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Binding of Dihydroartemisinin to Hemoglobin H: Role in Drug Accumulation and Host-Induced Antimalarial Ineffectiveness of α-Thalassemic Erythrocytes

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ABSTRACT

Dihydroartemisinin and other artemisinin derivatives are relatively ineffective against *Plasmodium falciparum* infecting α-thalassemic erythrocytes, namely hemoglobin (Hb) H or HbH/Hb Constant Spring erythrocytes, as compared with those infecting genetically normal erythrocytes. The variant erythrocytes accumulate radiolabeled dihydroartemisinin to a much higher extent than the normal ones, and the accumulated drug was retained after extensive washing, in contrast to the drug in normal erythrocytes which was mostly removed. At initial drug concentration of 1 mM, most (82–88%) of the drug was found in the cytosol fraction of both variant and normal erythrocytes. Binding of the drug to hemoglobins accounted for 40–70% of the total uptake. Hb H accounted for 10.9 ± 2.7% and 12.4 ± 6.2% of total protein in HbH and HbH/Hb Constant Spring erythrocytes. HbH bound with 28.7 ± 6.7% of the drug, whereas HbH/Hb Constant Spring erythrocytes bound with 21.8 ± 8.3% of the drug. Binding experiments showed that Hb H had 5–7 times the drug-binding capacity of Hb A. For Hb H, the maximum binding capacity (B_{max}) = 1.67 ± 0.17 mol/mol Hb, and the dissociation constant (K_d) = 66 ± 17 μM, and for Hb A, B_{max} = 0.74 ± 0.18 mol/mol Hb and K_d = 224 ± 15 μM. It is concluded that preferential binding of dihydroartemisinin to Hb H over Hb A accounts partly for the higher accumulation capacity of the α-thalassemic erythrocytes, which leads to its antimalarial ineffectiveness.

The artemisinins form a group of antimalarials derived from *Artemisia annua*, an herbal plant long used in China for the treatment of fevers (United Nations Development Program *et al.*, 1997; Klayman, 1993). They are sesquiterpenoids with an endoperoxide essential for antimalarial activity. DHART is more active than artemisinin against *Plasmodium falciparum*, and is probably the metabolically active form of the derivatives already in use or in advanced stages of development. With the threat of multidrug-resistant malaria on the rise, the artemisinins, which have proven to be effective against parasites resistant to chloroquine and other drugs, will be playing an increasing role in antimalarial chemotherapy. Although no resistance to these drugs has been reported so far from the field, it is important to understand factors that may contribute to the development of resistance and that may reduce the efficacy of the drugs in the future.

We have shown previously that the genetic type of the host erythrocytes can influence the efficacy of artemisinin derivatives against *P. falciparum* (Yuthavong *et al.*, 1989; Kamchonwongpaisan *et al.*, 1994). Parasites in culture infecting α-thalassemic erythrocytes, both of the genetic type α-thalassemia 1/α-thalassemia 2 (−/−/α) and α-thalassemia1/Hb Constant Spring ($-/\alpha^{CS}\alpha$), or of the phenotypes HbH and HbH/HbCS respectively, are more resistant to the artemisinins than the same parasites infecting genetically normal erythrocytes. Resistance is therefore generated from the host, not the parasite, and is caused by the competition from the erythrocytes, which take up the drugs in large quantities resulting in low medium concentration and low drug uptake of the parasite. Drug-binding sites may therefore be present in the variant erythrocytes and be responsible for the uptake. The search for such possible binding sites is important in the understanding of the apparent drug resistance of the parasite infecting α-thalassemic erythrocytes, and may yield information on the nature of the drug receptor. This article reports the results of the study on distribution and localization of dihydroartemisinin in α-thalassemic and normal erythrocytes. It was found that Hb H binds with the

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ABBREVIATIONS: DHART, dihydroartemisinin; Hb, hemoglobin; HbH, α-thalassemia 1/α-thalassemia 2; HbH/HbCS, α-thalassemia 1/hemoglobin Constant Spring; HEPES, 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid;

drug with much higher avidity than Hb A and that the former accounts for a significant portion of the drug taken up.

Experimental Procedures

Sample preparations. About 15 ml of venous blood from α-thalassemic patients (both HbH and HbH/HbCS phenotypes) and normal individuals was collected with citrate-phosphate-dextrose as anticoagulant. Whole blood was centrifuged at 800 × *g*, at 4° for 15 min, after which plasma and the buffy coat were removed. The packed erythrocytes were washed twice with culture medium composed of RPMI 1640 supplemented with 25 mM HEPES, pH 7.4, 0.2% $NaHCO_3$, and 40 μg/ml gentamicin. The erythrocytes were then resuspended in an equal volume of culture medium, and cell numbers were counted by an automated cell counter (Technicon, Bayer Diagnostics, Tarrytown, NY). For DHART inhibition assay, the packed erythrocytes were resuspended in a 10% human-serum-supplemented culture medium.

DHART inhibition assay. The antimalarial activity of DHART was measured against *P. falciparum* infecting normal and α-thalassemic erythrocytes using the [^{3}H] hypoxanthine incorporation method of Desjardins *et al.* (1979). Aliquots (25 μl) of serially diluted DHART in dimethylsulfoxide were pipetted into a microtitration plate containing 96 flat-bottomed wells. Parasitized erythrocyte suspension (200 μl) containing 1.5% hematocrit with 0.5% parasitemia were added. After 24-hr incubation in a candle jar at 37°, 25 μl of [^{3}H]hypoxanthine (0.5 μCi, specific activity 20–30 Ci/mmol; Amersham, Paisley, UK) were added into each well and the plate was reincubated under the same condition for 18 hr. Using a cell harvester (Nunc, Roskilde, Denmark), the cell suspension was aspirated through glass filter paper (no. 934-AH; Whatman, Maidstone, UK), and washed with distilled water. The disks were dried and placed in toluene-based scintillation fluid for counting in a b-counter (LS1801; Beckman Instruments, Palo Alto, CA). IC_{50} values were evaluated from the sigmoidal graph of percent [^{3}H]hypoxanthine incorporation versus log of drug concentration.

[^{14}C]dihydroartemisinin accumulation. Aliquots (140 μl) of 50% red blood cell suspension were incubated with 560 μl of 1.25 mM [^{14}C]DHART (specific activity 12.1 mCi/mmol; final concentration, 1.0 mM in 0.1% dimethylsulfoxide (a kind gift from Dr. Kenneth H. Davis, Jr., Chemistry and Life Sciences Division, Research Triangle Institute, NC)] in 1.5-ml microcentrifuge tube at 37° for 2 hr (Kamchonwongpaisan *et al.*, 1994). Cells were pelleted by centrifugation at 10,000 × *g* for 5 min. The packed erythrocytes were washed with 1 ml of culture medium three times and were then incubated with 700 μl of 2% sodium dodecyl sulfate solution at 60° for 1 hr. Solutions were bleached with 400 μl of 15% hydrogen peroxide at 60° for 12 hr. Four milliliters of Triton-based liquid scintillation fluid was added and the radioactivity was determined.

To study drug retention, 70 μl of [^{14}C]DHART-labeled packed erythrocytes were incubated in 1 ml of culture medium in triplicates for a further 3 hr, and the amounts of radioactivity remaining within the cells were measured hourly as described above for comparison with the initial unwashed cells.

[^{14}C]dihydroartemisinin distribution within red blood cells. One volume (70 μl) of packed [^{14}C]DHART-labeled erythrocytes was mixed with half a volume of lysis buffer (10 mM Tris-HCl, 1 mM EDTA, pH 8.8), and the cell suspension was then freeze-thawed to lyse the intact erythrocytes. The membrane fraction was separated by centrifugation at 10,000 × *g* for 15 min. Radioactivity in 105 μl of hemolysate was measured, and the amount of drug was calculated. The membrane fraction was washed five times with a buffer containing 1 mM EDTA and 0.2 mM phenylmethylsulfonyl fluoride in 5 mM Tris-HCl, pH 7.6, and then incubated with 500 μl of 2% sodium dodecyl sulfate solution at 60° for 1 hr. Four milliliters of Triton-based liquid scintillation fluid was added and radioactivity was determined for calculation of the amount of the drug in the membrane fraction.

Hemoglobin typing by cellulose acetate gel-electrophoresis. Two microliters of hemolysate from [^{14}C]DHART-labeled erythrocytes was electrophoresed on a cellulose acetate plate (cellogel; Chemetron, Milano, Italy) in Tris-glycine buffer, pH 8.6, at 280 V for 30 min. The cellulose acetate plate was stained with Ponceau S solution and destained with 5% acetic acid. Cellogel was dehydrated and dried, and the percentages of hemoglobin types were quantified using a densitometer (aDC; Helena, Beaumont, TX). Total hemoglobin concentrations were assayed by the cyanmethemoglobin method (Brown, 1988).

Hemoglobin binding capacity. Hemolysates (10–20 μl) from normal and thalassemic red blood cells was separated on a cellulose acetate plate as described above. Each lane was cut into areas containing band at origin, Hb A, Hb A_2, Hb H, Hb CS and area(s) with no Hb band. Corresponding areas from the same sample were pooled and eluted with 5 ml of distilled water by shaking overnight at room temperature. The radioactivity was determined after bleaching with 15% hydrogen peroxide in Triton-based liquid scintillation fluid. Drug-binding capacity of each Hb was calculated as moles of [^{14}C]drug per mole of Hb.

Hemoglobin isolation by carboxy methyl cellulose chromatography. Hemolysates, prepared from drug-free erythrocytes using the freeze-thaw technique as described above, were dialyzed in bis-Tris buffer (0.03 M bis-Tris, pH 6.1, with 0.01% potassium cyanide) at 4° for 12 hr. The dialyzed hemolysates were loaded onto a carboxy methyl cellulose column (1 × 20 cm, CM-52 cellulose; Whatmann), and washed with 1–2 column volumes of bis-Tris buffer at a flow rate of 50 ml/hr, followed by 800 ml of salt gradient (between 0.030 and 0.065 M sodium chloride in bis-Tris buffer) (Schroeder and Huisman, 1980). Ten-milliliter fractions of the effluent were collected. Conductance and absorption at 280 and 415 nm were measured. Fractions from the same peak of Hb were pooled, dialyzed in 10 mM phosphate buffer, pH 7.4, and concentrated. Hb concentrations were assayed by the cyanmethemoglobin method.

Binding constant measurements. Binding constants of DHART with Hb A and Hb H were measured by dialysis technique (Kabat and Mayer, 1961). The isolated hemoglobin was diluted to 10 μM with 10 mM phosphate buffer, pH 7.4, and 1 ml aliquots were placed in dialysis tubes (16 mm in diameter, retaining protein of molecular mass ≥ 12,000 Da; Sigma, St. Louis, MO). Each tube was incubated in 1 ml of [^{14}C]DHART (varying from 1×10^{-7} M to 5×10^{-4} M) in the same buffer at 37° for 20 hr. Then 500 μl of the solutions within and outside the tube was collected, and bleached with 500 μl of 15% hydrogen peroxide. Four milliliters of Triton-based liquid scintillation fluid was added, and radioactivity was measured. The concentrations of bound and free drugs were calculated and the binding curves were evaluated using the program ENZFITTER (Cambridge Biosoft, Northwich, UK).

Results

P. falciparum was found to be more resistant to dihydroartemisinin when infecting α-thalassemic erythrocytes, both of the HbH and the HbH/HbCS types, than when infecting genetically normal erythrocytes. The IC_{50} values were 9.6 ± 1.2 nM for HbH and 13.7 ± 7.2 nM for HbH/HbCS, which were 8.0 and 11.4 times higher than that of infected normal erythrocyte (1.2 ± 0.5 nM). This result was similar to those for artesunate (Yuthavong *et al.*, 1989) and artemisinin (Kamchonwongpaisan *et al.*, 1994) reported earlier. The variant erythrocytes took up higher amounts of dihydroartemisinin than normal erythrocytes, another finding similar to the previous result for artemisinin (Kamchonwongpaisan *et al.*, 1994), although the magnitude of the difference was lower for

dihydroartemisinin. Under the experimental conditions used, drug uptake of HbH erythrocytes (0.25 ± 0.13 pmol/106 cells) was 2.8 times, and of HbH/HbCS erythrocytes (0.44 ± 0.11 pmol/106cells) was 4.9 times, that for genetically normal erythrocytes (0.09 ± 0.05 pmol/106cells).

Most of the drug accumulated by the HbH and HbH/HbCS erythrocytes remained in the cells even after extensive washing (88% and 90%, respectively; (Fig. 1). In contrast, only 43% of dihydroartemisinin in genetically normal erythrocytes remained in the cells after similar washing. This result indicated that the drug in the thalassemic erythrocytes was much more tightly bound than that in genetically normal erythrocytes.

To investigate the factors responsible for high drug uptake by thalassemic erythrocytes, the cells were lysed after exposure to the radiolabeled drug and fractionated into membrane (pellet) and cytosol (supernatant) fractions. Fig. 2 shows that most (82–88%) of the drug was associated with the cytosol fraction for both genetically normal and thalassemic erythrocytes. The remaining drug was located in the membrane fraction. Drug-binding capacity of various cytosolic components was investigated further by electrophoresis of the lysates. Table 1 shows the amount and percentages of Hb A, Hb H, and bound dihydroartemisinin calculated from the associated radioactivity. For both HbH and HbH/HbCS erythrocytes, Hb H in the cells accounts for about 22–29% (mean 25.3 ± 7.7%) of the total drug found in the lysate, although it accounts for only 11–12% (mean 11.7 ± 4.4%) of the total Hb. In contrast, Hb A, accounting for 74–81 (mean 77.4 ± 5.7%) of total Hb, has only about 27% (mean 27.2 ± 7.3%) of the total drug associated with it. The drug-binding capacities of the two types of hemoglobin in these cells, calculated as mmole of drug per mole of hemoglobin, are shown in Fig. 3. Hb H has about five to seven times as much dihydroartemisinin bound as Hb A. The drug binding capacity of Hb H isolated from HbH and HbH/HbCS erythrocytes was 1.79 ± 0.24 and 1.35 ± 0.52 mmol/mol Hb, respectively, which were 7.5 and 4.7 times higher than drug-binding capacity of Hb A (0.24 ± 0.14 and 0.29 ± 0.16 mmol/mol Hb, respectively). The drug-binding capacity of Hb A in the thalassemic cells was not different from that in genetically normal cells.

The maximum binding capacities (B_{max}) and dissociation constants (K_d) for the binding between dihydroartemisinin and Hb H, as well as Hb A, were studied by equilibrium dialysis using isolated Hb of both types. Typical binding curves are shown in Fig. 4, and the values for B_{max} and K_d are shown in Table 2. B_{max} for Hb H binding was 1.67 ± 0.17 mol/mol Hb, whereas B_{max} for Hb A binding was 0.74 ± 0.18 mol/mol Hb. The K_d value for Hb H binding was 66 ± 17 μM, about 3-fold lower than the value of 224 ± 15 μM for Hb A binding.

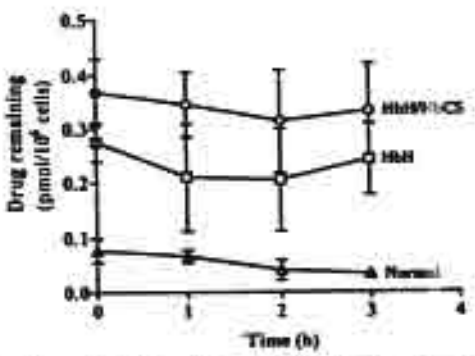

Fig. 1. Retention of [^{14}C]dihydroartemisinin in normal and α-thalassemic erythrocytes. [^{14}C]DHART-labeled normal and α-thalassemic erythrocytes were incubated with culture medium at 37°. At zero time and hourly intervals, cells were sedimented and radioactivity remaining in the cells was determined compared with initially unwashed cells. *Vertical bars*, standard deviation of three experiments.

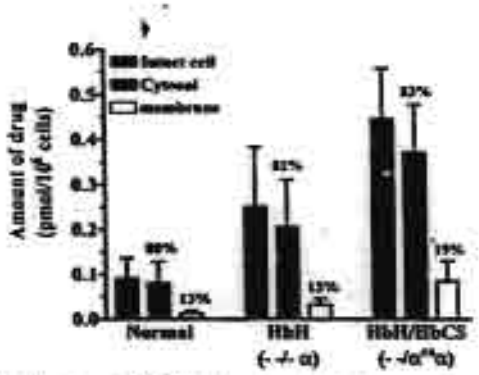

Fig. 2. Distribution of [^{14}C]dihydroartemisinin in normal and α-thalassemic erythrocytes. [^{14}C]DHART-labeled normal and α-thalassemic erythrocytes were lysed by hypotonic solution. Hemolysate and membrane fractions were separated by centrifugation. Drug content in cytosolic (hemolysate) and membrane compartments was measured. ■, mean ± standard deviation of drug in intact erythrocytes; ■, □, mean ± standard deviation of drug in cytosolic and membrane compartments, respectively. Amount of drug in both compartments is also demonstrated as percentages of intact cell.

Discussion

As in findings for artesunate (Yuthavong *et al.*, 1989) and artemisinin (Kamchonwongpaisan *et al.*, 1994), dihydroartemisinin showed less activity against *P. falciparum* in culture when the parasite infected α-thalassemic (Hb H or Hb H/Hb Constant Spring) erythrocytes than when it infected genetically normal red blood cells. We also show here that, as in the case of artemisinin (Kamchonwongpaisan *et al.*, 1994), dihydroartemisinin was preferentially accumulated by the α-thalassemic erythrocytes.

DHART and other derivatives are hydrophobic molecules and it is possible that the high uptake in the thalassemic erythrocytes was caused by binding with erythrocyte membrane. Indeed, it has been shown (Asawamahasakda *et al.*, 1994) that dihydroartemisinin binds with isolated erythrocyte membrane, although not with intact erythrocytes. The membranes of α-thalassemic erythrocytes have many unique features (Schrier, 1994), which may account for preferential binding with dihydroartemisinin. However, Fig. 2 shows that although a significant proportion was associated with the membrane fraction, most of the drug was located in the cytosol fraction. Although Asawamahasakda *et al.* (1994) showed that the drug binds with membrane proteins to a greater extent than cytosolic proteins on a drug per protein basis, the membrane fraction may account for only a small portion of the drug taken up, in view of the relatively small amount of membrane proteins compared with cytosolic proteins and of the possibility that not all the drug in the cytosol is protein-bound. Nevertheless, the possibility remains open that the erythrocyte membrane may play a crucial role in drug transport. It has been shown earlier (Kamchonwongpaisan *et al.*, 1994) that drug accumulation in both variant and

TABLE 1

Hemoglobin content and its associated [^{14}C] dihydroartemisinin in normal and α-thalassemic hemolysates

Hemolysates obtained from [^{14}C] DHART-labeled normal and α-thalassemic erythrocytes were separated on cellulose acetate plates in Tris-glycine buffer, pH 8.6. Percentages of each hemoglobin band were estimated by a densitometer (shown in parentheses). The amount of Hb (pmol/10^6 cells) in each band was calculated from percent Hb and total Hb assayed by cyanmethemoglobin method. [^{14}C] DHART in each Hb band was eluted and measured for calculation as pmol/10^6 cells and percent of total drug (shown in parentheses).

Hemolysates	Hb A		Hb H		Total Hb	Total drug in hemolysate
	Amount of Hb	Amount of bound drug	Amount of Hb	Amount of bound drug		
			pmol/10^6 cells (% of total)			
HbH/HbCS						
Patient 1	179 (78.1)	0.032 (26.4)	24 (10.5)	0.026 (21.5)	229	0.121
Patient 2	171 (67.4)	0.037 (26.6)	19 (7.4)	0.019 (13.7)	254	0.139
Patient 3	158 (75.6)	0.075 (28.7)	40 (19.4)	0.079 (30.3)	208	0.261
	169 ± 11[a] (73.7 ± 5.5)[a]	0.048 ± 0.024[a] (27.2 ± 1.3)[a]	28 ± 11[a] (12.4 ± 6.2)[a]	0.041 ± 0.033[a] (21.8 ± 8.3)[a]	230 ± 23[a]	0.174 ± 0.076[a]
HbH						
Patient 4	142 (84.3)	0.014 (15.2)	13 (7.8)	0.020 (21.7)	169	0.092
Patient 5	143 (78.0)	0.052 (38.2)	23 (12.7)	0.046 (35.1)	183	0.136
Patient 6	165 (80.9)	0.044 (28.0)	25 (12.2)	0.046 (29.3)	204	0.157
	150 ± 13[a] (81.1 ± 3.2)[a]	0.037 ± 0.020[a] (27.2 ± 8.2)[a]	20 ± 6[a] (10.9 ± 2.7)[a]	0.037 ± 0.015[a] (28.7 ± 6.7)[a]	185 ± 18[a]	0.128 ± 0.033[a]
Normal	300 (93.2)	0.067 (56.8)	—	—	322	0.118

[a] mean ± standard deviation

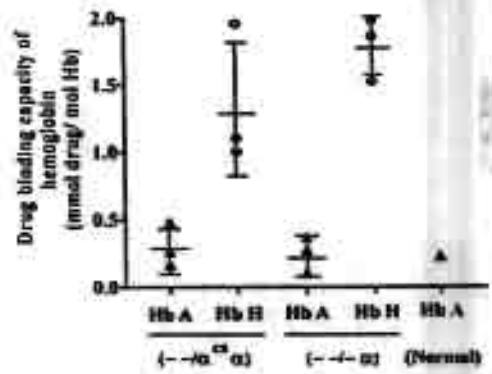

Fig. 3. [^{14}C]dihydroartemisinin binding capacity of hemoglobin. Hemolysates obtained from [^{14}C]DHART-labeled normal and α-thalassemic erythrocytes were separated on cellulose acetate plates in Tris-glycine buffer, pH 8.6. Hb contents and the amounts of associated drug were measured (shown in Table 1). This figure shows mean ± standard deviation of drug binding capacity of Hb A and H (millimoles of drug per mole of Hb (three experiments for α-thalassemic hemolysates and one experiment for normal hemolysate).

