading solution contained 70 mmol/L NaCl, 70 mmol/L KCl, and 55 mmol/L sucrose. Na-K pump was estimated as the oubain-sensitive fraction on Na$^+$ efflux into a media containing 130 mmol/L choline chloride and 10 mmol/L KCl. Triplicate samples were incubated for 5 minutes and 25 minutes at 37°C. The ouabain concentration was 0.1 mmol/L. Na-K-Cl cotransport was estimated as the bumetanide-sensitive fraction of the Na$^+$ and K$^+$ efflux into a media containing 140 mmol/L choline chloride and 0.1 mmol/L ouabain. The efflux times were 5 minutes and 25 minutes at 37°C with triplicate samples. The bumetanide concentration was 0.01 mmol/L. All media contained 1 mmol/L MgCl$_2$, 10 mmol/L glucose, and 10 mmol/L TRIS-MOPS (pH 7.4 at 37°C).

K-Cl cotransport from fresh cells was measured as either chloride-dependent or volume-dependent K$^+$ efflux. Flux media for chloride-dependent K efflux containing 100 mmol/L Na$^+$ and 1 mmol/L Mg^{2+} (the anion being either Cl$^-$ or NO$_3^-$), 10 mmol/L glucose and 10 mmol/L TRIS-MOPS (pH 7.4 at 37°C). Chloride-dependent K$^+$ efflux was calculated as the difference between K$^+$ efflux in chloride and nitrate media. Swelling-induced K$^+$ flux was calculated as the difference between K$^+$ efflux in NaCl hypotonic (100 mmol/L) and in NaCl isotonic (140 mmol/L) media. Incubation times at 37°C for flux measurements were 5 and 25 minutes. DIOA was used at a final concentration of 0.1 mmol/L.

When DTT was used, thalassemic and oxidant-treated cells were washed with CWS at 4°C and reincubated for additional 30 minutes at 37°C in isotonic-buffered KCl (130 mmol/L) solution containing 10 mmol/L DTT. After four washes with CWS at 4°C, cells were used for K$^+$ efflux measurements, as described above.

Na-Li exchange was estimated as the external Na$^+$-stimulated Li$^+$ efflux (differences between Li$^+$ efflux into 140 mmol/L NaCl and 140 mmol/L choline chloride) from cells containing 20 mmol Li$^+$/L cells. The nystatin procedure (loading solution with 110 mmol/L

KCl, 30 mmol/L LiCl and 55 mmol/L sucrose) was used to modify the red cell cation composition.[15]

Na-H exchange was estimated as the Na$^+$ efflux stimulated by hypertonic shrinkage (500 mOsm) from cells containing equal amounts of Na and K (nystatin technique). The media contained 140 mmol/L choline chloride and the osmolarity was increased with sucrose. 5-(N,N-hexamethylene-amiloride 10 μmol/L final concentration) was used as the specific inhibitor of the system. All media contained 1 mmol/L MgCl$_2$, 10 mmol/L glucose, 10 mmol/L TRIS-MOPS (pH 7.4 at 37°C), 0.1 mmol/L ouabain and 10 μmol/L bumetanide.

Preparation of thalassemia-like cells. Human erythrocytes containing normal Hb were incubated at 10% hematocrit with different concentrations of PHZ and MHZ (from 0.5 to 10 mmol/L) in a medium containing 130 mmol/L KCl, 10 mmol/L NaCl, 1 mmol/L NaCl, 1 mmol/L MgCl$_2$, 1 mmol/L K phosphate buffer, pH 7.4 and 10 mmol/L glucose (60 min at 37°C). At the end of the incubation, cells were washed five times in CWS and then processed as described above to measure cation transport. When experiments with DTT were performed, the oxidized cells were reincubated for additional 30 minutes at 37°C in isotonic buffered KCl (130 mmol/L) solution containing 10 mmol/L DTT. After four washes with CWS at 4°C, cells were used for K$^+$ efflux measurement. In preliminary experiments, sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) analysis was performed after oxidative treatment and showed membrane protein abnormalities similar to those described by Schrier and Mohandas.[8]

Cell density separation. To obtain density-fractionated light cells (density < 1.096) and dense cells (density > 1.114) discontinuous Percoll density gradient was used.[25] Density-separated cells were washed four times with CWS at 4°C and immediately used for cation transport measurements, as described above.