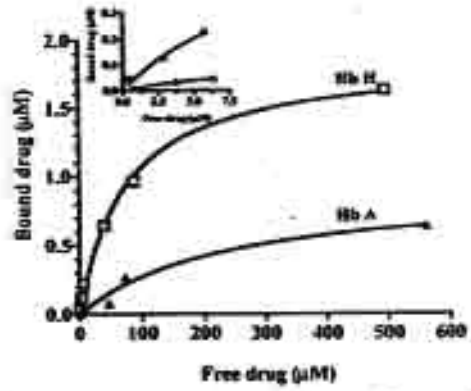

Fig. 4. Binding curve of DHART to hemoglobin. Hb A and Hb H were isolated from α-thalassemic erythrocytes by ion exchange chromatography. Binding of [^{14}C]DHART was conducted using the dialysis technique as described in Experimental Procedures. Maximum binding capacity (B_{max}) and dissociation constant were calculated from this curve (the values shown in Table 2).

normal erythrocytes depends on metabolic energy, possibly required for membrane transport of the drug.

In studies with isolated hemoglobin using the reversible binding model, it was found that Hb H-bound dihydroartemisinin with a higher affinity (lower K_d) and a higher maximum binding capacity (B_{max}) than did Hb A (Table 2). The binding affinity for Hb H was more than 3-fold that for Hb A, and the maximum binding capacity of Hb H with the drug was about 2-fold that of Hb A. The former seemed to bind two molecules of dihydroartemisinin, whereas the latter only bound one per molecule. Because Hb H has four β-globin subunits, and Hb A only two, it is possible that each molecule of the drug binds with a β-globin dimer. The mode of binding of Hb H with the drug remains to be further investigated.

Yang *et al.* (1994) reported that artemisinin binds covalently with hemoproteins including hemoglobin. However, from their data, it can be calculated that only approximately 0.003 molecule of the drug was covalently bound per hemoglobin molecule. Our reversible binding model is not invalidated by a small extent of covalent binding. Nevertheless, there may be a higher extent of covalent binding of dihydroartemisinin with hemoglobin in the cellular environment, because the drug can be activated by intracellular heme and iron (Meshnick *et al.*, 1996; Paitayatat *et al.*, 1997).

In α-thalassemic red blood cells, Hb H bound dihydroartemisinin five to seven times as much as Hb A on a molar basis although it accounts for only about 12% of the total Hb content. Hb H and Hb A in these erythrocytes account for a major portion (40–70%) of drug accumulation, but they are

TABLE 2

Maximum binding capacities (B_{max}) and dissociation constants (K_d) of dihydroartemisinin-hemoglobin complexes

The maximum drug bound per Hb molecule (B_{max}) and K_d of Hb binding to DHART were assayed by equilibrium dialysis. The values were calculated from binding curve (shown in Fig. 4) using the EDEFITTER program.

Hb	B_{max} (moles of drug/moles of hemoglobin)	K_d
		μM
Hb A		
Sample 1	0.55	236
Sample 2	0.77	208
Sample 3	0.90	229
	0.74 ± 0.18*	224 ± 15*
Hb H		
Sample 1	1.86	74
Sample 2	1.59	46
Sample 3	1.56	77
	1.67 ± 0.17*	66 ± 17*

* Mean ± standard deviation.

not the only factors responsible for preferential accumulation of the drug. Other factors, not yet identified, must also be responsible for drug accumulation of the variant erythrocytes.

A fraction of the drug may also be covalently bound to Hb and other protein components of the thalassemic erythrocytes. There is evidence that iron and/or heme are important in the action of artemisinin and its derivatives, which proceed through formation of free radicals (Meshnick *et al.*, 1996; Paitayatat *et al.*, 1997). Because thalassemic erythrocytes have been shown to be under oxidative stress (Shinar and Rachmilewitz, 1990), a portion of the drug may be induced to bind covalently with cellular protein components, through the enhanced stress, possibly through increased Fe(II)-Fe(III) cycling, after which the drug will become inactive. Failure to remove the bound drug by repeated washing may reflect both the tight noncovalent binding of the drug with HbH and its covalent binding with red cell protein components including hemoglobins. Inactivation of the drug may additionally help to explain the apparent resistance of malaria parasites infecting α-thalassemic erythrocytes.

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Distal Renal Tubular Acidosis and High Urine Carbon Dioxide Tension in a Patient With Southeast Asian Ovalocytosis

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• Southeast Asian ovalocytosis (SAO) is the best-documented disease in which mutation in the anion exchanger-1 (AE1) causes decreased anion (chloride [Cl^-]/bicarbonate [HCO_3^-]) transport. Because AE1 is also found in the basolateral membrane of type A intercalated cells of the kidney, distal renal tubular acidosis (dRTA) might develop if the function of AE1 is critical for the net excretion of acid. Studies were performed in a 33-year-old woman with SAO who presented with proximal muscle weakness, hypokalemia (potassium, 2.7 mmol/L), a normal anion gap type of metabolic acidosis (venous plasma pH, 7.32; bicarbonate, 17 mmol/L; anion gap, 11 mEq/L), and a low rate of ammonium (NH_4^+) excretion in the face of metabolic acidosis (26 μmol/min). However, the capacity to produce NH_4^+ did not appear to be low because during a furosemide-induced diuresis, NH_4^+ excretion increased almost threefold to a near-normal value (75 μmol/L/min). Nevertheless, her minimum urine pH (6.3) did not decrease appreciably with this diuresis. The basis of the renal acidification defect was most likely a low distal H^+ secretion rate, the result of an alkalinized type A intercalated cell in the distal nephron. Unexpectedly, when her urine pH increased to 7.7 after sodium bicarbonate administration, her urine minus blood carbon dioxide tension difference (U–B Pco_2) was 27 mm Hg. We speculate that the increase in U–B Pco_2 might arise from a misdirection of AE1 to the apical membrane of type A intercalated cells.

INDEX WORDS: Band 3 protein; anionic exchanger; NH_4^+ excretion; NH_4^+ production; U–B Pco_2; H^+-ATPase.

HEREDITARY ovalocytosis (southeast Asian ovalocytosis [SAO]) is common in parts of southeast Asia and Melanesia. It is the best documented disease in which mutation in the anionic exchanger-1 (AE1)[1,2] causes decreased anion transport[3] and increased membrane rigidity.[1] The red blood cells (RBCs) in SAO are resistant to malarial invasion, and this has been attributed to their altered membrane mechanical properties.[4]

AE1 (or band 3 protein) is the major integral membrane protein of the human RBC. It is composed of two domains with separate functions. The N-terminal 40-kd portion is located in the cytoplasm and acts as an anchor site to the membrane for components of the RBC skeleton, a structure critical to RBC integrity and the binding of several glycolytic enzymes and hemoglobin. The C-terminal 55-kd portion spans the bilayer and performs the exchange of chloride (Cl^-) for bicarbonate (HCO_3^-) ions.[5,6] The AE1 gene that encodes this RBC anion exchanger is located on chromosome 17q21-qter.[7]

AE1 is also found in the basolateral membrane of the type A, but not type B, intercalated cells of the kidney.[8,9] Most of the H^+ in the distal nephron is secreted across the apical membrane of type A intercalated cells through vacuolar H^+-adenosine triphosphatase (H^+-ATPase). There is also a role for an H^+,K^+-ATPase in mediating H^+ secretion across the apical membrane of the type A intercalated cells.[10] It is likely that homozygosity for SAO band 3 is lethal, not only because of the effects on RBC function, but possibly because HCO_3^-/Cl^- antiport is a critical component for H^+ secretion in the distal portion of the nephron (Fig 1).

At least five studies implied that mutations of the AE1 gene affected renal acidification. Bae-

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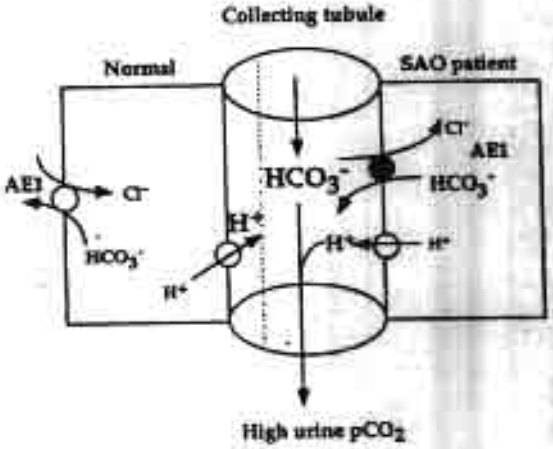

Fig 1. Proposed mechanism for a normal increased urine P_{CO_2} in the patient. Two possible explanations for the increased urine P_{CO_2} are a greater secretion of H^+ and/or a greater secretion of HCO_3^-. The barrel-shaped structure is the collecting duct, and the rectangles represent type A intercalated cells (normal on the left and SAO patient on the right). The abnormality of AE1 in the patient with SAO results in mistargeting of the protein to the apical membrane, where it functions to secrete bicarbonate and thereby increase, rather than decrease, the U–B P_{CO_2}.

hner et al[11] reported that renal tubular acidosis (RTA) occurred in a single family with hereditary elliptocytosis. Rysava et al[12,13] suggested that 2 of 10 patients with hereditary spherocytosis and a known AE1 gene mutation (substitution of G→A in the first nucleotide of intron 12, PRIBRAM band 3), had an incomplete form of RTA. Cope et al[14] implied that both glycosylation abnormality and band 3 mutation may be necessary to produce familial distal RTA (dRTA). Bruce et al[15] reported an association between familial dRTA and point mutations of the AE1 gene, and Jarolim et al[16] described the association of the heterozygous hypomorphic AE1 mutation R589H with dominant dRTA and normal RBCs.

We report a case with SAO and dRTA in which the distal H^+ secretory defect might arise from an altered anion (HCO_3^-/Cl^-) exchanger in the type A intercalated cells of the collecting duct. There was an unanticipated finding of a defect in distal H^+ secretion, resulting in a high value for the urine minus blood carbon dioxide tension difference (U–B P_{CO_2}).[17] Possible implications of this unexpected finding are discussed.

Table 1. Laboratory Values on Admission

	Serum	Urine
pH	7.32	6.6
Bicarbonate (mmol/L)	17	—
Sodium (mmol/L)	139	86
Potassium (mmol/L)	2.7	32
Chloride (mmol/L)	111	113
Anion gap (mEq/L)	11	5
BUN (mg/dL)	10	—
Creatinine (mg/dL)	0.7	—
Osmolality (mOsm/kgH_2O)	294	450

Abbreviations: BUN, blood urea nitrogen.

CASE REPORT

The chief complaint in a 33-year-old woman was generalized muscle weakness for the past 4 months. Her past medical history and review of systems were unremarkable. She was an elder sister in a family with two sibs. Only she and her father had SAO.

On admission, she was afebrile, blood pressure was 110/70 mm Hg while supine, respiratory rate was 20 breaths/min, and pulse rate was 86 beats/min. Postural changes in blood pressure and pulse rate were not detected. The patient was alert and oriented. The only abnormality on physical examination was a moderate degree of weakness of the proximal muscles in all extremities. Muscle bulk was normal, and the muscles were not tender. Cranial nerve function, sensory examinations, and deep tendon reflexes were normal.

On laboratory examination, her hematocrit was 39%, and ovalocytosis (75%) was prominent in the peripheral blood smear. The principal acid-base findings were metabolic acidosis with a normal anion gap in plasma (Table 1); a relatively low rate of excretion of NH_4^+, together with a high urine pH (6.6) and a low rate of excretion of citrate (Table 2); an ability to increase the rate of excretion of NH_4^+ threefold with a loop diuretic (Table 3); and a fractional excretion of bicarbonate of only 5% after a sodium bicarbonate load (Table 4). There was one surprising finding during the sodium bicarbonate load, which was a high value for urine P_{CO_2} (Table 4). There was also a high rate of excretion of potassium and transtubular $[K^+]$ gradient (TTKG)[18] given the degree of hypokalemia (Table 2).

The results of analysis of AE1 gene by polymerase chain reaction[19] showed that both the patient and her father were heterozygous for a 27-bp deletion in exon 11 (Fig 2), which confirmed that they had the mutation specific for SAO, whereas her mother and younger sister did not carry this mutation.

Table 2. Urine Values on Admission

Creatinine clearance (mL/min)	95
pH	6.6
NH_4^+ (μmol/min)	26
Citrate (μmol/min)	0.02
Potassium (μmol/min)	28
TTKG	7.7

Table 3. Urine Values After Oral Furosemide

	Control	After Diuresis
Flow rate (mL/min)	0.9	10
Sodium (μmol/min)	85	1080
Potassium (μmol/min)	28	73
pH	6.7	6.3
NH_4^+ (μmol/min)	26	75
Citrate (μmol/min)	0.17	<0.01

^{35}S-sulfate influx studies[3] for RBC anion transport of the patient and her father showed a 40% reduction in sulfate influx with normal 4,4-di-isothiocyanate-stilbene-2,2'-disulfonic acid (DIDS) sensitivity and pH dependence (Table 5).

DISCUSSION

The findings of hyperchloremic metabolic acidosis, hypokalemia with a relatively high TTKG and potassium excretion rate, a relatively low rate of excretion of NH_4^+ and citrate, and high urine pH (>5.5) are all typical for a patient with a decreased rate of distal H^+ secretion.[20] These results describe our patient with dRTA, whose disease is associated with the mutation of AE1 gene (deletion of 27-bp in exon 11). Nevertheless, no specific renal tissue was obtained because we could not do so on ethical grounds.

There are two major reasons why her rate of excretion of NH_4^+ might be low: a low availability of ammonia in the renal medullary interstitium and/or a low rate of H^+ secretion in the distal nephron. The high urine pH suggests there was a low rate of distal H^+ secretion.[20] To assess whether there was also a low $[NH_3]$ in the medullary interstitium, the patient was administered a loop diuretic, and the rate of excretion of NH_4^+ was measured as described by Vasuvattakul et al.[21] Because the rate of excretion of NH_4^+ increased by almost threefold during the furosemide-induced diuresis (Table 3) to typical values in healthy subjects with chronic acid loading,[21] this indicates that the rate of production of NH_4^+ in the patient's proximal tubular cells was not appreciably depressed. That her urine pH did not decrease to the range of 4 to 5 with this diuresis is consistent with the suspicion that her major defect was a low net rate of H^+ secretion in her distal nephron.[21,23] There did not seem to be a major defect of H^+ secretion in her proximal tubule because the fractional excretion of HCO_3^- after sodium bicarbonate administration was close to 5% when her plasma bicarbonate level was 27 mmol/L (Table 4). Therefore, all these results were consistent with the impression that her major defect should be a reduced rate of H^+ secretion in the distal nephron. This lesion would be anticipated if there was an impaired exit of HCO_3^- from these cells because of the AE1 defect, with the net result of a more alkaline intracellular pH.

Measurement of the U–B P_{CO_2} in alkaline urine can provide a qualitative reflection of the secretion of H^+ in the distal nephron.[17,24] After sodium bicarbonate loading (Table 4), the patient's plasma bicarbonate level was 27 mmol/L, urine pH increased to 7.7, and urine P_{CO_2} was 66 mm Hg (U–B P_{CO_2}, 27 mm Hg). The urine P_{CO_2} and U–B P_{CO_2} in the two patients with hereditary spherocytosis and incomplete dRTA coinherited with a mutation in the AE 1 gene[13] were also reported to be within the normal range after bicarbonate loading. There are three possible explanations for this normal increased urine P_{CO_2} in the face of a defect in distal net H^+ secretion. First, a reduction in luminal $[H^+]$ by the sodium bicarbonate load could permit more distal H^+ secretion if the luminal $[H^+]$ influences net H^+ secretion.[25] However, this sodium bicarbonate load should also alkalinize type A intercalated cells further, and this should augment the depression of H^+ secretion. Moreover, when the patient was administered an ammonium chloride (NH_4Cl) load for 3 days, NH_4^+ excretion was very low because of the low distal H^+ secretion. Second, a gradient defect, caused by an enhanced luminal membrane permeability of the collecting tubule to permit the back diffusion of H^+, is also associated with dRTA and a normal ability to increase

Table 4. Urine Values After Oral Sodium Bicarbonate Loading With a Urine pH >7.4

	Blood	Urine
pH	7.44	7.74
Bicarbonate (mmol/L)	26.9	92.4
Creatinine (mg/dL)	0.7	49
P_{CO_2} (mm Hg)	39	66
(U–B) P_{CO_2} (mm Hg)	27	
FE HCO_3^- (%)	5	

Abbreviation: FE HCO_3^-, fractional excretion of bicarbonate.

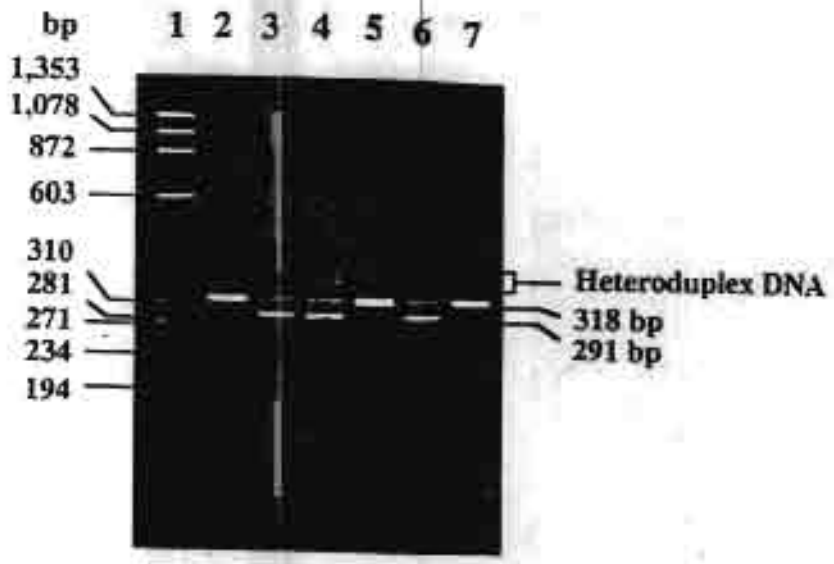

Fig 2. Agarose gel electrophoresis of polymerase chain reaction (PCR) products after amplifications of exon 11 of AE1 gene by PCR using exon 11 specific primers (AE1E×11L/AE1E×11R). Lane 1 is PhiX 174 DNA/HaeIII markers. Lanes 2 through 7 are PCR products resulted from amplifications of DNA samples of a healthy person, an individual with only SAO, patient's father, patient's mother, patient with dRTA and SAO, and patient's younger sister. The normal DNA sample gave PCR product with the size of 318 bp (lane 2), whereas that from the individual with SAO showed PCR products with the sizes of 318 and 291 bp, as well as heteroduplex DNA (lane 3). The DNA samples from the patient's father (lane 4) and the patient (lane 6) produced the PCR products the same as those of the individual with SAO, whereas those from the patient's mother (lane 5) and the patient's younger sister (lane 7) gave the PCR products the same as that of the healthy individual.

the urine P_{CO_2}.[17,24] A similar association has been reported in primary dRTA in an infant not previously exposed to amphotericin B[26] and in a patient with an early stage of primary Sjögren's syndrome[27] who also had the inability to decrease urinary pH in response to furosemide and markedly increased urinary excretion of NH_4^+. For this mechanism to operate, the urine pH must be much greater than the mid-6 range because the highest rates of NH_4^+ excretion occur when the urine pH is in the low-6 range in subjects with chronic metabolic acidosis (NH_4Cl loading,[28] chronic fasting).[29-31] There is a problem relating the urine pH to that in the lumen of the distal nephron when bicarbonate is the principal urine buffer because of the absence of luminal carbonic anhydrase in this nephron segment (for review, see[17,32,33]). As emphasized by Knepper

Table 5. ^{35}S-Sulfate Influx Studies for RBC Anion Transport

	Phenotype	SO_4^{2-} Uptake (10^{-7} mol/L/min/cell)*		
		No DIDS	+1.5 μmol/L DIDS†	%‡
Father	SAO	4.8 ± 0.02§	0.1 ± 0.00	1.1
Mother	Normal	8.1 ± 0.1	3.7 ± 0.5	45.3
Patient	SAO	5.1 ± 0.1	0.1 ± 0.02	1.8
Sister	Normal	7.7 ± 0.3	3.4 ± 0.3	44.8
Mean of 2 SAOs		4.9 ± 0.2	0.1 ± 0.01	1.5 ± 1
Mean of 5 controls		6.3 ± 0.5	4.9 ± 1.5	58.6 ± 12

*Initial rate of sulfate (SO_4^{2-}) uptake of the erythrocyte when incubated at 37°C with 3 mmol/L of [^{35}S] sodium sulfate, 70 mmol/L of sodium citrate, 10 mmol/L of Tris, pH 7.4 buffer.

†The erythrocytes were incubated at 37°C with 1.5 μmol/L of DIDS for 15 minutes before SO_4^{2-} uptake.

‡Percent of rate of SO_4^{2-} uptake, comparing with and without DIDS.

§Mean ± SD in duplicated experiment.

and Good,[34,35] one should expect high local carbonic acid concentrations in luminal fluid, and thus the $[H^+]$ in vivo will be much greater here than in the urine. Therefore, a greater luminal $[H^+]$ in the distal nephron would likely be present with bicarbonaturia and make the gradient limit for H^+ secretion a less likely explanation for the high urine P_{CO_2} in our patient. Third, the normal ability to increase urine P_{CO_2} during a bicarbonate diuresis could be the result of secretion of HCO_3^- by type A intercalated cells in these patients with AE1 abnormality (Fig 1). To explain why HCO_3^- might be secreted by type A intercalated cells, we suggest, as did Bruce et al,[15] that mistargeting of an active AE1 to the apical membrane of the type A intercalated cells might explain a decrease in net H^- (really HCO_3^-) secretion in patients with familial dRTA.[36] We hypothesize that the mutant AE1 protein in our patients was mistargeted to the apical membrane of the type A intercalated cells. The secretion of HCO_3^- would not only cause a high urine P_{CO_2}, but it should also cause an alkaline disequilibrium pH, making it even more difficult to trap ammonia in the luminal compartment. Secretion of HCO_3^- by type B intercalated cells is also a possible mechanism for the normal increased urine P_{CO_2}. Nevertheless, because AE in these cells is a different gene product and is not involved in the SAO abnormality, these cells probably do not have abnormal function in this patient. Moreover, if HCO_3^- were secreted by type B intercalated cells during a sodium bicarbonate load, the urine P_{CO_2} would be increased in most patients with a defect in distal H^+ secretion, but this is not consistent with the published data.[17]

The incidence of metabolic acidosis in SAO patients is low. However, the degree to which the maximum rate of excretion of NH_4^+ is decreased in SAO has never been studied. An incomplete form of dRTA might not produce clinical evidence of acidemia if there is enough capacity to excrete NH_4^+ relative to the acid load of the diet, especially if the subject is not on a high-protein diet. Future studies, including U–B P_{CO_2} measurements, are planned in affected persons with SAO.

The presenting feature in this patient was related to hypokalemia (weakness). Although her daily intake of potassium was not high (42 mmol/L/d), the major reason for her hypokalemia was excessive excretion of potassium (>10 to 15 mmol/L/d, reviewed in [18]). Because her osmole excretion rate was not high, the flow rate in her cortical collecting duct was not excessively high.[37] Hence, a high $[K^+]$ in the lumen of the cortical collecting duct was the principal reason for her high rate of excretion of potassium (TTKG, 7.7 [Table 2], rather than <2[18]). Because her urine consistently contained HCO_3^- (Table 2), perhaps the high TTKG reflected the kaliuretic actions of aldosterone when HCO_3^- remained in the lumen of the CCD because of low distal H^+ secretion, and possibly the secretion of HCO_3^-, as previously suggested.[23,38]

In summary, we report a case in which dRTA occurred in conjunction with SAO. The most likely explanation for the low rate of excretion of NH_4^+ was a low rate of H^+ secretion in the distal nephron, the result of an alkalinized type A intercalated cell consequent to impaired exit of HCO_3^-. There was an unanticipated high value for U–B P_{CO_2}, perhaps the result of secretion of HCO_3^-, which itself could also reduce the net rate of secretion of H^- in the distal nephron. The explanation might be from a mistargeting of the Cl^-/HCO_3^- exchanger to the luminal membrane of the type A intercalated cells.

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Long RT-PCR Amplification of the Entire Coding Sequence of the Polycystic Kidney Disease 1 (*PKD1*) Gene

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ABSTRACT

Characterization of mutations of the PKD1 *gene has been limited by the fact that three-fourths of this gene at its 5′ end is homologous to sequences of at least three other genes on the same chromosome. We have therefore developed a method of long reverse transcription PCR for selective amplification of the entire coding sequence of the* PKD1 *gene from its mRNA. A PCR primer specific to the sequence in the 3′ unique region of the* PKD1 *gene was synthesized for use coupled with a primer binding to sequence in the homologous region at a distance of about 13.6 kb apart. The commercial availability of RNase H-free reverse transcriptase for long cDNA synthesis and of an enzyme mixture containing* Taq *and* Pfu *DNA polymerases for long-range PCR have made this development possible. The long PCR product was proven to be derived from* PKD1*-mRNA. The results clearly indicated that the long PCR product contained the coding sequence derived from* PKD1*-mRNA. To our knowledge, this is the first report of a procedure that can reproducibly isolate full-length* PKD1 *coding sequence from its mRNA transcript, which will prove useful for screening and characterization of mutations in the* PKD1 *gene.*

INTRODUCTION

Characterization of mutations of a gene responsible for a human genetic disease requires the availability of its entire coding and genomic sequences. The polycystic kidney disease 1 (*PKD1*) gene, which has the size of approximately 52 kb containing 46 exons and encoding a 14-kb transcript (5,11,32) and whose defects account for about 85% of autosomal dominant polycystic kidney disease (ADPKD) cases (23), is one of the genes that are most difficult to isolate and identify (5,11,31,32). This is because of the presence of at least three highly homologous sequences of genes mapped more proximally on the same chromosome at the 16p13.1 region (31). Three-fourths of the *PKD1* gene, located in the 5′ part extending to a length of approximately 40 kb of DNA, is duplicated. The three homologous genes (*HG*) encoding transcripts with sizes of 21 (*HG-A*), 17 (*HG-B*) and 8.5 kb (*HG-C*) share about 97% identity with the reiterated part of the *PKD1* gene. The only region of the *PKD1* gene that is different from its homologs is a 10-kb sequence at its 3′ end, encoding a part of the transcript (3.5 kb) covering exons 33–46; whereas, all of the homologs have similar 3′ regions (31). This has made *PKD1* gene isolation, identification and mutation analysis very difficult. Most of the mutations observed so far in the *PKD1* gene are clustered around the unique 3′ region of the gene, which is the only easily accessible region (3,17,19,21,22,27,31,33–35). Therefore, the detection rate of mutation is only 10%–15% of the cases analyzed, and all of them are different, indicating that there is no mutational "hot-spot" area. It is believed that most of *PKD1* gene mutations occur in the duplicated region (22).

The mRNA transcripts of several genes are present from their illegitimate or ectopic transcriptions in human peripheral blood lymphocytes (6), and these mRNAs are correctly processed; although, their levels are extremely low (28). The *PKD1*-mRNA has also been found to be present in human lymphocytes (17,25–27,33,34). Many research groups have attempted to isolate the coding sequence of the *PKD1* gene from its mRNA transcript by reverse transcription polymerase chain reaction (RT-PCR) (17,19–22,25–27,31,33,34), but only partial coding sequences were obtained with a maximum size of 2440 bp. Until now, to our knowledge, there is no report on a method for isolation of the entire coding sequence of the *PKD1* gene from its mRNA transcript. Limitations of the previous RT-PCR techniques have resulted from both the inability of reverse transcriptase to synthesize full-length cDNAs and from the failure of *Taq* DNA polymerase to efficiently amplify more than 4 kb of DNA fragment. Recently, the commercial availability of genetically engineered reverse transcriptases that lack RNase H activity allows the synthesis of full-length cDNA from a long mRNA (16). Furthermore, modified PCR conditions using the combination of *Taq* and *Pfu* DNA polymerases that contain proofreading activity have made it possible to amplify long DNA targets (1,7).

Table 1. Nucleotide Sequences of PCR Primers for the Long RT-PCR and Nested PCR of *PKD1* Gene

Primer	Primer Sequences (5'→3') (nucleotide position[a])	PCR Product Size (bp)	Annealing Temperature (°C)
TH1F	CTG GGG ACG GCG GGG CCA TGC G (nt 175–196)	13634	68
TH1B	GGC CTG GGG CAA GGG AGG ATG ACA A (nt 13808–13784)		
SI2F	AGG AGC CTA GAC GTG TGG ATC G (nt 1595–1616)	1678	65
SI2B	CCT GCA TCC TGT TCA TCC GCT C (nt 3272–3251)		
SI4F	ATC TCT GCT GCC AAT GAC TCA G (nt 4562–4583)	1473	60
SI4B	GGG GAA GCT GTG GGA GAA AC (nt 6034–6015)		
SI9F	CTT CAG CAC CAG CGA TTA CGA CGT T (nt 11533–11557)	1650	65
SI9B	AGA AAG TAA TAC TGA GCG GTG TCC ACT C (nt 13182–13155)		

[a]The nucleotide positions are according to HUMPKD1A, GenBank Accession No. L33243 by Hughes et al. (11).

In this paper, we report a long RT-PCR method for amplification and isolation of the entire coding sequence of the *PKD1* gene from its mRNA transcript. Advantage was taken of the unique sequence at the 3′ region of the *PKD1* gene (and hence in its mRNA transcript) to design a PCR primer for selective amplification by PCR. This long PCR product with the length of 13634 bp was analyzed and shown to contain the full-length coding sequence of the *PKD1* gene, which could be used for screening, characterization of mutations and other types of studies.

MATERIALS AND METHODS

Peripheral Blood Samples and Lymphocyte Preparation

Blood samples were taken from 21 normal individuals and 15 ADPKD patients with prior informed consent. Approximately 15 mL of peripheral blood were collected into a tube containing EDTA-disodium salt as anticoagulant. Lymphocytes were prepared from peripheral blood samples by Ficoll Hypaque® gradient centrifugation using Lymphoprep™ (Nycomed Pharma AS, Oslo, Norway).

RNA Isolation

Total RNA was isolated from peripheral blood lymphocytes by using TRIzol® reagent (Life Technologies, Gaithersburg, MD, USA), following the manufacturer's instruction, with careful and gentle handling to preserve the integrity of long mRNA required. RNA pellet obtained in the final step was dissolved in 50 µL of sterile diethyl pyrocarbonate (DEPC)-treated water. RNA solution was diluted, and its concentration was determined from optical density $(OD)_{260}$ readings that were measured by a UV spectrophotometer. RNA was kept in DEPC-treated water at -70°C. For long-term storage, RNA was precipitated and kept in 75% ethanol at -70°C.

PCR Primers

Sequence of *PKD1*-mRNA (HUMPKD1A, Accession No. L33243) was retrieved from the Entrez database (GenBank®). PCR primers were designed by using the MacVector™ 4.5.1 Program (Scientific Imaging Systems [Eastman Kodak], New Haven, CT, USA) and OLIGO® Version 4.03 Primer Analysis Software (National Biosciences, Plymouth, MN, USA). The primers used for long RT-PCR (TH1F/TH1B), flanking the open reading frame (ORF) of *PKD1* (12906 bp), were designed and selected with the additional criterion that their melting temperatures (T_ms) were high enough to be able to perform PCR with two-step cycling conditions that combine annealing and extension steps at 68°C. The backward (TH1B) primer is specific to the 3′ unique sequence in the *PKD1* transcript; whereas, the forward (TH1F) primer is specific to the sequence in the reiterated region (Figure 1). Three pairs of primers for nested PCRs (SI2F/SI2B, SI4F/SI4B and SI9F/SI9B) were designed to amplify two regions in the homologous and one region in the unique sequences (Figure 1). These primers were custom-synthesized by BioService Unit, National Center for Biotechnology and Genetic Engineering (BIOTEC), National Science and Technology Development Agency (NSTDA), Bangkok, Thailand. Table 1 shows the sequences of PCR primers.

Synthesis of Full-Length cDNA

Full-length cDNA was synthesized by the reaction of RNase H-free reverse transcriptase and by using oligo$(dT)_{12-18}$ primer. An aliquot of total RNA (1–5 µg) was used for cDNA synthesis. The reaction mixture in a total volume of 21 µL contained 20 mM Tris-HCl (pH 8.4), 50 mM KCl, 2.5 mM $MgCl_2$, 500 µM dNTP mixture, 10 mM dithiothreitol (DTT), 0.5 µg of oligo$(dT)_{12-18}$ and 200 U of RNase H-free SUPERSCRIPT™ II RT (Life Technologies). RNasin® Ribonuclease Inhibitor (Promega, Madison, WI, USA) (30 U) was also added to protect mRNA template. The cDNA synthesis was performed at 42°C for 75 min and terminated by incubation at 70°C for 15 min.

Then, 2 U of RNase H (Life Technologies) were added, and the reaction mixture was incubated at 37°C for 20 min.

Long PCR

The full-length *PKD1*-cDNA sequence was amplified by long PCR using a pair of primers flanking the *PKD1*-ORF (TH1F/TH1B). The cDNA was amplified by using ELONGASE™ Enzyme Mix (Life Technologies) following the manufacturer's instructions. The enzyme mixture included thermostable *Taq* and *Pfu* DNA polymerases; the latter has proofreading activity, which reduces error rate of DNA synthesis. The reaction mixture (50 µL) contained 2 µL of cDNA, 1 U of ELONGASE Enzyme Mix, 60 mM Tris-SO_4 (pH 9.1), 18 mM $(NH_4)_2SO_4$, 1.2 mM $MgSO_4$, 200 µM dNTP mixture, 10% dimethyl sulfoxide (DMSO) and 200 nM of each primer.

A hot start at 95°C for 1 min and 30 s was performed before adding the enzyme mixture. PCR was carried out for 30 cycles in a GeneAmp® PCR System 2400 (PE Applied Biosystems, Foster City, CA, USA). Each cycle consisted of denaturation at 94°C for 15 s and a combined step of annealing and extension at 68°C for 15 min. A final extension step was carried out at 70°C for 10 min. The long RT-PCR product was analyzed by electrophoresis on 0.8% agarose gel in 0.5× TBE buffer (0.045 M Tris-borate, 0.001 M EDTA, pH 8.3) and visualized after staining by ethidium bromide.

Restriction Endonuclease Analysis of Long PCR Product

Restriction endonuclease sites in the *PKD1*-mRNA sequence were first analyzed by the MacVector™ 4.5.1 computer program. The restriction endonuclease digestions were performed by taking 20-µL aliquots of the long RT-PCR product and adding the following: *(i)* 20 U of either *Bam*HI, *Kpn*I or *Xho*I enzymes (Promega), *(ii)* a suitable buffer as supplied by the manufacturer and *(iii)* 0.1 µg/mL of bovine serum albumin (BSA) in a final volume of 30 µL. The reaction mixtures were incubated at 37°C for 2 h. The restriction fragments were then resolved by electrophoresis on 1% agarose gel followed by ethidium bromide staining.

Nested PCR

To reduce nonspecific amplifications caused by excessive templates, the long PCR product was diluted 100–1000-fold before amplification with each pair of primers in nested PCR. The nested PCR mixture (25 µL) contained 10 mM Tris-HCl (pH 8.3), 50 mM KCl, 1.5 mM $MgCl_2$, 200 µM dNTPs, 10% DMSO, 400 nM of each primer and 0.625 U of AmpliTaq Gold™ (PE Applied Biosystems). After an initial denaturation at 95°C for 10 min, 25 PCR cycles were performed as follows: *(i)* denaturation at 95°C for 20 s, *(ii)* annealing at 60°C for 20 s and *(iii)* extension at 72°C for 1 min and 30 s, followed by another 10 min of extension at 72°C in the final step. The sizes of nested PCR products were analyzed by electrophoresis on a 1.2% agarose gel in TBE buffer with ethidium bromide staining.

Direct Sequencing of Nested PCR Products

The nested PCR products were purified from gel by using the QIAquick™ Gel Extraction Kit (Qiagen GmbH, Hilden, Germany), following the manufacturer's instructions. Their sequences were determined by the manual direct-sequencing method using the AmpliCycle™ Sequencing Kit (PE Applied Biosystems).

RESULTS

We have developed a long RT-PCR method to isolate the entire coding region of the *PKD1* gene from its mRNA

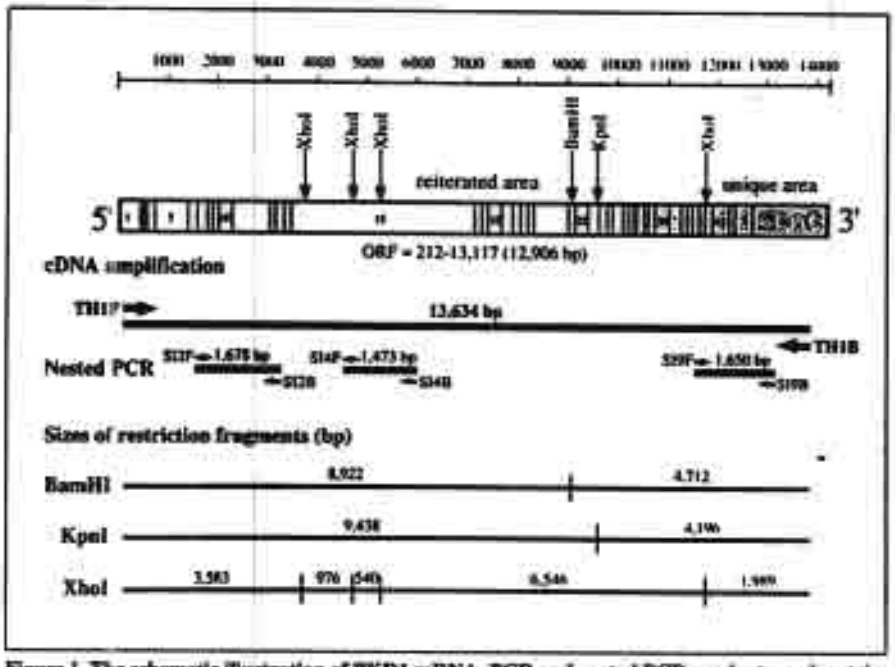

Figure 1. The schematic illustration of PKD1 mRNA, PCR and nested PCR products, and restriction fragments. The entire mRNA containing sequences of exons 1–46 is represented by horizontal bar. The boundaries of exons in the mRNA are indicated by vertical lines, and exon numbers are given for some exons. The ORF consisting of 12906 bp is located between the nt positions 212 and 13117 (HUMPKD1A; GenBank Accession No. L33243; Reference 11). The light shade area (between exons 1 and 32) represents the reiterated region, which is highly homologous to sequences in at least three other genes on the same chromosome. The darker shade area (between exons 33 and 46) represents the 3' unique region. Sites of restriction endonucleases *Bam*HI, *Kpn*I and *Xho*I, used to digest *PKD1* cDNA, are indicated by vertical arrows above the bar of mRNA, and the lower part of the figure shows sizes of fragments after digestions with the restriction enzymes. The extents of long PCR products are represented by solid lines under the bar of mRNA and of nested PCR products by solid lines under the long PCR product. Locations and directions of oligonucleotide primers for long PCR and nested PCR are indicated as solid horizontal arrows.

transcript that was prepared from peripheral blood lymphocytes. The first-strand cDNA synthesis was primed by oligo(dT)$_{12-18}$. The cDNA was subjected to amplification by using the forward (TH1F) primer specific to the reiterated region and the backward (TH1B) primer specific to the unique sequence in the coding region of *PKD1* transcript. The expected PCR product amplified by this pair of primers would be 13 634 bp in length (Figure 1). The conditions for long RT-PCR were optimized by varying amounts of RNA, concentrations of $MgSO_4$ and numbers of PCR cycles. The technique described herein can efficiently amplify the long PCR product by using 1–5 μg of good-quality total RNA. Amounts of RNA greater than 9 μg were found to be less efficient in generating the long PCR product. The optimal conditions for long cDNA synthesis and PCR are described in Materials and Methods.

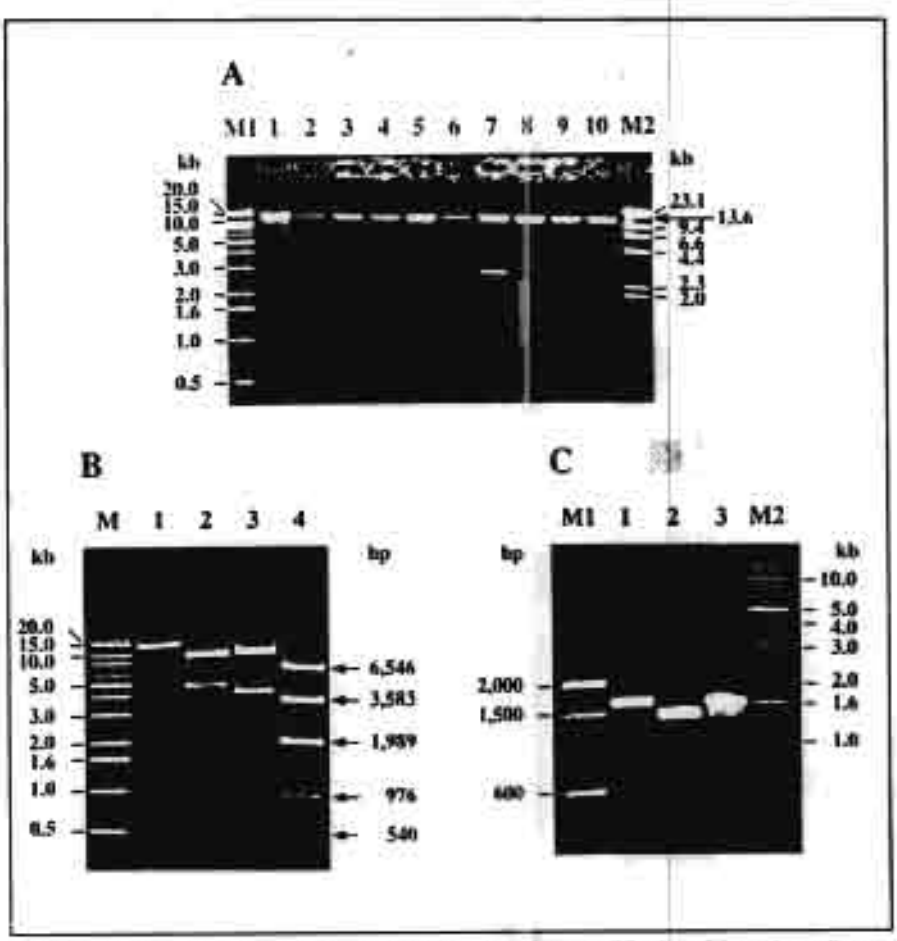

Figure 2. (A) Agarose gel-electrophoresis of PCR products from amplification of the entire coding sequence of the *PKD1* gene from its mRNA by the long RT-PCR method. Lanes M1 and M2 are 1-kb DNA Extension Ladder and λDNA/*Hin*dIII markers (Life Technologies), respectively. Lanes 1 and 2 are PCR products from samples of normal individuals. Lanes 3–10 are PCR products from samples of patients with ADPKD. The PCR product with the size of about 13.6 kb was detected in all samples. A smaller product with the size of <3 kb, present in lane 7, was also irregularly observed in other samples from both normal individuals and patients; it is possibly a nonspecific PCR product. (B) Gel electrophoresis of restriction fragments of the long PCR product. Lane M is 1-kb DNA Extension Ladder. Lane 1 is undigested PCR product. Lanes 2–4 are products after digestions with *Bam*HI, *Kpn*I and *Xho*I, respectively. Digestions of the long PCR product with *Bam*HI (lane 2) and *Kpn*I (lane 3) resulted in two restriction fragments with the lengths of 8922 and 4712 bp, and of 9438 and 4196 bp, respectively, and with *Xho*I (lane 4), five restriction fragments with the lengths of 6546, 3583, 1989, 976 and 540 bp. (C) Agarose gel-electrophoresis of nested PCR products from amplifications of the long PCR product by using three sets of *PKD1*-specific primers. Lanes M1 and M2 are 100-bp DNA Ladder and 1-kb DNA Extension Ladder, respectively. Lanes 1–3 are the nested PCR products from amplifications of the long PCR product with three sets of primers, SI2F/SI2B, SI4F/SI4B and SI9F/SI9B, resulting in DNA fragments sizes of 1678, 1473 and 1650 bp, respectively.