RESULTS

Cation transport pathways in thalassemic erythrocytes. Hematologic data of the patients are summarized in Table 1. Activities of the major cation transport pathways in erythrocytes of β-thalassemic and α-thalassemic patients are shown in Figs 1A and 2A, respectively. To evaluate the relative magnitude of the changes in transport activities observed in thalassemic compared with normal cells, values were expressed as percentage of the control (=100% of activity). The data were also corrected for the different volume of thalassemic cells as compared with normal cells and are thus expressed based on a constant number of 1.1 × 10^{13} cells per liter of cells. Although quantitative differences were observed between α trait and Hb H disease, and between β trait and severe β thalassemia, qualitatively similar results were obtained for all the cation transports irrespective of the pathologic condition considered (Figs 1A and 2A). The most relevant data were (1) substantial stimulation of K-Cl cotransport and Na-Li countertransport; (2) a twofold increase of Na-K pump (with the exception of the α-trait condition); and (3) a relevant reduction of the Na-K-Cl cotransport activity (Figs 1A-2A). The Na-H exchange was not increased in either α- or β-thalassemia RBCs (Figs 1A and 2A).

The different effects on four transport systems (increased Na-K pump, K-Cl cotransport, Li countertransport, and decreased Na-K-Cl cotransport) and the lack of an increase in Na-H exchange, that is known to be elevated in young cells,[26,27] indicate that cell age is not the only determinant for the increased rate of transport observed in thalassemic

Table 1. Hematologic Data of Normal Controls and Thalassemic Patients

	Hb (g/dL)	Hct (%)	Cell Na (mmol/kg Hb)	Cell K (mmol/kg Hb)	Cell Na + K (mmol/kg Hb)	Reticulocytes (%)
Control (n = 16)	13.4 ± 3.4	45.1 ± 5.1	40 ± 4.8	331 ± 39.3	372 ± 29.3	1.5 ± 0.3
β trait (n = 16)	11.4 ± 2.7	39.2 ± 4.9	33 ± 8.1	255 ± 42.3	288 ± 13.4	5.4 ± 1.3
β severe (n = 6)	8.2 ± 0.7	28.5 ± 3.4	33 ± 6.8	204 ± 26.3	239 ± 15.6	20 ± 4.7
α trait (n = 3)	12.6 ± 2.5	38.3 ± 5.3	38 ± 7.5	308 ± 35	346 ± 27.5	2 ± 0.9
Hb H (n = 3)	9.5 ± 0.4	33.1 ± 6.7	37 ± 7.2	293 ± 27.1	330 ± 25.4	4.2 ± 1.4

Data are expressed as mean ± SD.

RBCs. Thus, studies in normal RBCs rendered thalassemia-like by exposure to PHZ or MHZ were performed to determine the effect of oxidative damage.

Cation transports properties of thalassemia-like RBCs. The mean values of the activities of the major RBC cation transport pathways in normal erythrocytes treated with different concentrations of PHZ or MHZ (β- or α-thalassemia–like erythrocytes, respectively) are shown in Figs 1B and 2B.

Exposure of erythrocytes to PHZ- and MHZ-induced changes in cation transport qualitatively similar to those of β and α thalassemia. The only noteworthy difference concerned the Na-K pump, which was strongly inhibited after exposure to both oxidant drugs (Figs 1B and 2B).