We have successfully tested this procedure with RNA samples that were prepared from peripheral blood lymphocytes of 21 normal individuals and 15 patients with ADPKD. Figure 2A shows part of the data.

To prove that the long PCR product contained *PKD1* coding sequence, we initially analyzed restriction endonuclease sites known to be present in the sequence of *PKD1* mRNA in the long PCR product. The three restriction enzymes selected for this analysis were *Bam*HI, *Kpn*I and *Xho*I, which have 1, 1 and 4 sites, respectively, in the *PKD1* coding sequence (Figure 1). The predicted sizes of fragments after digestions of the *PKD1* coding sequence with the restriction enzymes were 8922 and 4712 bp for *Bam*HI, 9438 and 4196 bp for *Kpn*I and 3583, 976, 540, 6546 and 1989 bp for *Xho*I (see Figure 1). When the long PCR product that was prepared from a normal RNA sample was digested with the three selected enzymes, it was found that the digested DNA fragments had predicted lengths (Figure 2B).

To further prove the authenticity of the long-PCR product, DNA fragments were amplified by nested PCR using 3 pairs of primers (SI2F/SI2B, SI4F/SI4B and SI9F/SI9B) that were specific to sequences in the reiterated and unique regions of the *PKD1*-mRNA transcript (Figure 1) to observe whether the PCR products with expected sizes would be produced or not. The expected lengths of the nested PCR products amplified by these three pairs of primers were 1678, 1473 and 1650 bp, respectively (Figure 1). In this experiment, when the long PCR product was amplified without dilution, both larger PCR products on a smear of background and also product with the expected length were obtained. The larger PCR products and smear seemed to result from excessive DNA templates. Amplifications of the homologous sequences would produce single-stranded products and their amounts should be minute since the backward primer in the primary PCR (TH1B) was specific only to the 3′ unique sequence of the *PKD1* gene. Serial dilution of the long PCR product from 10–10000-fold was performed to reduce the template before using it in the nested PCRs. We found that 100–1000-fold dilutions of the primary PCR product generated the best results. Less dilution still produced nonspecific products, and more dilution resulted in less or no specific products. The results showed that the three nested PCR products had the lengths as expected (Figure 2C).

Finally, to verify that the long PCR product was derived from *PKD1* mRNA, we performed direct sequencing of the three nested PCR products amplified by the three pairs of primers (SI2F/SI2B, SI4F/SI4B and SI9F/SI9B). The nucleotide sequences thus determined were identical to the corresponding regions in the *PKD1* transcript. The nucleotide sequences obtained were located between the positions 1633–1841 (209 nucleotides [nt]), 4610–4709 (100 nt) and 11575–11699 (125 nt) in the *PKD1* mRNA (with reference to the sequence of HUMPKD1A; GenBank Accession No. L33243; Reference 11) (data not shown).

DISCUSSION

The main problem that has delayed progress in studies of the *PKD1* gene is the presence of homologous sequences in at least three potentially active genes on the same chromosome, which interfere with isolation of both the gene and its transcript. We first attempted to isolate *PKD1*-mRNA, which was ectopically transcribed in peripheral blood lymphocytes, by capture with a biotinylated specific-oligonucleotide probe and streptavidin-coated magnetic beads. However, this was unsuccessful, probably because of a minute amount of the *PKD1* transcript present in the peripheral blood lymphocytes. We have therefore developed a long RT-PCR method to selectively amplify the entire coding sequence of the *PKD1* gene from its transcript, by using one PCR primer specific to the sequence in the 3′ unique region of the *PKD1* gene together with the primer specific to the sequence located within the reiterated area at a distance of 13634 bp. The long RT-PCR method could successfully amplify the entire coding sequence of *PKD1* gene from its mRNA. The long RT-PCR product was proven to be derived from *PKD1*-mRNA by demonstrating the presence of *(i)* identical restriction endonuclease maps, *(ii)* correct sizes of the nested PCR products and *(iii)* identical nucleotide sequences in three separated regions.

Although nucleotide sequences of the three homologous genes (*HG-A*, *HG-B* and *HG-C*) have not been available for comparison with the sequences obtained from sequencing experiments, the presence of 100% identity between sequences analyzed in the three regions (altogether 434 nt) with those of the corresponding regions in the reference *PKD1* mRNA confirms that the sequence of amplified product is the bona fide *PKD1* sequence. The most compelling evidence is the absolute identity of the 125-nt sequence of the nested PCR product from the unique region, amplified by SI9F/SI9B primers, to the corresponding region in the reference *PKD1* mRNA.

Many research groups have previously attempted to isolate the coding sequence of the *PKD1* gene from its mRNA for characterization of mutations. However, this was mainly successful in isolation of its unique sequence in the 3′ region (17,19,21,22, 27,31,33–35). Three groups could carry out amplifications of the unique sequence in the 3′ region (between exons 33–46) and part of the reiterated region (located before exons 32) of the *PKD1* gene. Roelfsema et al. (26) isolated the *PKD1* coding sequence from its mRNA prepared from peripheral blood lymphocytes by cDNA synthesis and amplifications of eleven overlapping fragments (each fragment of less than 1 kb) covering 6336 bp (between exons 16 and 46), and seven out of eight novel mutations were identified in the repeated part of the *PKD1* gene. Peral et al. (20) developed an anchored RT-PCR to amplify the *PKD1* coding sequence from its mRNA isolated from lymphoblastoid cell lines, using one primer situated within the single-copy region and one within the reiterated area to identify mutations in the duplicated region. The size of longest PCR product that could be isolated was 2440 bp, extending from exons 22–34 in the *PKD1* transcript, and six out of eleven mutations were identified within the duplicated region. A long-range PCR using a primer specific to the unique region was developed by Watnick et al. (36) to

amplify the *PKD1* gene spanning 10 kb (between exons 23–34) from genomic DNA. Although the methods of these workers could amplify parts of the sequence in the duplicated region, the entire coding sequence of the *PKD1* gene was not obtained.

To our knowledge, the long RT-PCR method developed in this report is the only one that could successfully and reproducibly generate the entire coding sequence of the *PKD1* gene as a single PCR product from the mRNA that was prepared from peripheral blood lymphocytes. This method is rapid—the whole process can be finished within 15 h.

The full-length *PKD1* coding sequence generated by long RT-PCR can be used for cloning or mutation analysis. Some mis-incorporations or errors might be introduced during generation of the full-length *PKD1* cDNA by the long RT-PCR method. However, the use of a mixture of *Taq* and *Pfu* DNA polymerases would alleviate this problem since *Pfu* polymerase contains proofreading activity (1). The clone containing full-length *PKD1* cDNA generated by the long RT-PCR method should be thoroughly evaluated by complete sequence analysis before using it in other work or further study. In cloning complete cDNAs generated from genomes of three RNA viruses including tick-borne encephalitis (10), hepatitis A (30) and hepatitis C (24) by the long RT-PCR method similar to the one described in this work, it was found that the cDNA clones had characteristics of the original genomes, confirming the high fidelity of cDNA generation by the long RT-PCR method.

The long RT-PCR method for analyzing *PKD1* mutations can be of limited usefulness in some cases in which mutations diminish the quantity of *PKD1* mRNA (14); although, the normal and stable expression of mutant alleles at the mRNA level has been observed in peripheral blood lymphocytes (17,25,27,33), cell lines and tissues (22,31). Analysis of mRNA for *PKD1* mutations can have an advantage over analysis from the *PKD1* gene, because mutations that cause abnormal RNA processing (such as exon skipping, RNA deletion or insertion) could also be detected (20,31). However, one should be aware of aberrantly spliced transcripts that can be unrelated to hereditary defects and can complicate detection and analysis of truly abnormal transcripts (2,13). Therefore, the mutations causing abnormal RNA processing must be demonstrated.

The entire coding sequence of the *PKD1* gene that was amplified and isolated by the long RT-PCR method can be used for screening mutations by the following methods: *(i)* single-strand conformation polymorphisms (SSCP) (18), *(ii)* heteroduplex analysis (HA) (12), *(iii)* denaturing gradient gel electrophoresis (DGGE) (9), *(iv)* ribonuclease (RNase) cleavage (15), *(v)* chemical cleavage of mismatch (CCM) (8), *(vi)* dideoxy fingerprinting (ddF) (29) and *(vii)* cleavage fragment-length polymorphism (CFLP) (4). The study of mutations of the *PKD1* gene will provide insight into the functions of polycystin and its peptide domains, the molecular pathogenesis of ADPKD and the effect(s) of the mutations on clinical phenotypes of the patients.

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Autosomal recessive distal renal tubular acidosis associated with Southeast Asian ovalocytosis

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Autosomal recessive distal renal tubular acidosis associated with Southeast Asian ovalocytosis.

Background. A defect in the anion exchanger 1 (AE1) of the basolateral membrane of type A intercalated cells in the renal collecting duct may result in a failure to maintain a cell-to-lumen H^+ gradient, leading to distal renal tubular acidosis (dRTA). Thus, dRTA may occur in Southeast Asian ovalocytosis (SAO), a common *AE1* gene abnormality observed in Southeast Asia and Melanesia. Our study investigated whether or not this renal acidification defect exists in individuals with SAO.

Methods. Short and three-day NH_4Cl loading tests were performed in 20 individuals with SAO and in two subjects, including their families, with both SAO and dRTA. Mutations of *AE1* gene in individuals with SAO and members of the two families were also studied.

Results. Renal acidification in the 20 individuals with SAO and in the parents of the two families was normal. However, the two clinically affected individuals with SAO and dRTA had compound heterozygosity of 27 bp deletion in exon 11 and missense mutation G701D resulting from a CGG→CAG substitution in exon 17 of the *AE1* gene. Red cells of the two subjects with dRTA and SAO and the family members with SAO showed an approximate 40% reduction in sulfate influx with normal 4,4'-di-isothiocyanato-stilbene-2,2'-disulfonic acid sensitivity and pH dependence.

Conclusion. These findings suggest that compound heterozygosity of abnormal *AE1* genes causes autosomal recessive dRTA in SAO.

Southeast Asian ovalocytosis (SAO) is a hereditary condition that is widespread in parts of Southeast Asia and Melanesia. It has been shown that SAO results from a mutation in the red cell membrane band 3 or the anionic (HCO_3^-/Cl^-) exchanger 1 (AE1) [1, 2]. The N-terminal fragment of the abnormal band 3 migrates slower than normal in sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) [3]. Sequencing of the abnormal erythrocyte *AE1* gene in SAO showed that it contained two linked mutations: a deletion of codons 400 to 408 in the boundary of cytoplasmic and membrane domains and a point mutation in the first base of codon 56 (K56E), the Memphis I polymorphism [4].

Anion exchanger 1 is also found in the basolateral membrane of the type A intercalated cells of renal collecting ducts, which are involved in H^+ secretion [5, 6]. Studies of human kidneys have indicated that, although the protein in the basolateral membrane of type A intercalated cells is reactive toward monoclonal antibodies to the membrane transport domain of AE1 [6, 7], several antibodies to the cytoplasmic domain of AE1 are unreactive [6], which is consistent with renal AE1 being truncated at the NH_2 terminus [8]. A promoter that gives rise to these kidney transcripts is present in erythroid intron 3 of the human *AE1* gene [8, 9].

A defect in AE1 of the basolateral membrane of type A intercalated cells of the collecting duct may result in a failure to establish or maintain a cell-to-lumen H^+ gradient, and leads to distal renal tubular acidosis (dRTA) [5, 10]. Three studies and a review have shown that mutations of the *AE1* gene affect renal acidification [11–14]. There are at least two reports indicating an association between dRTA and hereditary elliptocytosis [15, 16], which is uncommon among Caucasians, but a related condition, SAO, is widespread in parts of Southeast Asia, with a prevalence reaching 30% in certain ethnic groups [17].

To examine the possibility that a defect in renal acidification may be associated with subjects with SAO, the renal acidification function and a detailed characterization of the *AE1* gene were studied in SAO individuals and members of two unrelated families with dRTA and

Key words: band 3 protein, anion exchanger 1, *AE1* gene, DNA sequencing, renal acidification.

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SAO. In this report, we describe a novel compound heterozygosity of mutated *AE1* genes in the subjects with SAO and dRTA, and an autosomal recessive mode of inheritance of the abnormal genes associated with the two combined defects.

METHODS

Subjects

The study population consisted of 20 individuals with SAO, two unrelated subjects with SAO and dRTA (as defined by a low rate of NH_4^+ excretion and an inability to lower the urine pH below 5.5 in the presence of systemic acidosis, $HCO_3^- < 20$ mEq/liter) and their family members and 11 individuals with normal red blood cell morphology living in the same region as the control subjects. All subjects were placed on a normal diet, and medications were terminated one week prior to the study. This investigation was approved by the Human Ethics Committee of the Prince of Songkla University, Thailand.

Clinical studies

Renal acidification was studied using a short acid loading by administration of 0.1 g/kg NH_4Cl, as previously described by Wrong and Davies [18], in 10 individuals with SAO, the two family members and seven normal control subjects; simultaneously, a chronic acid loading was achieved by administration of 0.1 g/kg/day NH_4Cl for three days with diuresis on the fourth day induced by furosemide (20 mg p.o.) [19] in another 10 individuals with SAO and four normal control subjects. To achieve urinary osmolality >800 mOsm/kg H_2O, intranasal 1-deamino-D-arginine vasopressin (DDAVP) was given after 16 hours of water deprivation [20].

Venous blood pH was measured using blood gas analyzer (model 178, Corning). The concentration of bicarbonate in plasma was calculated using the pK value of 6.10 and a solubility factor of 0.0301 [21, 22]. Analytical methods for determination of NH_4^+, sodium, potassium, chloride, creatinine, and osmolality were as previously described [23].

The clearance of creatinine provided an approximation of the glomerular filtration rate [24]. The transtubular K concentration gradient (TTKG) was calculated to reflect the driving force for K secretion [25].

Values were reported as mean ± SEM, and comparisons between groups were made by analysis of variance (ANOVA).

DNA analysis

Polymerase chain reaction primers. The sequence of *AE1* gene was retrieved from Entrez database (GenBank, NCBI). Nineteen pairs of polymerase chain reaction (PCR) primers were designed for amplifications of two overlapping regions in intron 3 (one for the potential kidney promoter and another for the possible 5' sequence of transcript expressed in kidney) and 17 regions in exons 4 to 20 of the *AE1* gene (Table 1). The primers for each exon would anneal to sequences in introns, flanking both sides of the exon. The sizes of PCR products obtained from amplifications using these primers were usually less than 400 bp, except those for the two regions in intron 3. These primers were synthesized by BioService Unit of the National Center for Genetic Engineering and Biotechnology (Biotec, Bangkok, Thailand).

DNA samples. Leukocyte genomic DNAs were prepared from 10 ml ethylenediaminetetraacetic acid (EDTA) blood samples by standard DNA extraction method, which consisted of steps of proteinase K digestion, phenol-chloroform extractions, and ethanol precipitation [26]. DNA samples were finally dissolved in sterile distilled water, and their amounts were estimated from absorbances measured by ultraviolet-visible spectrophotometer at wavelength 260. A small part of stock DNA sample was diluted to 50 ng/μl for using in PCR.

Polymerase chain reaction. Polymerase chain reaction was performed by mixing 125 ng DNA sample, 2.5 μl of 10 × buffer (Perkin-Elmer Cetus, Norwalk, CT, USA), 1.5 μl of 25 mM $MgCl_2$, 2.5 μl of 2 mM dNTP mix, 12.5 pmol each of forward (L) and reverse (R) primers, and 0.25 units of *Taq* polymerase (Perkin-Elmer Cetus) in a total volume of 25 μl. The reaction mixture was overlaid with one drop of mineral oil, and amplification was performed for 35 cycles in Thermal Cycler 480 (Perkin-Elmer Cetus). Each cycle was comprised of denaturation at 94°C for one minute (5 min for the first cycle), annealing at 58 to 70°C (depending on pair of primers; Table 1) for one minute, and extension at 72°C for one minute (5 min for the final cycle). After amplifications, PCR products were examined by running on 2% agarose gel electrophoresis and ethidium bromide staining.

Single strand conformational polymorphism (SSCP). Two microliters of the PCR product were mixed with 8 μl of sample running buffer (containing 95% formamide, 0.05% bromophenol blue, 0.05% xylene cyanol, 20 mM EDTA, and 10 mM NaOH). The mixture was heated at 95°C for 10 minutes to denature DNA into single strands and was then cooled on ice for five minutes before loading onto nondenaturing polyacrylamide gel. The polyacrylamide gel with the size of 90 × 80 mm and thickness of 1 mm contained 10% acrylamide:bis-acrylamide (49:1). Electrophoresis was run in 1 × TBE buffer at 20 mA for two to six hours at room temperature. Double-stranded DNA might also be run by mixing 2 μl of the PCR product with 8 μl sample running buffer (without 10 mM NaOH) and loading onto the same gel without heating.

After electrophoresis, the gel was fixed with 40% methanol for 10 minutes, soaked in 160 mM HNO_3 for

Table 1. Oligonucleotide primers for amplifications of the *AE1* gene

Exon	PCR primer sequence	Position	Annealing temp °C	Product size bp
Intron 3.1	5'-CAGTTTGGGACAAGGGCCTG-3'	6995–7014	67	491
	5'-TGATGAAGTGAAGGGACCTCTCC-3'	7463–7485		
Intron 3.2	5'-TGGGAGGAGAGAAGGGAGTCTG-3'	7364–7383	67	402
	5'-CGGTGTCGTGAGCTGAAAACC-3'	7745–7765		
Exon 4	5'-GTCTCTGAGGCTCACAGTGGATG-3'	7673–7695	63	226
	5'-ATCCCCTTGCTCCTCTCTTCC-3'	7878–7898		
Exon 5	5'-TGAGCACCCACTATGCCCTG-3'	8522–8541	63	299
	5'-CAGCACCCCACAACAATCCTC-3'	8800–8820		
Exon 6	5'-AGATGAGGATTGTTGTGCGGTG-3'	8796–8817	63	262
	5'-CAAGTGGGCTGGGGAAGTG-3'	9039–9057		
Exon 7	5'-CACCACTGATAGCTCAGCCTGAAC-3'	9407–9430	60	343
	5'-TGAGAAAGCTCTCTCCTTGCCC-3'	9628–9649		
Exon 8	5'-GAGAATGGGAAGGGGAGGATG-3'	9739–9760	60	244
	5'-GGTCCAGGCTGAGGGAAAGAC-3'	9963–9983		
Exon 9	5'-TCTTCAGCACACCCACCCTG-3'	9998–10017	60	299
	5'-TCAGCCACCATGCAGGTCC-3'	10278–10296		
Exon 10	5'-TCCTTTCCCTCCGCAGGTC-3'	10726–10744	58	332
	5'-ACAGAGGCTACGCTGAGGTGTC-3'	11036–11057		
Exon 11	5'-CCTCACCTCCTCCAGCTACTCC-3'	11163–11184	62	318
	5'-CAGAAGTTGGGGCTGAGACAGAG-3'	11458–11480		
Exon 12	5'-GCTCTATGGGCTCCTGGAAATG-3'	11529–11550	58	293
	5'-AAAGGGTCTTGGGGCAAGG-3'	11803–11821		
Exon 13	5'-CTGTCATGTCCCCCGCAC-3'	11765–11782	58	339
	5'-TGTCTCAGTCTTATACACAACCTCC-3'	12079–12103		
Exon 14	5'-TGGTGGTATTTTCCAGCCCAAG-3'	13484–13505	60	320
	5'-GCACTGAGGAATTTGGAGCGG-3'	13783–13803		
Exon 15	5'-AAGGCAGGAGGTGGGGAGTGACTG	14045–14078	70	201
	5'-GGAAATGAGGACCTGGGGGGTATC	14222–14245		
Exon 16	5'-TCCTGCTCCCACCCTTCCCC-3'	14673–14692	68	276
	5'-TCTGCCTCCCACCCTCCCAG-3'	14929–14948		
Exon 17	5'-TGGAGGAGGCAGGGGAGAAC-3'	15980–15999	70	347
	5'-GGGGCAGGAGGATGGTGAAG-3'	16307–16326		
Exon 18	5'-ATATGGTGCCTGTGTTTTATTCCC-3'	17705–17728	65	332
	5'-TGCCTATCACACCCCAGCAC-3'	18017–18036		
Exon 19	5'-GGTACAGGACCCTTTTCTGG-3'	17973–17992	60	334
	5'-GCCTGCCCTAGTTCTGAGAC-3'	18287–18306		
Exon 20	5'-TCTCACCCTGTCTCTCTCCTG-3'	18819–18839	65	198
	5'-GAGGTGCCCATGAACTTCTG-3'	18997–19016		

six minutes, washed with deionized water, and soaked in deionized water for five minutes. It was then stained in 0.2% $AgNO_3$ solution for 20 minutes with gentle shaking, washed with deionized water, and soaked in deionized water for five minutes. The $AgNO_3$ solution and washing water were pooled and added with a few drops of HCl to convert $AgNO_3$ to AgCl before discarding. The gel was soaked in developer containing 3% Na_2CO_3 and 0.0185% formamide in deionized water for 4 to 10 minutes. When DNA bands were clearly observed, a solution of 10% citric acid in deionized water was immediately added into the developer to stop the staining reaction. The SSCP pattern on the gel was recorded into a computer by scanning with a scanner. The gel was also dried on a piece of filter paper for long-term storage.