Changes in the transport activities were progressively more evident with increasing concentrations of the oxidants. For PHZ-treated erythrocytes, concentrations of 5 mmol/L yielded changes of Na-Li countertransport, Na-K-Cl and K-Cl cotransport activities similar to those of β-thalassemic cells (Fig 1B); at this concentration, Na-H exchange was
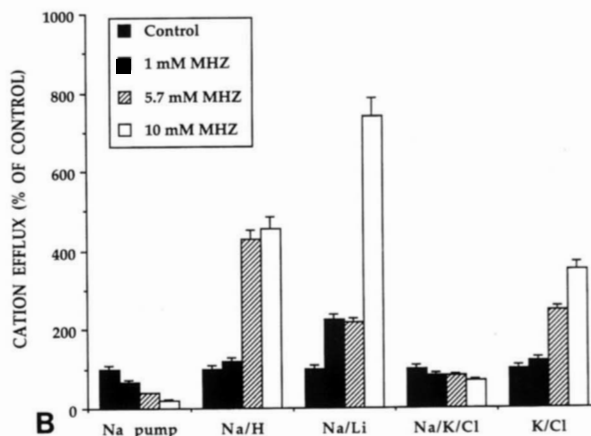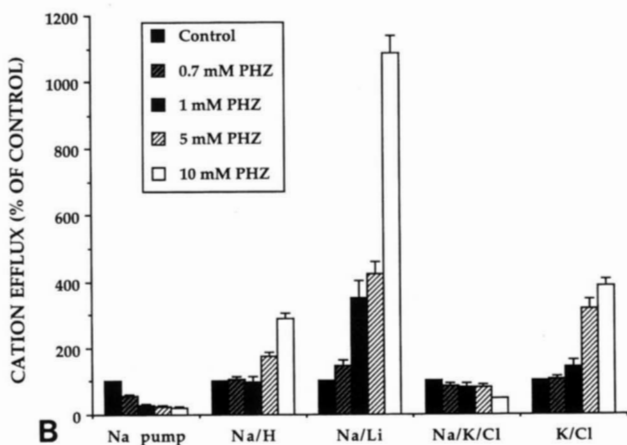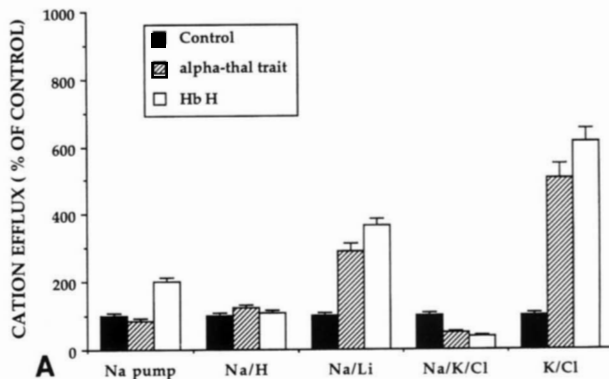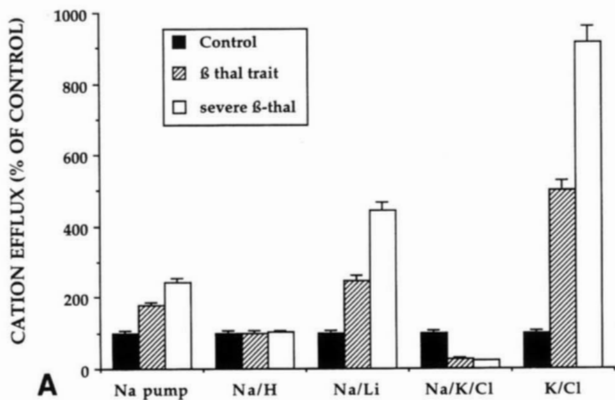

Fig 1. (A) The principal cation transport pathways of human erythrocytes in normal control, β-thalassemia trait, and severe β thalassemia (β-thalassemia severe). Results expressed as mean ± SD (n = 6). (B) The principal cation transport pathways of human erythrocytes in β-thalassemia–like RBCs (normal RBCs treated with PHZ). Results expressed as mean ± SD (n = 3).

Fig 2. The principal cation transport pathways of human erythrocytes in normal control, α-thalassemia trait, Hb H disease (A) (results expressed as mean ± SD), and α-thalassemia–like RBCs (normal RBCs treated with MHZ) (B), [results expressed as mean ± SD (n = 3)].

Table 2. K-Cl Cotransport in Density-Fractionated Normal Control and Thalassemic Erythrocytes

	K-Cl Cotransport (mmol/L cell × h)				
	Control (n = 3)	β Trait (n = 3)	β Severe (n = 3)	α Trait (n = 3)	Hb H (n = 3)
Top	2.5 ± 1.6	8.0 ± 2.3	14.6 ± 3.1	5.8 ± 1.7	6.9 ± 2.9
Bottom	0.7 ± 0.9	3.0 ± 1.1	10.9 ± 2.1	3.8 ± 0.9	4.1 ± 1.7

Top fraction, density less than 1.096; bottom fraction, density greater than 1.114.

twofold stimulated, whereas it was unaffected by lower concentrations of PHZ (Fig 1B). A progressive inhibition of the Na-K pump was observed with increasing concentrations of PHZ (Fig 1B).

For α-thalassemia–like erythrocytes, exposure to 5.7 mmol/L MHZ reproduced changes in Na-Li countertransport, Na-K-Cl and K-Cl cotransport activities, similar to those of α-thalassemic cells; at these and higher concentrations, Na-H exchange was several-fold stimulated, whereas it was unaffected by lower concentrations of MHZ (Fig 2B). Similarly to PHZ, Na-K pump was progressively inhibited by increasing concentrations of MHZ (Fig 2B).

Properties of K-Cl cotransport in thalassemic erythrocytes. In consideration of the markedly increased K loss through K-Cl cotransport observed in β-thalassemia and β-thalassemia–like RBCs (Fig 1), additional experiments were designed to elucidate the bases for the activation of the system in β thalassemia. Because K-Cl cotransport is represented mostly in young erythrocytes and reticulocytes,[19] the observed increased activity could be a consequence of the presence of younger cells. However, if this is the case, the increased activity should still be limited to the lightest density fractions, as in normal human RBCs.[19] K-Cl cotransport was measured in density-fractionated cells (top fraction, least-dense cells; bottom fraction, densest cells). Table 2 shows that a sizable K-Cl cotransport was present in the dense fraction of thalassemic cells, whereas it was absent in the dense fraction of normal cells. Thus, inactivation of K-Cl cotransport in cells of high density is absent in thalassemic erythrocytes. Because only three subjects with severe β thalassemia were studied, it was not possible to determine whether splenectomy affects the activity of K-Cl cotransport in the different density fractions.

The susceptibility to inhibition by DIOA and OKA are well-recognized characteristic of K-Cl cotransport.[16,17] The short-term effects of DIOA on K-Cl cotransport (measured as chloride-dependent or volume-stimulated K efflux) in α- and β-thalassemia erythrocytes are shown in Fig 3, A and B. About 50% of K-Cl cotransport was DIOA-sensitive in severe β thalassemia, Hb H disease and β-thalassemia trait, whereas in α trait, the inhibition by DIOA was only 28% (Fig 3, A and B). Similar results were obtained on both β- and α-thalassemia–like erythrocytes (PHZ = 5 mmol/L, MHZ = 5.7 mmol/L) in presence of DIOA (Fig 3) and with the protein phosphatase inhibitor OKA (10 μmol/L).

To evaluate the role of sulphycryl (SH)-groups oxidation on K-Cl cotransport in thalassemia, K efflux was measured in thalassemia and thalassemia-like RBCs pretreated with

the reducing agent DTT (10 mmol/L). DTT strongly reduced and almost normalized K^+ efflux in both β- and α-thalassemia conditions (Fig 4, A and B), as well as in thalassemia-like erythrocytes (Fig 4, A and B).