Mobility shift of single strand DNA from the normal pattern indicated the presence of a possible mutation. The PCR product of the exon that showed mobility shift was analyzed by direct DNA sequencing.

Direct DNA sequencing. To identify mutation in the exons of *AE1* gene observed in the PCR-SSCP analysis, the PCR product was purified from a preparative agarose gel and sequenced by manual direct DNA sequencing using Thermo Sequenase Cycle Sequencing Kit (Amersham Life Science Inc., Arlington Heights, IL, USA) or by an automated sequencing machine (ABI-PRISM™ 310 Genetic Analyzer; ABI, USA) using an ABI PRISM™ Dye Terminator Cycle Sequencing Ready Reaction Kit.

Red cell anion transport studies

^{35}S-SO_4 influx into red blood cells was measured in the two patients with SAO and dRTA and their family members, and normal controls in the presence and absence of the inhibitor, 4,4'-di-isothiocyanato-stilbene-2,2'-disulfonic acid (DIDS). The studies were performed at 37°C in buffer of 70 mM sodium citrate, 3 mM sodium sulfate, and 10 mM Tris, pH 7.4 [13].

Table 2. Renal acidification function after three days of NH_4Cl loading in individuals with Southeast Asian ovalocytosis (SAO) compared with controls

	SAO (N = 10)	Controls (N = 4)
Serum		
Creatinine *mg/dL*	0.9 ± 0.1	1.1 ± 0.1
K^+ *mM*	3.8 ± 0.1	3.7 ± 0.1
HCO_3^- *mM*		
Pre-acid loading	26 ± 0.8	27 ± 0.1
Post-acid loading	20 ± 0.7	20 ± 1.6
Venous pH		
Pre-acid loading	7.35 ± 0.02	7.37 ± 0.03
Post-acid loading	7.32 ± 0.01	7.29 ± 0.02
Urine		
C_{Cr} *ml/min*	93 ± 6	87 ± 9
pH		
Pre-acid loading	6.0 ± 0.1	6.0 ± 0.3
Post-acid loading	5.0 ± 0.1	4.9 ± 0.1
After furosemide	4.5 ± 0.1	4.4 ± 0.1
NH_4^+ *μmol/min*		
Pre-acid loading	22 ± 0.3	23 ± 4
Post-acid loading	65 ± 6	65 ± 4
After furosemide	75 ± 6	63 ± 7

Table 3. Renal acidification after short acid loading in individuals with Southeast Asian ovalocytosis (SAO) compared with controls

	SAO (N = 10)	Controls (N = 7)
Serum		
Creatinine *mg/dL*	1.1 ± 0.1	1.0 ± 0.2
K^+ *mM*	3.8 ± 0.04	3.9 ± 0.1
HCO_3^- *mM*		
Pre-acid loading	25 ± 0.7	25 ± 0.9
Post-acid loading	20 ± 0.6	22 ± 0.8
Venous pH		
Pre-acid loading	7.37 ± 0.02	7.35 ± 0.01
Post-acid loading	7.31 ± 0.05	7.30 ± 0.02
Urine		
C_{Cr} *ml/min*	83 ± 6	90 ± 14
pH		
Pre-acid loading	5.9 ± 0.1	5.6 ± 0.1
Post-acid loading	5.0 ± 0.1	4.9 ± 0.1
NH_4^+ *μmol/min*		
Pre-acid loading	28.6 ± 3	21.5 ± 6
Post-acid loading	39.4 ± 6	36.7 ± 4

RESULTS

Clinical studies

Renal acidification was performed in 20 individuals with SAO and the 11 controls. The NH_4^+ excretion rate and urine pH after a three-day NH_4Cl load are shown in Table 2. Neither subject groups (10 individuals vs. 4 controls) had a statistical significant difference in the NH_4^+ excretion rate (65 ± 6 vs. 65 ± 4 μmol/min) or urinary pH (5.0 ± 0.1 vs. 4.9 ± 0.1) following the acid load. After diuresis with oral furosemide on the fourth day of the acid load, the urinary pH decreased significantly in both groups, but there was no significant difference between the two groups (4.5 ± 0.1 vs. 4.4 ± 0.1). The increment of NH_4^+ excretion during the peak diuresis was not significantly different between the two groups (75 ± 6 vs. 63 ± 7 μmol/min). The maximum urine osmolality after 16 hours of water deprivation and intranasal DDAVP administration was also not significantly different between the two groups (940 ± 41 vs. 850 ± 46 mOsm/kg/H_2O).

Table 3 provides a summary of the results of urinary acidification studies after the short acid load. Blood pH values after the acid loading of 10 SAO and 7 control subjects were less than 7.35. Urine pH and NH_4^+ excretion rate after the acid load between both groups were not significantly different (5.0 ± 0.1 vs. 4.9 ± 0.1 and 39 ± 6 vs. 37 ± 4 μmol/min, respectively)

Pedigrees (KSN and YAT) of two subjects with SAO and dRTA are shown in Figure 1. Propositi (II-1 in both families) presented with history of growth retardation, SAO, and hypokalemia (Table 4). Complete dRTA was diagnosed by low NH_4^+ excretion rate in both propositi (3.3 and 4.3 μmol/min, respectively) as well as by the inability to lower the urine pH below 5.5 (7.3 and 6.7, respectively) in the presence of metabolic acidosis (venous pH 7.26 and 7.27 and serum HCO_3^- 9 and 14 mEq/liter, respectively). No abnormal renal acidification was detected in both sets of parents (I-1 and I-2).

Screening and characterization of AE1 gene mutations

Polymerase chain reaction-SSCP analysis was used to screen for mutations in exons 4 to 20 of the *AE1* gene and in intron 3, the promoter region of the kidney isoform. DNA samples from the propositi, siblings, as well as the parents of the two families were also analyzed. Figure 1 shows the results of PCR-SSCP analysis for exons 11 and 17 of one normal individual (N) and members of the two families. In the YAT family, the father (I-1) showed a mobility shift in exon 17, and the mother (I-2) showed a mobility shift in exon 11. In the KSN family, the father (I-1) demonstrated a mobility shift in exon 11, whereas the mother (I-2) showed a shift in exon 17. The DNA samples of both KSN and YAT families revealed mobility shifts in both exons 11 and 17. Except for a mobility shift of exon 4 (caused by the MspI polymorphism, confirmed by sequencing; Fig. 5), the PCR-SSCP patterns of all other exons, including intron 3, were normal (data not shown).

Because the mobility shifts of exons 11 and 17 of *AE1* gene detected by PCR-SSCP in the two patients were the same, amplified DNA of these two exons from the propositus of KSN family were sequenced. Exon 11 had a deletion of 27 bp corresponding to codons 400 to 408 (Fig. 2), whereas exon 17 contained a nucleotide substitution of G to A in codon 701 (CGG→CAG), resulting in an amino acid change from glycine to aspartic acid (G701D) (Fig. 3). Thus, the *AE1* gene of the propositi of

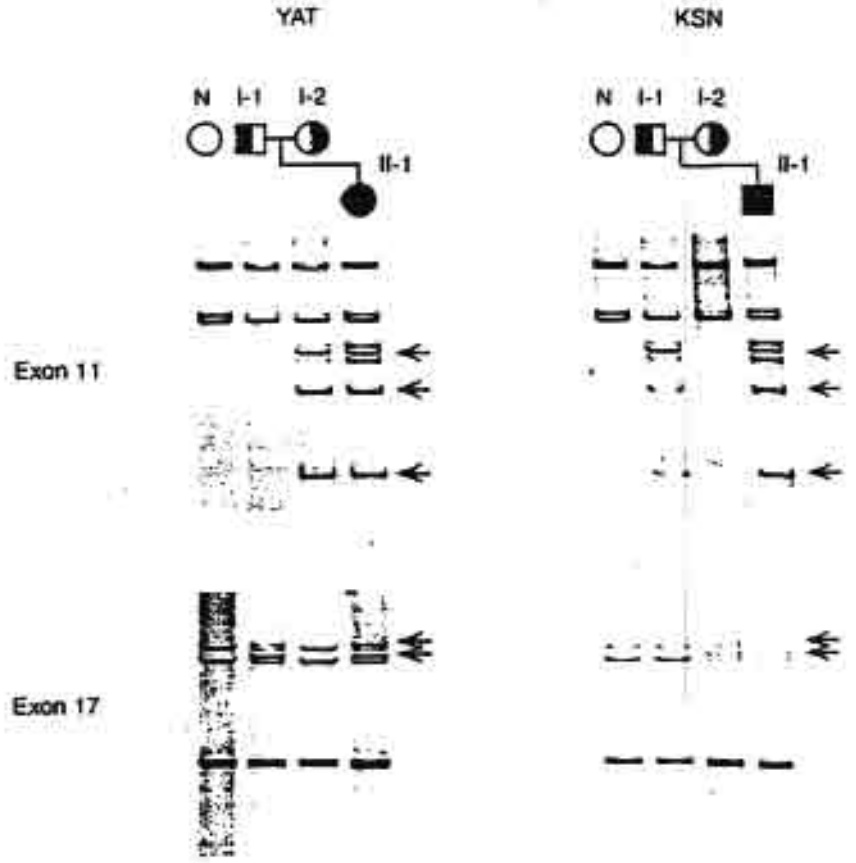

Fig. 1. Screening of mutations in exons 11 and 17 of the *AE1* gene in the two patients with Southeast Asian ovalocytosis (SAO) and distal renal tubular acidosis (dRTA) and their parents by the PCR-SSCP technique. The two patients (II-1 in both families) had mobility shifts of single-stranded DNAs in both exons 11 and 17 (arrows), whereas their parents had the mobility shifts in either exon 11 (I-2 in family of YAT and I-1 in family of KSN) or exon 17 (I-1 in family of YAT and I-2 in family of KSN). "N" is normal individual.

Table 4. Values in blood and urine collections from the two patients with SAO and dRTA

	KSN: II-1	YAT: II-1
Serum		
Creatinine *mg/dL*	0.5	0.6
BUN *mg/dL*	13	13
Na^+ *mM*	137	141
K^+ *mM*	3.3	3.4
Cl^- *mM*	116	111
HCO_3^- *mM*	8.7	14
Venous pH	7.26	7.27
Urine		
TTKG	10.4	10.3
Flow rate *ml/min*	0.4	0.8
pH	7.3	6.7
NH_4^+ *μmol/min*	3.3	4.3

Abbreviations are: SAO, Southeast Asian ovalocytosis; dRTA, distal renal tubular acidosis; BUN, blood urea nitrogen; TTKG, transtubular K^+ concentration gradient.

both families was a compound heterozygosity of 27 bp deletion in exon 11 and missense mutation (CGC→CAG) in exon 17. The sequencing results also showed the presence of homozygous band 3 Memphis I (Fig. 5) in the two patients. The presence of exon 11 deletion and exon 17 missense mutation in both patients was also confirmed by the detection of a shorter PCR product and elimination of *HpaII* restriction site on the amplified DNA, respectively, by gel electrophoresis (Fig. 4). Mutations of *AE1* gene were also analyzed by PCR-SSCP method in 20 individuals with SAO and in normal subjects. SAO individuals had mobility shifts in exons 4 and 11.

Anion transport property of the red cells of the two families

An influx of [^{35}S] sulfate into the red cells of members of the two families was compared with that of red cells from 10 normal controls taken at the same time. Red cell samples from the propositi of the KSN and YAT families and family members with SAO showed a consistently lower anion transport activity than the normal samples in both the presence and absence of DIDS (Table 5). Family members with only the exon 17 mutation had normal anion transport and DIDS activity.

DISCUSSION

Mutation of the *AE1* gene in SAO has been the subject of a number of studies [1, 4, 27]. The underlying molecular defect is a 27 bp deletion in exon 11 of the *AE1* gene, resulting in the loss of 9 amino acids (codons 400 to 408) in the band 3 protein, which is also associated with the

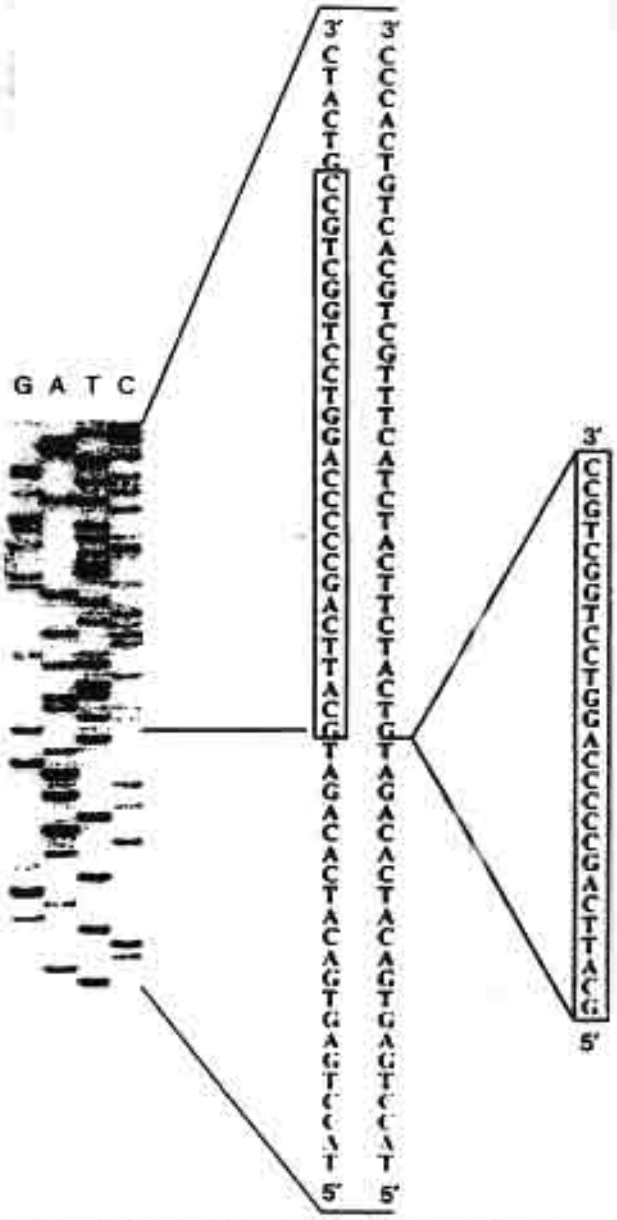

Fig. 2. Sequencing analysis of exon 11 of the *AE1* gene in the patient with dRTA and SAO (II-1, family of KSN), showing nucleotide sequence of exon 11 with 27 nucleotide deletion superimposing the normal sequence. Identical 27 nucleotides in the normal and deleted alleles (the latter is separated from the nucleotide stretch) are blocked. The deletion of 27 nucleotides in one allele resulted in shifting of the remaining nucleotide sequence superimposing the normal sequence in the autoradiogram.

Memphis I (K56E) polymorphism. Although SAO occurs with high frequency in parts of Southeast Asia and Melanesia, no homozygous individual for the *AE1* mutation has been identified, suggesting that homozygosity for this mutation may be lethal [1].

Anion exchanger 1 in red cells is important for the transport of carbon dioxide from the tissue to the lung and for acid secretion in type A intercalated cells of the kidney [28]. Total deficiency of red cell band 3 caused by a nonsense mutation has been reported in cattle [29]. Animals showed a moderate uncompensated anemia with hereditary spherocytosis and retarded growth, which was attributed to mild acidosis. The band 3-deficient animals had defective renal acid secretion and could not acidify urine pH below 7.5 despite metabolic acidosis. In dRTA, acid secretion in the distal nephron is impaired, leading to the development of metabolic acidosis [10, 30]. Recently, several studies have demonstrated associations of the *AE1* mutations and dRTA: Rysava et al reported that 2 out of 10 patients with hereditary spherocytosis and band 3 PRIBRAM (G—A in the first nucleotide of intron 12) had an incomplete form of dRTA [14]; Bruce et al reported an association between familial dRTA and point mutations of the *AE1* gene, namely, R589H, R589C, and S613F [12]. The *AE1* mutation, R589H, has also been reported in two other studies [13, 31]. An intragenic 13 bp duplication resulting in deletion of the last 11 amino acids of *AE1* gene in one dRTA subject has also been demonstrated [31]. Mutations in the *AE1* gene appear to cause autosomal dominant dRTA [12, 13, 31], but the molecular mechanism is unknown.

There have been two previous studies showing the association between dRTA and elliptocytosis or SAO [15, 16]. The presence of the two conditions in the same individuals suggests that there may be a common underlying molecular defect. However, mutation of the *AE1* gene in individuals with both of these conditions was not demonstrated. In this study, 20 individuals with SAO, confirmed by the presence of 27 bp deletion in exon 11 of the *AE1* gene, showed no abnormal renal acidification following the three-day NH_4Cl loading ($N = 10$; Table 2) or by short acid loading ($N = 10$; Table 3). The rate of excretion of NH_4^+ increased by almost threefold, and the urine pH decreased below 5.0 after three-day acid loading and during the furosemide-induced diuresis to typical values of normal subjects [19]. This suggests that the rate of production of NH_4^+ in the proximal tubular cells was not appreciably depressed. Thus, SAO mutation of the *AE1* gene in the heterozygous condition is not sufficient to cause dRTA.

The two clinically affected unrelated patients in the KSN and YAT families with dRTA and SAO showed a low rate of NH_4^+ excretion and an inability to lower the urine pH below 5.5 in the presence of systemic acidosis (Table 4). There was also a high transtubular $[K^+]$ gradient (TTKG) [25] given the degree of hypokalemia. No abnormal renal acidification was detected in either set of parents. Analysis of *AE1* gene mutation by PCR-SSCP method showed that the two patients (II-1 in both families) had the same mobility shifts in exons 11 and 17, whereas the parents had mobility shift in either exon

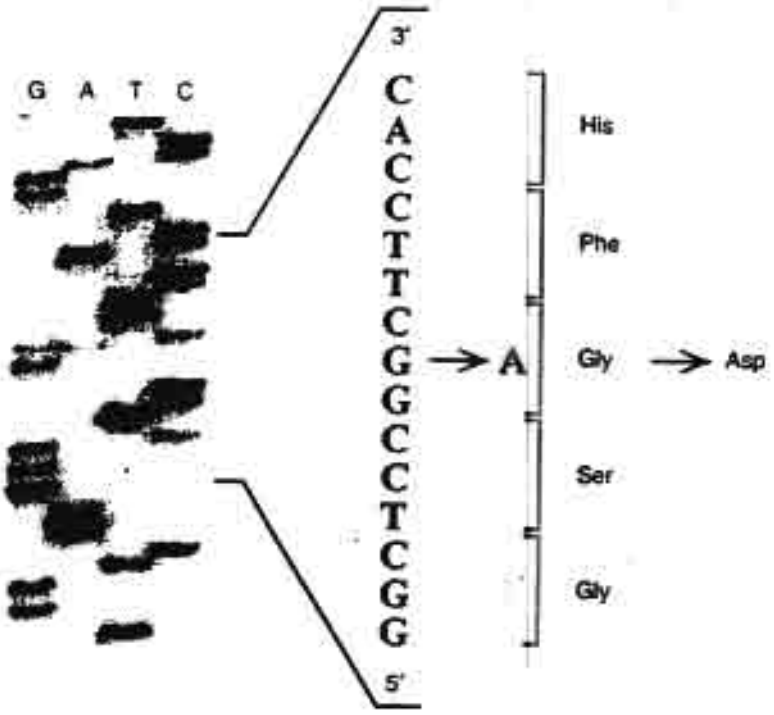

Fig. 3. Sequencing analysis of exon 17 of *AE1* gene in the patient with SAO and dRTA (II-1, family of KSN). A substitution from G to A in the second nucleotide of codon 701 was observed. This substitution results in missense mutation changing the amino acid at the position 701 from glycine to aspartic acid (G701D).

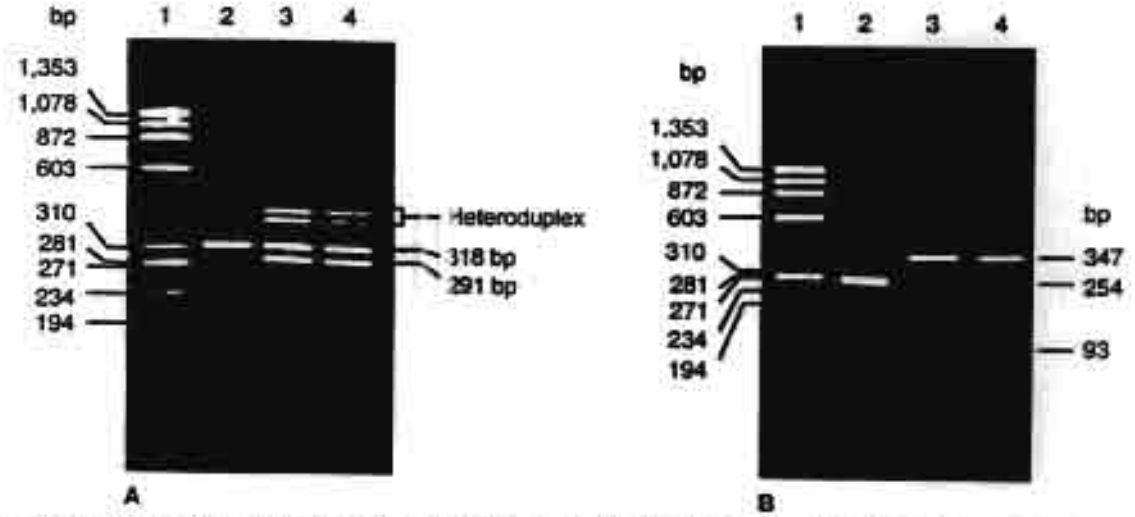

Fig. 4. Detection of exon 11 deletion and exon 17 (CGG→CAG) missense mutation in the patients (II-1) of KSN and YAT families by agarose gel electrophoresis. (*A*) PCR products from amplifications of exon 11 of *AE1* gene with AE1Ex11L/AE1Ex11R primers. Normal control sample (lane 2) showed only a PCR product with the size of 318 bp. DNA samples from the patients of the KSN (lane 3) and YAT (lane 4) families who had 27 bp deletion in exon 11 in one allele of the *AE1* gene resulted in PCR products with the sizes of 318 and 291 bp, and also their heteroduplexes. (*B*) PCR products from amplifications of exon 17 with AE1Ex17L/AE1Ex17R primers and digestions with *Hpa*II restriction endonuclease, which could digest the normal (CCGG) but not the mutant (CCAG) sequences. A normal control sample (lane 2) showed digested fragments with the sizes of 254 and 93 bp. DNA samples from the patients of the KSN (lane 3) and YAT (lane 4) families who had exon 17 missense mutation in one allele of the *AE1* gene revealed both digested (254 and 93 bp) and undigested (347 bp) PCR products. Lane 1 in both sets is Phix174 DNA/*Hae*III markers.

11 (I-2 in family YAT and I-1 in family KSN) or exon 17 (I-1 in family YAT and I-2 in family KSN; Fig. 1). DNA sequencing (Figs. 2 and 3) and gel electrophoresis (Fig. 4) revealed that exon 11 contained a 27 bp deletion typical of SAO [4] and exon 17 had a single nucleotide substitution of G to A in the second nucleotide of codon 701 (CGG→CAG), resulting in a G701D missense mutation. This is the first report of a compound heterozygosity

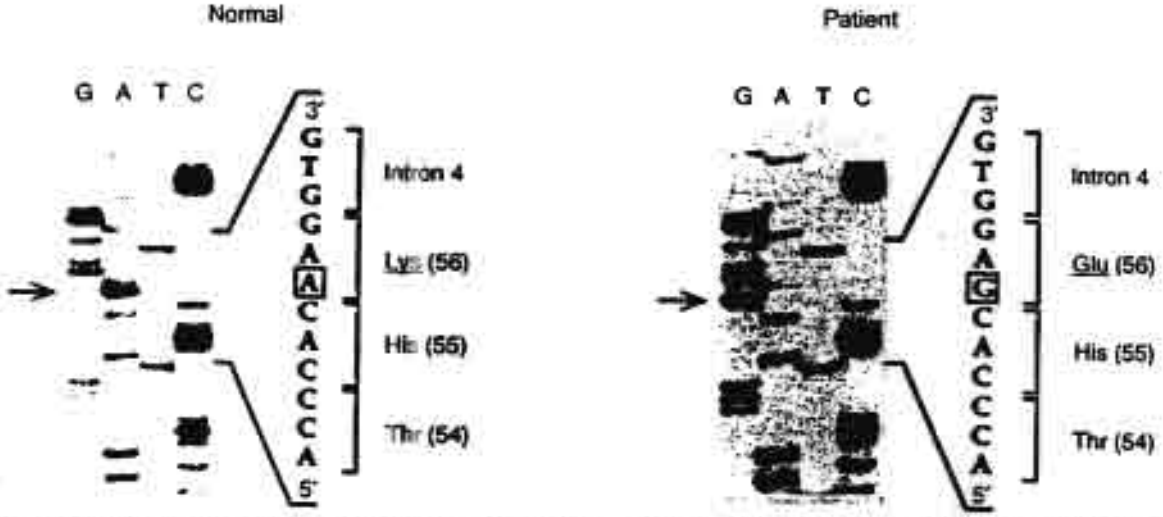

Fig. 5. Sequencing analysis of exon 4 of the *AE1* gene in a normal individual and the patient with SAO and dRTA (II-1, the family of KSN). The normal individual had AAG (code for lysine), but the patient had GAG (code for glutamic acid) at codon 56. The band 3 variant that had glutamic acid at the position 56 was previously described as band 3 Memphis I. The patient who had the 27 bp deletion in exon 11 and the G→A substitution in codon 701 in exon 17 was homozygous for band 3 Memphis I. Therefore, these two mutations were linked to band 3 Memphis I polymorphism.

Table 5. Characterization of [^{35}S]SO_4 influx into red cells from members of families of YAT and KSN, compared with healthy control cells

	Genotype	Phenotype	SO_4 uptake *10–17 mol/min/cell*		
			No DIDS	1.5 μM DIDS	%
YAT family					
I–1	G701D		6.45	2.12	32.9
I–2	Ex 11Δ27	SAO	4.78	0.08	1.7
II–1	Ex11Δ27/G701D	SAO + RTA	4.77	0.13	2.7
KSN family					
I–1	Ex 11Δ27	SAO	3.57	1.48	24.1
I–2	G701D		6.56	2.35	35.8
II–1	Ex11Δ27/G701D	SAO + RTA	4.03	0.15	3.7
Controls			6.0 ± 0.8		

for *AE1* mutations associated with SAO and dRTA, to our knowledge. The sequencing results also showed the presence of homozygous band 3 Memphis I (Fig. 5) in the two patients, indicating that the two mutations linked with band 3 Memphis I polymorphism. Studies of the influx of [^{35}S] sulfate into red cells of the two patients and their family members with SAO indicated a consistently lower anion transport activity than the normal red cells (Table 5). Individuals with exon 17 mutation had normal red cell anion transport activity.

Glycine 701 is located at the beginning of membrane span 9 of band 3, which is in a highly conserved region in the AE protein family across several species [28], which indicates its structural or functional importance. Although the presence of both SAO and G701D mutations had no additional affect on the influx of [^{35}S] sulfate into red cells than the presence of the SAO mutation alone, the HCO_3^-/Cl^- anion exchanger activity in the type A intercalated cells of the renal collecting duct in individuals with the combined mutations may be abnormal. Two siblings with dRTA and hemolytic anemia have recently been found to carry a homozygous G701D missense mutation of the *AE1* gene, which causes recessively transmitted dRTA in this kindred with apparently normal erythroid anion transport in the parents and affected children [32].

An expression study of the G701D mutation in *Xenopus* oocytes has shown that the mutant protein was not transported to the surface of the cell membrane [32]. However, when it was co-expressed with glycophorin A, the erythroid band 3 chaperonin, both AE1 surface expression and AE1-mediated Cl^- transport were rescued. This suggests that the G701D mutation may lead to decreased or absent AE1 accumulation at the basolateral membrane of the type A intercalated cells in the collecting duct. Therefore, the presence of both SAO and G701D mutations would have a greater effect to the type A intercalated cells than the presence of either mutation alone.

and this would explain the abnormal urinary acidification in the patients with the compound heterozygosity.

Although mutations of the *AE1* gene have been reported to be associated with autosomal dominant dRTA [12, 13, 31], the presence of the compound heterozygosity of *AE1* mutations associated with SAO and dRTA shown in our study, and of homozygosity of AE1 mutation associated with dRTA and hemolytic anemia in that of Tanphaichitr et al [32] indicate an autosomal recessive mode of inheritance.

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Cleavage of DNA Induced by 9-Anilinoacridine Inhibitors of Topoisomerase II in the Malaria Parasite *Plasmodium falciparum*

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Due to resistance by *Plasmodium falciparum*, the most virulent strain of the four species of human malaria parasites, to most currently used antimalarial drugs, development of new effective antimalarials is urgently needed. Derivatives of 9-anilinoacridine, an antitumor drug, have been shown to inhibit *P. falciparum* growth in culture and to inhibit parasite DNA topoisomerase II activity *in vitro*. Using KCl–SDS precipitation assay to detect the presence of protein–DNA complexes within parasite cells, an indicator of DNA topoisomerase II inactivation, derivatives containing 3,6-diNH, substitutions with 1′-electron donating (NMe_2, CH_2NMe_2, $NHSO_2Me$, OH, OMe), and 1′-electron withdrawing (SO_2NH_2) groups produced protein–DNA complexes. However, the antimalarial pyronaridine, 9-anilinoazaacridine, did not generate protein–DNA complexes, although it was capable of inhibiting *P. falciparum* DNA topoisomerase II activity *in vitro*. These results should prove useful in future designs of novel antimalarial compounds directed against parasite DNA topoisomerase II. © 2000 Academic Press

Malaria is one of the most prevalent of human parasitic diseases caused by unicellular organisms. Approximately 300 million people worldwide are affected by malaria and between 1 and 1.5 million people, mostly children in sub-Sahara Africa, die every year from the disease (1). The most virulent malaria parasite, *Plasmodium falciparum*, has become widely resistant to nearly all currently employed antimalarials and new drugs are urgently needed (2). As the malaria parasite divides rapidly within the host red cell, DNA replicating enzymes offer suitable key targets for new antimalarial drugs.

Antimicrobial and anticancer therapeutic agents have recently been synthesized and employed against DNA topoisomerases (3–5). Topoisomerases are essential for the modification of topology of nucleic acids. One important function that the enzymes perform is to transiently cleave a phosphodiester bond in DNA, and then transfer a segment of another DNA strand through the break before resealing. DNA topoisomerases are divided into two types: type I enzyme breaks one DNA strand for the passage of a second strand, and the type II enzyme breaks both strands of one DNA duplex for the passage of a second DNA double strand (4, 6–10). DNA cleavage is a transesterification reaction, and a covalent protein–DNA intermediate is formed during the transient DNA cleavage stage. This covalent topoisomerase II–DNA complex can be trapped *in vitro* by the addition of a protein denaturant such as sodium dodecyl sulfate (SDS) and is termed a cleavable complex (11, 12).

Topoisomerase inhibitors act by stabilizing the covalent topoisomerase–DNA complexes with an enzyme-linked DNA break on a single strand or both strands (13). The trapping of such cleavable complexes prevents enzyme turnover and hinders the reclosure of DNA breaks. This enhances DNA cleavage levels in living cells (13, 14). Drug-promoted DNA–protein adducts have proven extremely valuable because they provide a simple method to detect the existence of inhibitor-sensitive topoisomerase activity within cells and a means for assaying inhibitor potency *in vivo* (15, 16).

9-Anilinoacridine derivatives have well described biological actions and many have been used successfully to treat different forms of leukemia (17). The mammalian topoisomerase II is the intracellular target of these drugs, which stabilize the cleavable complexes (18, 19). Cell death is dependent on the formation of these cleavage complexes, resulting in DNA damage, rather than from loss of topoisomerase II activity per se (15). Available evidences support a model whereby the acridine moiety intercalates into DNA and the 9-anilino side group projects into the DNA minor groove where it

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interacts with the enzyme (20). The antitumor activity of 9-anilinoacridines is significantly affected by alterations to the chemical groups on the 9-anilino moiety, presumably due to changes to their contact with the enzyme. Thus moving the 3'-OMe group of the clinical antileukemic drug, amsacrine, to the 2'-position abolishes activity (21).

These observations led us to seek 9-anilinoacridine compounds with specificity for topoisomerase II in other organisms, by modifying the substituents on the anilino moiety. Consistent with this notion, a series of 9-anilinoacridines were synthesized with varied anilino substituents which showed differences in structure-activity relationship against *P. falciparum* and human Jurkat leukemia cells (22). Previous studies have identified 3,6-diamino substitution on the acridine ring as greatly increasing drug potency against malaria parasite *in vitro* (23, 24). However these results do not prove that these compounds actually inhibit the target, DNA topoisomerase II, within the malaria parasite. We have, therefore, taken advantage of the ability of topoisomerase II inhibitors to generate *in situ* enzyme–DNA adducts (the so-called cleavable complexes) to examine the ability of a series of antimalarial 9-anilinoacridines, including pyronaridine (an azaacridine), to reach their putative parasite target.

MATERIALS AND METHODS

Parasite culture. *Plasmodium falciparum* K1 (chloroquine- and pyrimethamine-resistant) was isolated in 1979 from an infected individual in Kanchanaburi province, Thailand (25) and was maintained under continuous culture *in vitro* using the candle jar method of Trager and Jensen (26).

In vitro assessment of antimalarial activity. *In vitro* antimalarial testing of drugs against *Plasmodium falciparum*-infected erythrocytes was a modification of the [^{3}H]-hypoxanthine incorporation method of Desjardins *et al.* (27). In brief, unsynchronized parasite culture with mostly ring stages was used. Drugs were initially dissolved in dimethyl sulfoxide (DMSO) and diluted with RPMI 1640 culture medium supplemented with 25 mM Hepes buffer, 32 mM $NaHCO_3$, and 10% human serum to the required concentrations, with a final concentration of DMSO not exceeding 0.01% (v/v). A 200-μl aliquot of 1.5% cell suspension with 1.0% parasitemia was preexposed to 25 μl of the medium containing drug for 24 h in 96-well tissue culture plate and incubated at 37°C prior to the addition of 0.5 μCi [^{3}H]hypoxanthine (specific activity = 28.0 Ci/mmol, Amersham) in 25 μl of medium. After further incubation for 18–24 h, parasite DNA was harvested from each microtiter well onto filter paper (Whatman grade 934 AH) using an automated sample harvester. [^{3}H]-hypoxanthine incorporation in each well was determined in a Beckman liquid scintillation counter model LS-1801. The IC_{50} values (concentrations of drug to inhibit parasite growth by 50%) were obtained from the dose–response curves. Each drug concentration was investigated in triplicate.

KCl–SDS precipitation assay of protein–DNA complex. Parasite culture was synchronized to yield ring stage (5.0% parasitemia and 1.5% cell suspension) (28). A 0.3 ml aliquot of this mixture (50% cell suspension, 5.0% parasitemia) was added to 9.7 ml of complete medium. This cell suspension was then dispensed into 60 × 15 mm plastic culture petri dish. One μCi of [^{3}H]hypoxanthine (specific activity = 28.0 Ci/mmol, Amersham) was added to each culture dish which was incubated in a candle jar at 37°C for 18 h. Formation of topoisomerase II–DNA covalent complexes was quantitated using the KCl–SDS precipitation assay (12). Infected erythrocytes were treated for 4 h with drugs (IC_{50} concentration); negative control was a parasite suspension without drug. Erythrocytes were sedimented and washed once with phosphate-buffered saline (PBS: 137 mM NaCl, 2.7 mM KCl, 10 mM Na_2HPO_4, 1.8 mM KH_2PO_4, pH 7.4). Parasites were liberated by adding 0.15% (v/v) saponin in PBS at room temperature for 15 min, and then were sedimented by centrifuging for 10 min at 2000 *g* and washed with PBS. The parasite pellet was lysed by adding 500 μl of prewarmed lysis solution (1.25% SDS, 5 mM EDTA, 0.5 mg/ml salmon sperm DNA, pH 8.0, 65°C). The suspension was vortexed vigorously and heated to 65°C for 10 min with occasional mixing. One sample was resuspended in 3 ml of cold 325 mM KCl, and a duplicate in 10% TCA. Precipitates were collected by a minicell harvester onto Whatman grade 934 AH paper filter discs and washed with either 325 mM KCl or 10% TCA solution. The filter discs were dried and radioactivity incorporated counted as described above. The amount of protein–DNA complex formed was reported as percent radioactivity in KCl-precipitated pellet compared to TCA-precipitated sample.

RESULTS AND DISCUSSION

We have previously shown that analogs of 9-anilinoacridines inhibited the growth of *P. falciparum* K1 strain in culture (22–24). Studies using partially purified *P. falciparum* DNA topoisomerase II indicated that these compounds could also inhibit parasite enzyme activity as determined by a decatenation assay. Whether topoisomerase II was primarily the target of 9-anilinoacridines within the parasite was unclear. To obtain evidence for inhibition by 9-anilinoacridines of parasite topoisomerase II *in situ* the formation of topoisomerase II–DNA cleavable complexes (protein-linked DNA breaks) was evaluated by using a KCl–SDS assay (12).

The 9-anilinoacridine derivatives employed were selected from our previous study (22), choosing both those that are highly effective and others less effective in inhibiting malaria parasite growth in culture. These compounds can also be divided into two groups on the basis of their minimum inhibitory concentration (MIC) against *P. falciparum* topoisomerase II. One group consists of compounds (7c, 7e, 7i, 7j, and 7n) that have low MIC values (6–12.5 μM) and contain C-3,6-acridine ring substitution with amine moiety (see Table 1). The other group, which have compounds with higher MIC values (50–100 μM), contains one compound (7d) with a C-3,6-diamino-acridine ring substitution and two compounds containing other substituents (3,6-dichloro (22n) and 3,6-diazido (17r)) at these positions. In addition, two anticancer drugs that act by stabilizing covalent enzyme-cleaved DNA complexes (amsacrine and etoposide) and the two other currently used antimalarial agents (chloroquine and pyronaridine) were included in the study.

Because the compounds tested do not affect the parasites equally, quantitation of cleavable complex formation was conducted at the IC_{50} value of each drug.

TABLE 1

Effects of 9-Anilinoacridines and Other Drugs on *Plasmodium falciparum* Growth *in Vitro* and Formation of Cleavable Complex *in Situ*

Compound	Acridine substituent	Anilino substituent	IC_{50} (μM)[a]	Percent precipitated DN.
7c	3,6-diNH$_2$	1′-NMe$_2$	0.034	18.0 ± 1.4[b]
7d	3,6-diNH$_2$	1′-CH$_2$NMe$_2$	0.04	11.2 ± 1.6[b]
7e	3,6-diNH$_2$	1′-NHSO$_2$Me	0.03	22.7 ± 3.0[b]
7i	3,6-diNH$_2$	1′-OH	0.05	18.0 ± 1.7[b]
7j	3,6-diNH$_2$	1′-OMe	0.15	13.8 ± 1.8[b]
7n	3,6-diNH$_2$	1′-SO$_2$NH$_2$	0.02	12.1 ± 2.9[b]
17r	3,6-diN$_3$	1′-CONH$_2$	0.06	5.2 ± 1.2
22n	3,6-diCl	1′-SO$_2$NH$_2$	6.2	8.9 ± 1.7
Amsacrine	H	1′-NHSO$_2$Me 3′-OMe	3.2	14.7 ± 0.5[b,c]
Etoposide			31	17.3 ± 2.1[b,c]
Chloroquine			0.59	2.1 ± 0.2
Pyronaridine			0.003	6.4 ± 1.2
None				4.1 ± 1.2

[a] Concentration of drug to reduce incorporation of [^{3}H]hypoxanthine by *P. falciparum* K1 by 50%.
[b] Statistically significantly different from nodrug control, $P < 0.01$, $n = 3$.
[c] Measured at IC_{90}.

Table 1 clearly demonstrates that 9-anilinoacridine derivatives with 3,6-diamino substituents were inhibiting *P. falciparum* growth by targeting parasite topoisomerase II *in situ*. The nature of the 1′-anilino substituents (electron donating: 7c, 7e, 7i, 7j; and electron withdrawing: 7n) had little effect on the amount of DNA precipitation (cleavable complex) although compound 7d, without such a group, produced the least product. Compound 7d was the least effective drug among the group in inhibiting *P. falciparum* topoisomerase II *in vitro* (MIC = 50 μM) (22). Comparable yields of cleavable complexes for the six derivatives of 3,6-diamino-9-anilinoacridine indicated that the drugs acted by binding to DNA, and that differences in their IC_{50} values against *P. falciparum* growth reflected variation in uptake efficiency and cytotoxicity. Alterations of the acridine moiety have been reported to affect mammalian cell cytotoxicity and DNA binding affinity similarly, but modifications of the anilino group alter cytotoxicity without affecting DNA binding (20).

On the other hand, derivatives with 3,6-diN$_3$ (17r) and 3,6-diCl (22n) substitutions could not stimulate DNA-protein covalent adduct formation, even when the drug concentrations were raised to IC_{90} values (data not shown), consistent with their insensitivity to inhibition of parasite DNA topoisomerase II *in vitro*. These anilinoacridine analogs may be acting at other targets within the malaria parasite. It has been suggested that the azido derivative could be a prodrug, in which case its metabolite need not affect DNA topoisomerase II (22).

The antitumor drugs, amsacrine and etoposide, have been shown to stimulate the formation of cleavable complex formation in mammalian cells (11, 29). However, these drugs are not effective against *P. falciparum* topoisomerase II (MIC = 1000 μM) and treatment with IC_{90} levels was required to produce significant amounts of cleavable complex formation within the parasites.

As expected the antimalarial drug chloroquine failed to stabilize topoisomerase II–DNA complex. Chloroquine is known to inhibit malaria parasite heme polymerization activity (30).

Pyronaridine, which has 1′-OH and two pyrrolidine residues on an anilino ring attached to a benzonaphthyridine nucleus, is effective for treatment of chloroquine-resistant *P. falciparum* (31). Its IC_{50} value against *P. falciparum in vitro* is 0.003 μM with MIC against topoisomerase II of 11 μM (23). Surprisingly it failed to show inhibitory activity against *P. falciparum* topoisomerase II *in situ*. Studies of pyronaridine on *P. falciparum* ultrastructure revealed that the earliest and most distinct changes induced by the drug occurred in the parasite food vacuole (32). Recently it has been demonstrated that pyronaridine exhibits *in vitro* heme polymerization inhibitory property (33).

The 9-anilinoacridine analogs with C-3,6-diamino ring substitution have proven to be superior to the 3,6-diCl and 3,6-diN$_3$ derivatives both in terms of biological activity and toxicity toward parasite topoisomerase II. However, as this study has shown, it is not possible to predict *a priori* that inhibition of *Plasmodium falciparum* topoisomerase II *in vitro* necessarily indicates that this is indeed the target *in situ*. Inhibitors that act against malaria parasite topoisomerase II both *in vitro* and *in vivo* can be identified based upon the additional demonstration of their ability to generate *in situ* cleavable complexes. Such knowledge will be of assistance in the design of future antimalarial drugs based on the 9-anilinoacridine structure.