DISCUSSION

The "membrane lesion" occurring in thalassemias is complex and not completely understood. Among the different changes observed, an altered cation membrane permeability has been reported, but the underlying mechanism has not been elucidated. As previously shown by others,[9,10] we found that erythrocyte K^+ content was significantly reduced in β-thalassemia erythrocytes (Table 1). The transport of monovalent cations was also altered in α- and β-thalassemia RBCs. We observed (1) a very strong (fourfold to ninefold) stimulation of K-Cl cotransport and Na-Li countertransport; (2) a twofold increase of Na-K pump (with the exception of the α-trait condition); (3) a relevant reduction of the Na-K-Cl cotransport activity and no changes in Na-H exchange activity (Figs 1A-2A). It is worth noting that K-Cl cotransport was stimulated not only in β thalassemia,[20] but also in
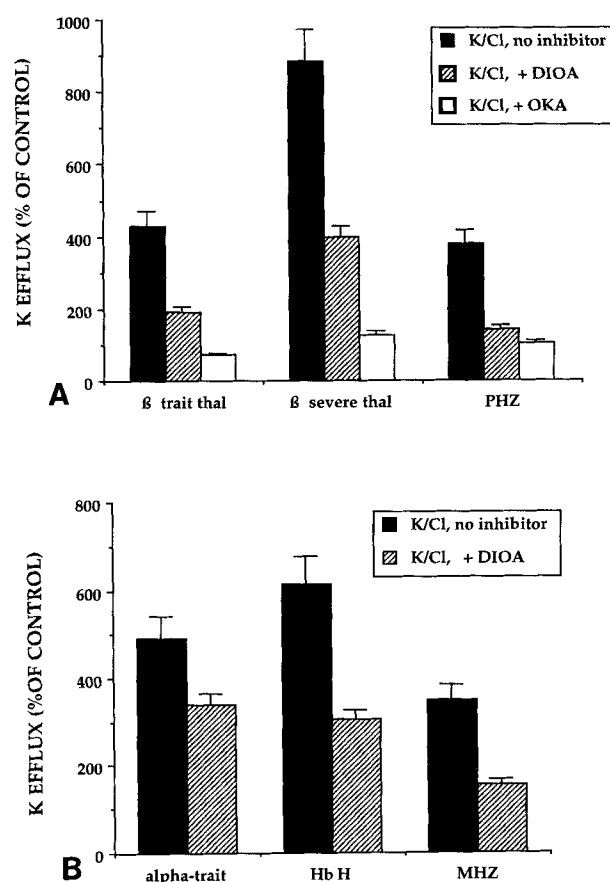

Fig 3. Effects of DIOA and okadaic acid (OKA) on RBC K-Cl cotransport. (A) Effects on β trait, severe β-thalassemia erythrocytes, and β-thalassemia–like RBCs (PHZ, 5 mmol/L; results expressed as mean ± SD; n = 4). (B) Effects of DIOA on α trait, Hb H, and α-thalassemia–like (MHZ, 5.7 mmol/L) erythrocytes (results expressed as mean ± SD; n = 4).
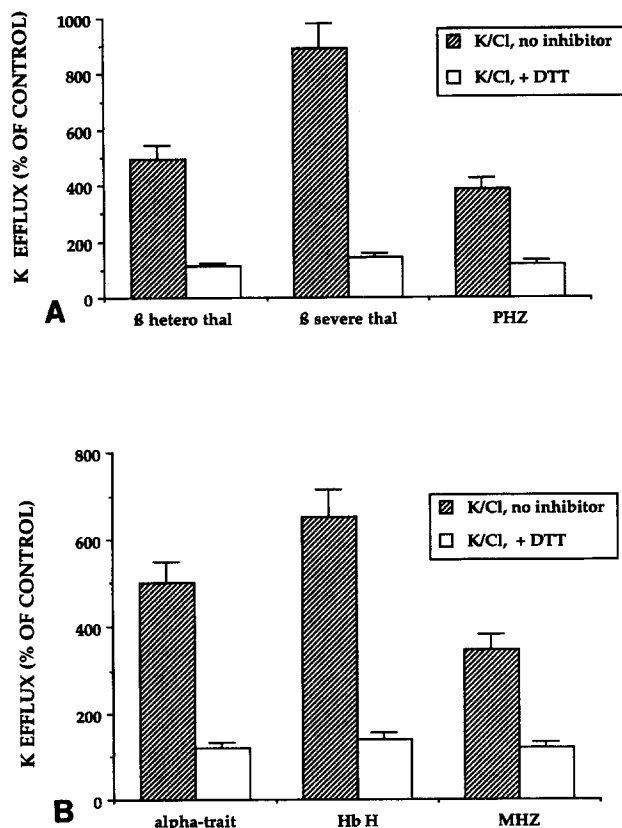
Fig 4. Effect of DTT treatment (10 mmol/L) on K-Cl cotransport. (A) Effect of DTT in β trait, severe β thalassemia, and β-thalassemia-like (PHZ, 5 mmol/L) erythrocytes. (B) Effect of DTT in α trait, Hb H, and α-thalassemia-like (MHZ, 5.7 mmol/L) erythrocytes. Data are expressed as mean ± SD (n = 4).