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Inactivation of Artemisinin by Thalassemic Erythrocytes

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ABSTRACT. *Plasmodium falciparum* infecting α-thalassemic erythrocytes (Hb H or Hb H/Hb Constant Spring) is resistant to artemisinin derivatives. Similar resistance, albeit at a much lower level, is shown by the parasite infecting β-thalassemia/Hb E erythrocytes. The resistance is due to host-specific factors, one of which is the higher uptake of the drugs by thalassemic erythrocytes than normal erythrocytes, due to binding with Hb H. In addition to higher drug binding, incubation of artemisinin with α-thalassemic erythrocytes resulted in preferential inactivation of the drug. Both thalassemic and normal erythrocytes have the capability to inactivate the drug. Addition of serum can protect against inactivation by normal erythrocytes, but not by thalassemic erythrocytes. Incubation with either the hemolysate or the membrane fraction from these erythrocytes also resulted in preferential inactivation of the drug. The drug was also inactivated by purified Hb H. It is concluded that the ineffectiveness of artemisinin derivatives against *P. falciparum* infecting thalassemic erythrocytes is due partly to competition of the host cell components for binding with the drugs, and partly to inactivation of the drugs by the cell components. BIOCHEM PHARMACOL 59;11:1337–1344, 2000. © 2000 Elsevier Science Inc.

KEY WORDS. *Plasmodium falciparum*; malaria; thalassemia; artemisinin; erythrocytes; artemisinin inactivation

Falciparum malaria continues to afflict increasing millions across the tropical latitudes of the world. It remains one of the most lethal and widespread diseases due to the emergence of parasites resistant to most available antimalarial drugs [1]. Artemisinins, highly effective antimalarial drugs derived from *Artemisia annua* Linn., have played an important role for many years in the treatment of these resistant parasites, with no significant occurrence of resistance as yet [2]. *In vitro* evidence for artemisinin resistance was found when α-thalassemic erythrocytes, both Hb H[1] and Hb H/Hb CS, with genotypes of α-thal1/α-thal2 (--/-α) and α-thal1/Hb CS (--/α^{cs}α), respectively, were used as parasite hosts [3–5]. Similar reduction in artemisinin sensitivity of the parasite was also found in the old cell fractions of α-thal trait (αα/-α) and β-thal trait erythrocytes, compared with the same cell fraction of normal erythrocytes [6]. This host-dependent artemisinin resistance may be of epidemiological significance, since α-thalassemic genes are found in malaria endemic areas, and, thus, are potential sources of drug resistance [7]. Therefore, it is important to understand the factors responsible for this host-dependent artemisinin resistance.

We have shown previously that the apparent artemisinin resistance of *Plasmodium falciparum* infecting α-thalassemic erythrocytes is due mainly to the higher capacity of uninfected α-thalassemic erythrocytes for drug accumulation as compared with that of genetically normal erythrocytes [4]. This phenomenon results in depletion of the drug from the parasite environment. Subsequently, we showed that Hb H accounts for the increased binding capacity of Hb H erythrocytes, and that the binding capacity of Hb H is 5–7 times that of Hb A [5]. There is also an increase in these cells of other intraerythrocytic components, such as heme and non-heme irons [8, 9]. These react with artemisinins [2] and may also interfere with drug effectiveness. In this report, we present evidence for preferential artemisinin inactivation by α-thalassemic erythrocytes as an additional mechanism for this host-dependent artemisinin resistance.

MATERIALS AND METHODS

Materials

Artemisinin was purchased from the National Center of Natural Science and Technology, Hanoi, Vietnam. Artemisinin was recrystallized from a methylene chloride/hex-

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[1] Abbreviations: Hb, hemoglobin; Hb CS, hemoglobin Constant Spring; α-thal, α-thalassemia; β-thal, β-thalassemia; and K_d, dissociation constant.

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ane mixture to give white needles (m.p. 154–156°). Dihydroartemisinin was prepared from artemisinin by reduction with sodium borohydride [10] and recrystallized from a methylene chloride/hexane mixture to give white needles (m.p. 151–153°). Radioactive 15-[^{14}C]artemisinin was a gift from the Research Triangle Institute. The specific activity of [^{14}C]artemisinin was 26.1 Ci/mol. 2,8-[^{3}H]Hypoxanthine was purchased from Moravek Biochemicals. The specific activity of [^{3}H]hypoxanthine was 20–30 Ci/mmol.

Subjects

Thalassemic blood samples were obtained from the Division of Hematology, Department of Medicine, Faculty of Medicine, Siriraj Hospital, Mahidol University, where hemoglobin types were identified. Subjects had the following genotypes: Hb H (α-thal1/α-thal2), Hb H/Hb CS (α-thal1/Hb CS), and β-thalassemia with Hb E (β-thal/Hb E). All were non-splenectomized and had received no blood transfusions for at least 3 months before the collection of blood. Citrate–phosphate–dextrose solution was used as an anticoagulant.

In Vitro Culture of P. falciparum

A chloroquine-resistant strain of *P. falciparum* (K1) was obtained from an infected individual in the Kanchanaburi province of Thailand [11]. Parasites were maintained continuously in human erythrocytes using RPMI 1640 medium supplemented with 25 mM HEPES, pH 7.4, 0.2% $NaHCO_3$, 40 μg/mL of gentamicin, and 10% human serum [12]. Parasite growth was synchronized at the ring stage by 5% sorbitol treatment [13], and the schizont stage was collected by Percoll centrifugation [14]. Washed thalassemic blood cells were co-cultivated with schizont-infected erythrocytes for at least 96 hr before determining antimalarial sensitivity of the infecting parasites.

Antimalarial Activity Assay

In vitro antimalarial activity was determined by using the [^{3}H]hypoxanthine incorporation method [15]. Briefly, 25-μL aliquots of drug solutions of different concentrations were placed in a 96-well plate together with 200 μL of a 1.5% cell suspension of parasitized erythrocytes containing 1–2% parasitemia at the early ring stage. The mixtures were incubated in a candle jar at 37°. After 24 hr of incubation, 25 μL (0.25 μCi) of [^{3}H]hypoxanthine was added to each well. The mixtures were incubated further under the same conditions for 18–24 hr. DNA of parasites was harvested onto glass filter paper (Unifilter®, Packard). The filters were dried, and liquid scintillation fluid was added for radioactivity measurement in a 6-probe liquid scintillation counter (Packard). An IC_{50} value was determined from the sigmoid curve of percent [^{3}H]hypoxanthine incorporation against drug concentration.

In some experiments, to explore the effect of Hb H on the antimalarial activity of dihydroartemisinin, isolated Hb A and Hb H prepared from lysate of Hb H erythrocytes [5] were added to the parasites together with dihydroartemisinin. Final concentrations of Hb H and Hb A in the tests ranged from 7.5 to 60 μM.

Effect of Intact Erythrocytes on Artemisinin Inactivation

An aliquot (70 μL) of washed erythrocytes was incubated at 37° with 630 μL of [^{14}C]artemisinin in culture medium without serum (incomplete medium) for 2 hr. The final concentration of the radiolabelled drug was 1 μM. At the end of the incubation, the cell mixture was centrifuged at 10,053 *g* (Hettich, Mikro 24–48R centrifuge) for 30 sec at 4° to separate free drug from intact cells. The supernatant was used for determining artemisinin effectiveness, and the cell pellet was used for measuring artemisinin accumulation.

In some experiments, to determine the protective effect of serum on artemisinin inactivation by erythrocytes, medium containing from 10 to 100% serum was used in place of incomplete medium. In these experiments, cells were incubated with the radiolabelled drug, and then the drug effectiveness was determined from the supernatants of the cell mixtures at various time points for up to 4 hr.

Determination of Artemisinin Effectiveness

Supernatant was diluted to appropriate concentrations with culture medium. Antimalarial activity of diluted samples was determined in triplicate as described above. An aliquot (100 μL) of the undiluted supernatant was mixed with 900 μL of water and 4 mL of Triton X-100-based liquid scintillation fluid for determination of radioactivity. Then the concentration of [^{14}C]artemisinin was calculated from its specific activity. The drug effectiveness index was defined as IC_{50} of control/IC_{50} of sample.

Determination of [^{14}C]Artemisinin Accumulation in Intact Erythrocytes

After the incubation, cells were washed three times with cold 10 mM PBS solution to remove excess drug. Cells were lysed with 10 vol. of hypotonic solution (10 mM phosphate, pH 7.4). An aliquot of the lysate (500 μL) was incubated with an equal volume of 2% SDS solution at 60° for 1 hr. Then the mixture was bleached with 2 mL of 15% hydrogen peroxide at 60° for 12 hr. Next, 4 mL of Triton X-100-based liquid scintillation fluid was added for measurement of radioactivity in a liquid scintillation counter (Beckman). The results were expressed as amount of the drug (picomoles) per 10^{7} cells.

TABLE 1. Amount of artemisinin accumulation in intact cells, cytosol (D_c), and membrane (D_m) compartments of uninfected normal and thalassemic erythrocytes

Erythrocyte Compartment	[^{14}C]Artemisinin (pmol/10^9 cells)			
	Normal	Hb H	Hb H/Hb CS	β-thal/Hb E
Intact cells	57.0 ± 10.0	337.1 ± 129.9*	657.0 ± 122.5*	223.8 ± 45.3*
Cytosol (D_c)	63.8 ± 11.3	304.1 ± 103.9*	509.2 ± 124.8*	207.9 ± 44.7*
$\%D_c$†	88.6 ± 1.6	85.2 ± 5.0‡	83.3 ± 8.1‡	88.9 ± 3.4‡
Membrane (D_m)	8.3 ± 2.0	58.3 ± 35.2*	95.2 ± 22.9*	26.2 ± 10.1*
$\%D_m$§	12.1 ± 2.5	14.8 ± 5.0‡	16.7 ± 8.1‡	11.1 ± 3.4‡
D_c/D_m Ratio	7.5 ± 1.7	6.4 ± 2.8‡	5.8 ± 2.7‡	8.6 ± 2.7‡

Intact erythrocytes, membrane, and cytosol were incubated at 37° for 2 hr, with 1 μM of [^{14}C]artemisinin in culture medium without serum as a 10% cell suspension or equivalent. After incubation, free drug was separated from the intact cells, membrane, and cytosol by centrifugation for intact cells and membrane, and by ultracentrifugation through 10-kDa cut-off membranes for cytosol. After washing, the pellets and the cytosol-retentate were treated as described in the text for measurement of radioactivity. The results (means ± SEM), expressed as amounts of the drug per 10^9 cells, are from three duplicate experiments. Statistical analyses were performed by using a non-parametric Mann-Whitney U test.

*$P = 0.05$, $N = 3$.

† $\%D_c = D_c \times 100/(D_c + D_m)$.

‡ Not significantly different, $N = 3$.

§ $\%D_m = D_m \times 100/(D_c + D_m)$.

Effect of Cytosol and Membrane on Artemisinin Inactivation

One milliliter of 50% (v/v) erythrocyte suspension was lysed with 3.5 mL of hypotonic solution with freeze-thawing to obtain complete lysis. An aliquot (630 μL) of the lysate was centrifuged at 22,620 *g* for 10 min at 4°. The pellet was washed with 10 mM phosphate buffer, pH 7.4, five times, to remove bound hemoglobin. Supernatant and pellet were used as cytosol and membrane samples, respectively.

Cytosol and membrane preparations equivalent to 10% (v/v) of red blood cells were incubated with 1 μM [^{14}C]artemisinin at 37° for 2 hr. The cytosol sample was centrifuged in a Centricon 10® tube to separate free drug from hemolysate. The filtrate was used for determining the drug effectiveness index. The retentate was adjusted to its original volume with hypotonic solution and treated with SDS and hydrogen peroxide to determine artemisinin accumulation as described. Free drug was separated from membrane by centrifugation at 22,620 *g*. Drug effectiveness index and accumulation then were determined as described.

Statistical Analysis

The Mann–Whitney U test was used for comparing the data from normal and variant erythrocytes based on independent random samples.

RESULTS AND DISCUSSION

Artemisinin Resistance of P. falciparum *Infecting Variant Erythrocytes*

Resistance to artesunate of normally susceptible *P. falciparum* when infecting thalassemic erythrocytes was first reported in 1989 [3]. Similar findings of resistance to artemisinin [4] and dihydroartemisinin [5] were reported subsequently. In this study, the resistance of *P. falciparum* to artemisinin was confirmed again in Hb H-containing erythrocytes *in vitro*. The IC_{50} values were 42.3 ± 29.5 nM for Hb H ($N = 9$) and 62.5 ± 43.3 nM for Hb H/Hb CS ($N = 6$), approximately 12 and 17 times higher than that of *P. falciparum* infected normal erythrocytes (3.6 ± 1.8 nM, $N = 5$). This host-specific resistance also was found with parasites infecting β-thal/Hb E erythrocytes, albeit with a lower IC_{50} value (9.0 ± 1.8 nM, $N = 4$). The IC_{50} values for artemisinin against the parasites in these variant erythrocytes were significantly higher than those in normal erythrocytes ($P < 0.01$) for the three variants. These findings are also in line with a recent report where artemisinin sensitivities of the parasites were found to be reduced in the old cell fractions of α- and β-thal trait erythrocytes as compared with the same fraction of normal controls [6].

Increased Artemisinin Accumulation in Thalassemic Erythrocytes

Preferential accumulation [4, 5] and increased binding of artemisinin in Hb H-containing erythrocytes due to the presence of Hb H [5] are the major factors that contribute to the apparent resistance of parasites to the drug. The increase in artemisinin accumulation was also confirmed in this study. As shown in Table 1, after incubation of [^{14}C]artemisinin with variant erythrocytes, the amounts of artemisinin accumulated in Hb H and Hb H/Hb CS erythrocytes were, respectively, 5.9 and 11.5 times that for normal erythrocytes. This phenomenon was also observed, but to a lesser extent, in β-thal/Hb E erythrocytes. The levels of [^{14}C]artemisinin accumulation of these variant erythrocytes were significantly higher than that of normal erythrocytes ($P < 0.05$).

Artemisinin Inactivation by Erythrocytes

The differences between the fold increase in IC_{50} values and in drug accumulation of artemisinin in α-thalassemic erythrocytes compared with normal erythrocytes indicated the presence of an additional mechanism for decreasing artemisinin effectiveness. We hypothesize that this mechanism involves preferential inactivation of the drug by the thalas-

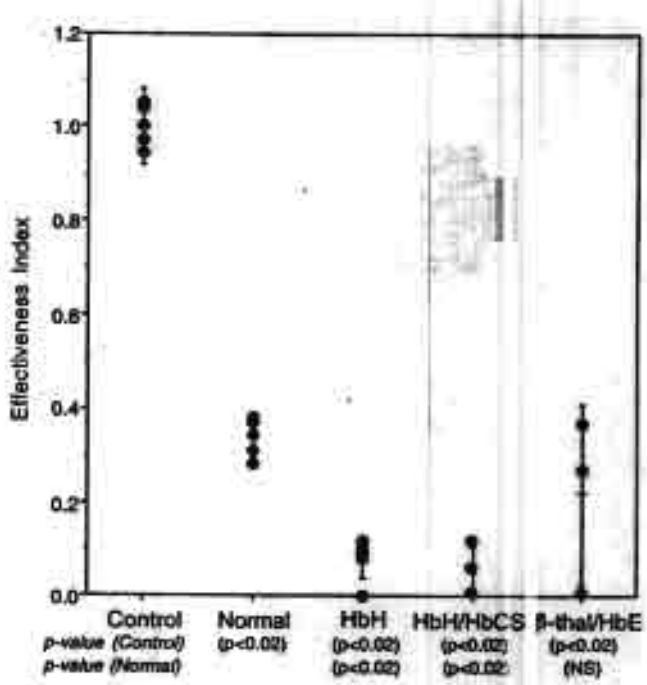

FIG. 1. Effectiveness index of [^{14}C]artemisinin following exposure to thalassemic and normal erythrocytes for 2 hr. Data points and means ± SEM are shown. Numbers of samples in the tests were 6 for control and normal, 5 for Hb H, 4 for Hb H/Hb Constant Spring (Hb CS), and 3 for β-thal/Hb E.

semic erythrocytes. To explore this artemisinin-inactivation hypothesis, the effectiveness of the drug, defined as IC_{50} for artemisinin in control incubated without erythrocytes/IC_{50} in the sample, was determined after incubation of [^{14}C]artemisinin with intact erythrocytes from normal and thalassemic individuals in incomplete medium for 2 hr. The results are shown in Fig. 1. The effectiveness index of [^{14}C]artemisinin following exposure to normal erythrocytes decreased significantly to 0.34 ± 0.04 (N = 6) as compared with control without erythrocytes (1.00 ± 0.08). This decrease in [^{14}C]artemisinin effectiveness was not due to instability of the drug, since the effectiveness index of [^{14}C]artemisinin incubated in the medium remained unchanged up to 12 hr of incubation (data not shown). The effectiveness indices of [^{14}C]artemisinin following exposure to both types of Hb H-containing erythrocytes significantly decreased to a greater extent than that of [^{14}C]artemisinin exposed to normal erythrocytes: 0.08 ± 0.04 for Hb H (N = 5) and 0.05 ± 0.05 for Hb H/Hb CS (N = 4). The effectiveness index of [^{14}C]artemisinin exposed to β-thal/Hb E erythrocytes (0.22 ± 0.19, N = 3) was not significantly different from that when exposed to normal erythrocytes. These results indicated that artemisinin was inactivated by all types of erythrocytes, but preferentially by Hb H-containing erythrocytes.

Protective Effect of Human Serum against Artemisinin Inactivation

Since artemisinin and its derivatives are effective against malarial parasites *in vitro* and *in vivo*, where serum is present, it is possible that serum exerts a protective effect against inactivation of artemisinin by the erythrocytes. To investigate the effect of serum on artemisinin activity upon exposure to erythrocytes, similar incubations were carried out in the presence of increasing amounts of serum. The data are shown in Fig. 2. Upon exposure to normal erythrocytes, [^{14}C]artemisinin effectiveness was retained in the presence of serum (Fig. 2A). The presence of 50% serum resulted in full retention of artemisinin effectiveness for up to 4 hr of incubation. However, for Hb H-containing erythrocytes, the presence of serum did not improve the effectiveness index of artemisinin, only delaying the inactivation process (Fig. 2, B and C). These data indicate that serum protects against artemisinin inactivation by decreasing artemisinin entry into the erythrocytes.

The role of human serum in protecting or stabilizing the drug against inactivation by normal erythrocytes could be due to the presence of proteins in serum. It has been reported that serum albumin, the major protein in serum, can bind non-covalently to many drugs and small molecules [16, 17] including artemisinin [18]. In addition, α_1-acid glycoprotein, an acute phase protein found at high levels during infection, has also been reported to bind artemisinin non-covalently with a greater binding affinity than albumin [19]. Binding of the drug to these serum proteins may account for the protection of the drug *in vitro* by decreasing the rate of drug transportation into uninfected normal erythrocytes or by competing for the drug with components in the cells.

In Hb H-containing erythrocytes, human serum was not able to protect artemisinin from inactivation. The results also showed a faster rate of artemisinin inactivation by both Hb H and Hb H/Hb CS erythrocytes than by normal erythrocytes. This indicates that there was competition for artemisinin by components within the cells (e.g. Hb H and Hb A) and those outside (e.g. serum components such as serum albumin and α_1-acid glycoprotein). The binding affinities of four major binding components can be listed as follows: α_1-acid glycoprotein with arteether (K_d = 4.4 ± 0.4 μM), human serum albumin with arteether (K_d = 84 ± 7 μM), Hb H with dihydroartemisinin (K_d = 66 ± 17 μM), and Hb A with dihydroartemisinin (K_d = 224 ± 15 μM) [5, 19]. There are two artemisinin binding sites in α_1-acid glycoprotein and Hb H, and one in human serum albumin and Hb A [5, 19]. Although α_1-acid glycoprotein may possess stronger drug binding affinity than Hb H, assuming that artemisinin derivatives have similar binding characteristics, the glycoprotein is present in much lower concentration in normal human serum, thus driving the binding towards Hb H. Binding of artemisinin to Hb H probably is also favored over binding to human serum albumin. These considerations argue for favored localization of artemisinin in Hb H-containing cells and its subsequent inactivation there. Even if artemisinin does not bind to Hb H with as high affinity as to the serum proteins, inactivation would still result if it could dissociate from the serum proteins and penetrate the erythrocytes.