α thalassemia (although to a smaller extent). Whereas these findings help to explain the relative dehydration of β-thalassemia erythrocytes, they cannot account for the relative overhydration of Hb H disease. The Ca-activated K channel (Gardos pathway[11]) was not part of these studies. It remains to be determined if the number of channel and their regulation by internal Ca is altered in thalassemic cells.

The relevant alterations of membrane transport observed in thalassemia RBCs could be reproduced in normal RBCs treated with PHZ or MHZ (Figs 1 and 2). MHZ and PHZ produced well-defined changes on both membrane proteins (confirmed by SDS-PAGE analysis[8]) and membrane cation transport, which strongly mimicked the abnormalities in Na-Li countertransport, Na-K-Cl and K-Cl cotransport activities observed in α and β thalassemia. The only exception was represented by the activity of the Na-K pump, which was inhibited in oxidized erythrocytes (Fig 2). It is worth noting that in rabbit erythrocytes, oxidation decreases the Na-K pump activity, whereas cell age increases it.[22] The twofold stimulation of Na-K pump in thalassemia appears to be a consequence of two opposing processes: stimulation caused by the presence of younger cells and inhibition caused by concomitant oxidative membrane damage. In a previous report, ^{3}H-ouabain binding studies on α- and β-thalassemia

erythrocytes showed a 2.6- to 10-fold increase above normal.[28] Because we have not measured the number of pumps in our patients, the relative effect of oxidative damage can not be determined. A discrepancy between increased pump sites and increased flux would suggest oxidative damage effect. The similarity between changes in membrane transport observed in thalassemia and thalassemia-like RBCs indicates that membrane damage rather than cell age is the main determinant of the changes we observed in thalassemia erythrocytes.

We have shown here that β-thalassemia erythrocytes have increased K-Cl cotransport[20] (Fig 1). Another distinguishing feature of β-thalassemia erythrocytes is that increased K-Cl cotransport was observed in the top and bottom density fractions of thalassemia RBCs (Table 2). K-Cl cotransport is usually observed in the least-dense, reticulocyte-rich fraction of normal RBCs, and is absent in denser fractions.[19] This finding is similar to previous reports in SS[13] and CC[15] cells and indicates that cells with increased K-Cl cotransport are present throughout the density span of thalassemia RBCs. Thus, K-Cl cotransport is a major pathway for K loss and dehydration not only in SS and CC cells, but also in β-thalassemia erythrocytes.

The role of oxidation in K-Cl cotransport activation is shown by the effects of DTT (Fig 4, A and B). Treatment with DTT reduced K-Cl cotransport in thalassemia erythrocytes to values close to control. Thus, oxidation may represent "a third factor" capable of modulating activation of K-Cl cotransport in addition to cell age and presence of $\beta 6$-$\beta 7$ positively charged mutations on Hb.[20] The effect of oxidation on K-Cl cotransport has been shown in experimental models using normal cells,[21] is potentiated by exposure to NEM[29] and can also be shown in rabbit erythrocytes.[22]

Membrane oxidation plays a relevant role in the alterations of membrane cation transport observed in thalassemic RBCs. It is also a major factor in the activation of K-Cl cotransport in thalassemic RBCs, which is an important determinant of the relative dehydration observed in β-thalassemia erythrocytes.

ACKNOWLEDGMENT

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