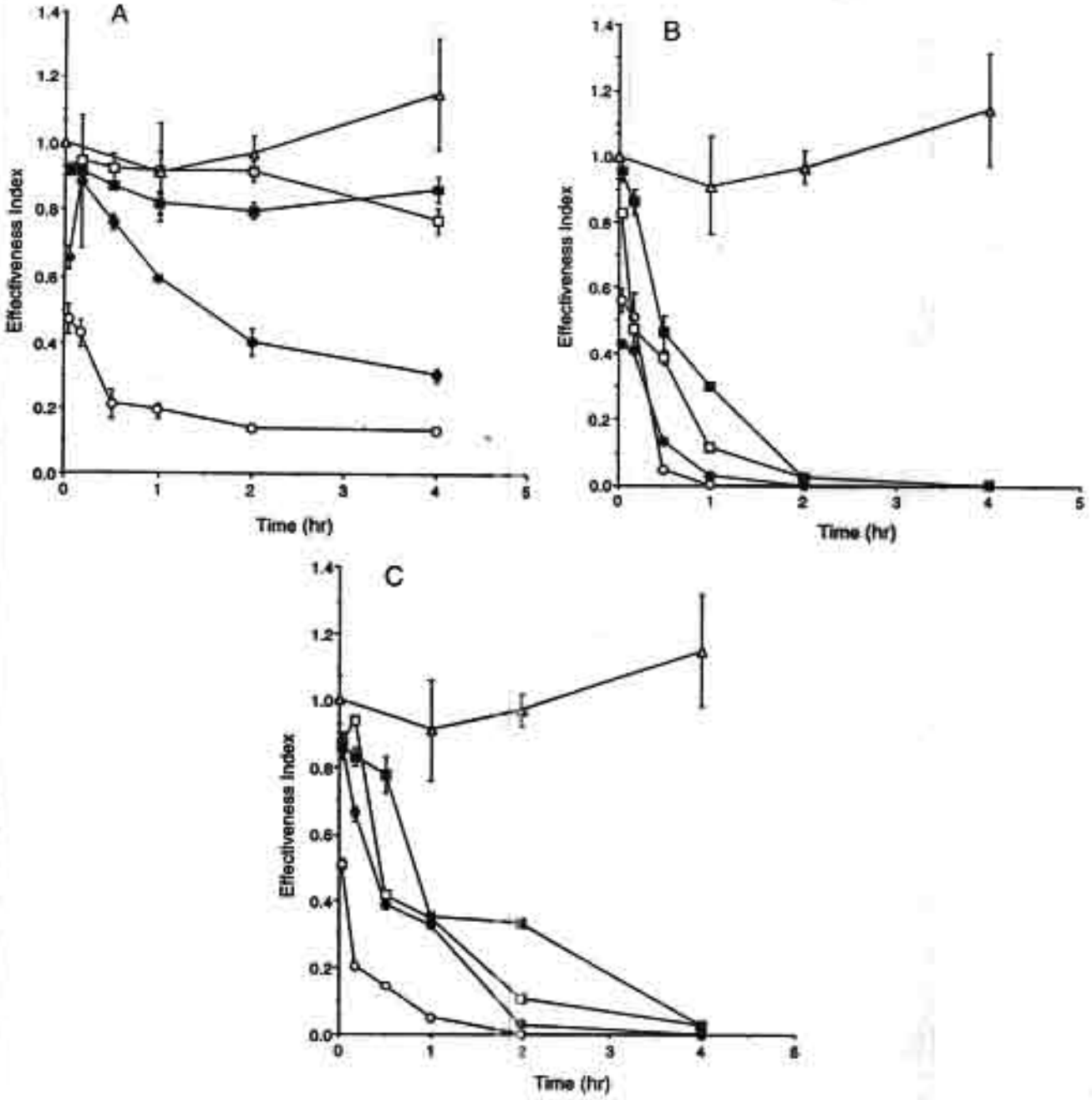

FIG. 2. Effectiveness index of [^{14}C]artemisinin following exposure to erythrocytes in the absence (○) and presence of 10% (●), 50% (□), and 100% (■) human serum, and (△) in the control medium without cells and serum. (A) Normal erythrocytes, (B) Hb H erythrocytes, and (C) Hb H/Hb CS erythrocytes. The experiments were performed twice using two different sets of samples. The data shown here are means ± SD from one of the two experiments where similar results were obtained.

Effect of Cytosolic and Membrane Compartments on Artemisinin Inactivation

Distributions of [^{14}C]artemisinin in erythrocyte membrane and cytosolic fractions were investigated. As shown in Table 1, the amount of drug was higher in the cytosol compartment than in the membrane fraction of both normal and variant erythrocytes. Cytosol and membrane from both types of Hb H-containing erythrocytes accumulated [^{14}C]artemisinin to a higher extent than those of normal and β-thal/Hb E erythrocytes. The ratios of the drug in the two compartments for these variant erythrocytes were not significantly different from normal. These values were also in line with the previous report using dihydroartemisinin [5].

To investigate further the role of the two compartments in inactivating artemisinin, radiolabelled drug was incubated with washed membrane and cytosol of normal and thalassemic erythrocytes, and free drug fractions were separated for determination of drug effectiveness. The results of the effects of cytosolic fractions and of membrane

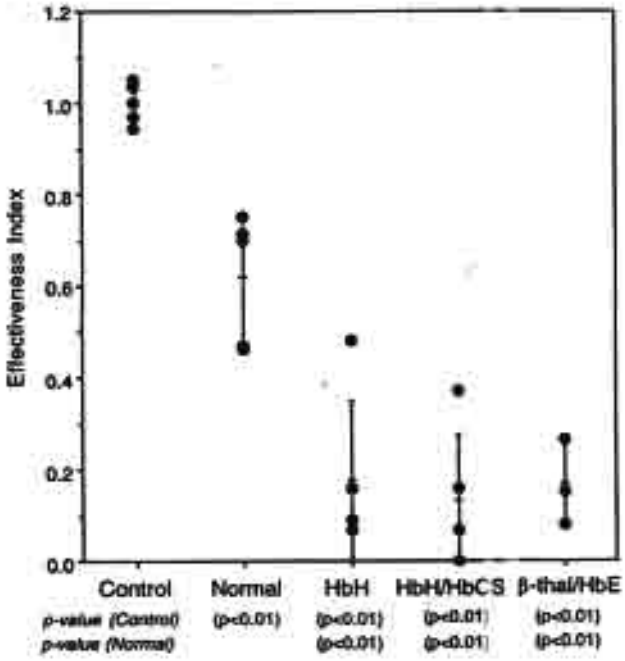

FIG. 3. Effectiveness index of free [^{14}C]artemisinin obtained from thalassemic and normal hemolysates after a 2-hr incubation. Data points and means ± SEM are shown. Numbers of samples in the tests were 5 for all.

fractions are shown in Figs. 3 and 4, respectively. The effectiveness index of free artemisinin extracted after 2 hr of incubation with the cytosolic fraction of Hb H, Hb H/Hb CS, β-thal/Hb E, and normal erythrocytes decreased markedly from 1.0 in control to 0.18 ± 0.17, 0.14 ± 0.14, 0.17 ± 0.08, and 0.62 ± 0.14, respectively. These effectiveness indices of the drugs from the cytosolic fractions of variant erythrocytes were also significantly less than the index from normal erythrocytes (Fig. 3). Upon incubation with membrane fraction, drug effectiveness was also decreased significantly in the presence of Hb H and Hb H/Hb CS membranes (the indices were 0.41 ± 0.17 for Hb H and 0.41 ± 0.09 for Hb H/Hb CS), and to a lesser extent in the presence of membrane from β-thal/Hb E (0.67 ± 0.26) and normal erythrocytes (0.81 ± 0.05). Both cytosolic and membrane components of normal and thalassemic erythrocytes inactivated artemisinin, and the inactivation was most pronounced in the cytosolic fraction of Hb H-containing erythrocytes.

Role of Hb H on Artemisinin Inactivation

The role of Hb H in Hb H-containing erythrocytes on artemisinin antimalarial activity has been suggested to be due to preferential binding of artemisinin and its derivatives to Hb H, thereby causing the drugs to accumulate at high concentrations in these variant erythrocytes [5]. To determine whether Hb H could also inactivate the drug, purified Hb H was added to the culture medium, and the antimalarial activity of dihydroartemisinin was tested. Addition of Hb H to the malaria culture caused a large increase in the dihydroartemisinin IC_{50} value, whereas addition of Hb A showed little effect (Fig. 5). When the concentrations of dihydroartemisinin were corrected for the portion of the drug bound to added Hb H (K_d = 66 μM) [5], IC_{50} values were still anomalously high, indicating a role of Hb H in dihydroartemisinin inactivation.

Since artemisinin inactivation occurred in normal as well as β-thal/Hb E erythrocytes, with the cytosolic fraction playing a major role in the inactivation process, factors other than Hb H alone must also be responsible for drug inactivation. It has been reported that antioxidant enzymes, e.g. catalase, glutathione peroxidase, glutathione reductase, and superoxide dismutase, are present in increased amounts in thalassemic erythrocytes [20, 21]. Iron is also found at high levels in both α- and β-thalassemic erythrocytes [8, 9]. Interaction of artemisinin with some of these cytosolic components may lead to its inactivation. In addition, in the presence of iron [2], artemisinin binding and/or alkylation of proteins in the cells can also lead to a decrease in drug availability. This hypothesis is supported by various reports on the interaction of artemisinin with iron, redox metal, heme, and proteins [2, 22–27].

In a study of the pharmacokinetics of artesunate in α-thalassemic subjects, it was found that plasma drug concentrations of biologically active drug metabolites in the plasma of the thalassemic subjects are higher than normal, and the volume of distribution is 15-fold lower [28]. Although this result is surprising, since higher uptake of the drug by thalassemic erythrocytes [4, 5] would be expected to lead to lower plasma concentrations and higher volume of distribution, possible explanations were given as slow re-

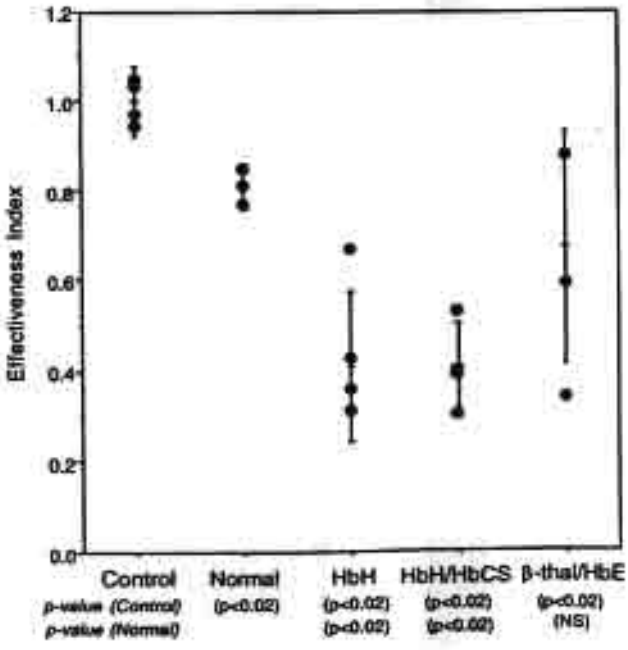

FIG. 4. Effectiveness index of free [^{14}C]artemisinin obtained from thalassemic and normal membranes after a 2-hr incubation. Data points and means ± SEM are shown. Numbers of samples in the tests were 4 for all.

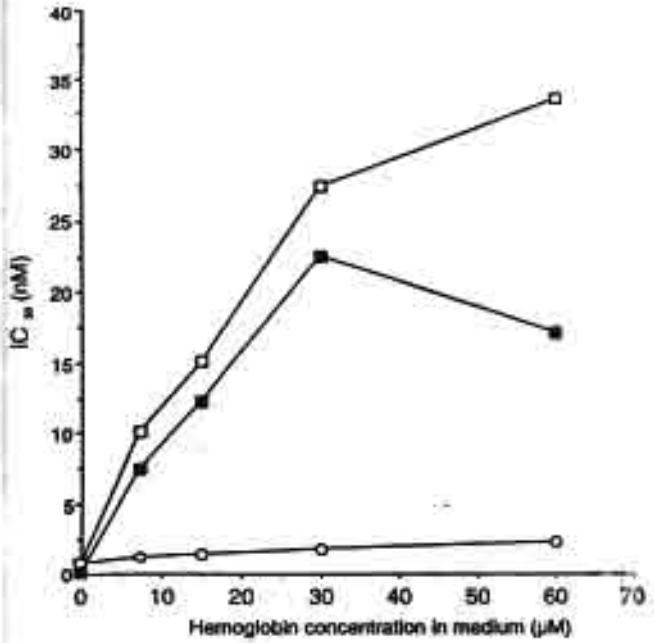

FIG. 5. Effect of Hb H on the IC_{50} values of artemisinin against *P. falciparum* in vitro. Key: (○) Hb A; (□) Hb H; and (■) corrected Hb H. The data were averaged from a triplicate measurement.

lease of the drug and metabolites into the plasma, and differences in drug metabolism. Our present report of artemisinin inactivation by thalassemic erythrocytes is not necessarily in conflict with the pharmacokinetic studies on artesunate [28], since different drugs were used, and plasma concentrations are determined by complex factors not limited to drug inactivation.

In conclusion, the results reported here show the presence of an additional mechanism responsible for resistance to artemisinin by *P. falciparum* infecting α-thalassemic red cells in vitro, namely, the inactivation of artemisinin. The host-specific resistance, resulting both from drug binding to Hb H and other erythrocyte components and from its inactivation, may be an important consideration in the clinical use of the drug for malaria treatment, especially in areas with a high frequency of thalassemic genes. Although no artemisinin-resistant malaria parasites have been detected to date, drug-resistant parasites and high recrudescence rates may result if artemisinin and its derivatives are used without awareness of the significance of this host-specific effect.

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Gametocytocidal activity of pyronaridine and DNA topoisomerase II inhibitors against multidrug-resistant *Plasmodium falciparum* in vitro

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Abstract

Gametocytocidal activities of pyronaridine and DNA topoisomerase II inhibitors against two isolates of multidrug-resistant *Plasmodium falciparum*, KT1 and KT3 were determined. After sorbitol treatment, pure gametocyte cultures of *Plasmodium falciparum* containing mostly young gametocytes (stage II and III) obtained on day 11 were exposed to the drugs for 48 h. The effect of the drugs on gametocyte development was assessed by counting gametocytes on day 15 of culture. Pyronaridine was the most effective gametocytocidal drug against *P. falciparum* isolates KT1 and KT3 with 50% inhibitory concentration of 6 and 20 nM, respectively. Moreover, the 50% inhibitory concentration of pyronaridine was lower than that of primaquine which is the only drug used to treat malaria patients harboring gametocytes. Prokaryotic (norfloxacin) and eukaryotic (amsacrine and etoposide) DNA topoisomerase II inhibitors were only effective against asexual but not sexual stages of the malaria parasites. Pyronaridine has both schizontocidal and gametocytocidal activities against the human malaria parasite, *P. falciparum*.

Keywords: Gametocytocidal activity; Pyronaridine; DNA topoisomerase II inhibitors; *Plasmodium falciparum*

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1. Introduction

Malaria still remains one of the major health problems in tropical countries, and among the four species of malaria parasites infecting humans, *Plasmodium falciparum* is the most virulent. Chemotherapy has played a major role in alleviating suffering and in reducing mortality caused by *P. falciparum* infection. Unfortunately, resistance to most currently used antimalarials has appeared in *P. falciparum* and continues to increase in many parts of the world [1]. Most of the currently used antimalarial drugs affect only the asexual stage of the parasite, except primaquine which can also act as a gametocytocidal drug.

Pyronaridine, a 9-anilino-aza-acridine synthesized in the 1970s, has been developed primarily from Chinese research efforts and has been used in China for more than 15 years [2,3]. It is highly effective against chloroquine-sensitive and -resistant strains of *P. falciparum* [4,5] and good antimalarial activity has also been reported in Thailand [6]. Pyronaridine is a highly active blood schizontocide and has already undergone extensive trials in human against both *P. falciparum* and *P. vivax* [7,8]. Although an effect of pyronaridine on the ultrastructure of malaria parasite has been reported [9,10] and our previous study showed that decatenation activity of *P. falciparum* DNA topoisomerase II was inhibited by pyronaridine [11], the mechanism of action of pyronaridine is still not known.

Since inhibition of *P. falciparum* sexual stage should not be overlooked, and only one drug, primaquine, is currently used to combat *P. falciparum* gametocytes, a search for new gametocytocidal drugs is urgently needed. Therefore, in this study, in vitro gametocytocidal activities of pyronaridine and a number of DNA topoisomerase II inhibitors were determined against two isolates of gametocyte-producing *P. falciparum* from Thailand.

2. Materials and methods

2.1. Parasites

Gametocyte-producing isolates, KT1 and KT3, of *Plasmodium falciparum* were collected from two infected patients at Thong Pha Phum District, Kanchanaburi Province, Thailand. Multidrug resistant K1 strain originally taken from this province [12] was used as a control parasite for determination of drug resistance. KT1 and KT3 isolates were successfully cultured in our laboratory for at least 3 years and continuously produced gametocytes under our culture conditions [13,14]. Morphological and functional maturation of KT3 isolate have already been reported [13] and KT1 isolate behaved similarly.

2.2. Cultivation of Plasmodium falciparum

P. falciparum KT1 and KT3 isolates were cultured continuously in RPMI medium supplement with 15% human plasma using human erythrocytes (O,Rh+) previously treated with PIGPA (Pyruvate, Inosine, Glucose, Phosphate, Adenine) solution [13]. In gametocyte cultivation, 50 mg/l (final concentration) of hypoxanthine were also added. Culture dishes were placed in candle jars and incubated at 37°C. The culture medium was changed every 3 days.

2.3. Test of in vitro drug sensitivity against asexual stage of P. falciparum KT1 and KT3 isolates

Mefloquine, amsacrine, etoposide and primaquine were dissolved in dimethylsulfoxide (DMSO). The final concentration of DMSO did not exceed 0.1% (v/v). Chloroquine, cycloguanil and pyronaridine were dissolved in sterile distilled water. Pyrimethamine was dissolved in 0.5% lactic acid and the final concentration of lactic acid in culture was not allowed to exceed 0.0005%. Norfloxacin was diluted with 0.1 M HCl and the final concentration of HCl was less than 1 μM. The stock drug solutions were diluted to the desired concentrations with culture medium.

The activities of drugs against *P. falciparum* KT1 and KT3 were measured as 50% inhibitory concentration (IC_{50}) by incubating 1.5% erythrocyte suspension containing 0.5% initial parasitemia with drugs for 24 h at 37°C. [^{3}H]hypoxanthine (0.25 μCi, 6.2 Ci/mmol, Amersham, UK) was then added to each sample and parasite cultures were incubated for an additional 24 h. IC_{50}

values were recorded as the concentration of drug required to inhibit (by 50%) the incorporation of [^{3}H]hypoxanthine into parasite DNA, compared with untreated control.

2.4. Test of in vitro gametocytocidal effect

After synchronization of *P. falciparum* growth with sorbitol treatment [15], gametocyte culture was started with 1% initial parasitemia containing mostly ring forms in 2% erythrocyte suspension. The medium was changed on day 4, 6 and 8 of the culture. Pure gametocytes of *P. falciparum* KT1 and KT3 isolates were obtained by adding 2.5 volumes of 5% (w/v) sorbitol to packed erythrocytes for 5 min once a day, starting from day 9 until day 11 of culture. Approximately 450 μl aliquots of this suspension were transferred to a 24-well plate which contained 50 μl of drug in each well. After 24 h incubation, drug was again replaced and cultures were incubated for an additional 24 h. All wells then received complete medium without drug and cultivations were continued for 2 more days. Thin blood films were prepared on day 15 of cultivation and gametocytes were counted per 10000 erythrocytes. The effect of each drug concentration was investigated in triplicates. Gametocytocidal activity of drug was recorded as the concentration of drug that inhibited gametocytes by 50% as compared with untreated control.

3. Results

3.1. In vitro antimalarial drug sensitivity of the asexual stage of P. falciparum KT1 and KT3 isolates

Asexual parasites were cultured in the presence of five known antimalarials for 48 h and IC_{50}s of these drugs against *P. falciparum* KT1 and KT3 isolates were determined by measuring uptake of [^{3}H]hypoxanthine compared with K1 strain. Both *P. falciparum* isolates were resistant to chloroquine, pyrimethamine and cycloguanil, but were still sensitive to mefloquine compared with K1 strain (Table 1). The IC_{50}s of the drugs against KT1 isolates were not significantly different from those of KT3 except for that of cycloguanil in KT3 isolate which was approximately six times less than that in KT1 isolate. Primaquine was also able to inhibit asexual parasite growth only at a higher concentration than chloroquine and mefloquine.

Table 1
IC_{50} values of current antimalarials against asexual stages of *P. falciparum* KT1 and KT3 isolates as determined by [^{3}H]hypoxanthine uptake method compared with K1 strain

Drugs	IC_{50} (μM)		
	KT1 isolate	KT3 isolate	K1 strain*
Chloroquine	0.2	0.4	0.23
Mefloquine	0.03	0.01	0.02
Pyrimethamine	34.0	35.5	38.5
Cycloguanil	42.0	7.6	8.5
Primaquine	1.1	2.0	ND

*Chloroquine–pyrimethamine-resistant K1 strain [12]; ND = not determined.

3.2. In vitro activity of pyronaridine and DNA topoisomerase II inhibitors against the asexual stage of P. falciparum KT1 and KT3 isolates

IC_{50}s of pyronaridine and DNA topoisomerase II inhibitors, namely, amsacrine, etoposide and norfloxacin, were determined. All compounds could inhibit parasite growth in vitro and IC_{50}s were found to be between 0.002 and 43 μM (Table 2). Pyronaridine showed the highest activity against the asexual stage of both parasite isolates (IC_{50} = 2 nM). Among the DNA topoisomerase II inhibitors, eukaryotic DNA topoisomerase II inhibitors, amsacrine and etoposide, were more active against both *P. falciparum* isolates than norfloxacin, a prokaryotic DNA topoisomerase II (gyrase) inhibitor.

3.3. Pure gametocyte cultures of P. falciparum KT1 and KT3 isolates

Gametocytes of KT1 and KT3 isolates produced in cultivation could undergo a maturation process and stages I–V identified on the basis of morphology [13]. After sorbitol treatments on day 9, 10 and 11, there was 99% reduction in the

Table 2
IC_{50} values of pyronaridine and DNA topoisomerase II inhibitors against asexual stages of *P. falciparum* KT1 and KT3 isolates compared with K1 strain

Drugs	IC_{50} (μM)		
	KT1 isolate	KT3 isolate	K1 strain[a]
Pyronaridine	0.002	0.002	0.0027
Amsacrine	1.2	1.4	0.5
Etoposide	17.0	21.0	12.5
Norfloxacin	31.5	43.0	ND

[a]Chloroquine-pyrimethamine-resistant K1 strain [12]; ND = not determined.

Table 3
IC_{50} values of pyronaridine, DNA topoisomerase II inhibitors and primaquine against gametocytes of *P. falciparum* KT1 and KT3 isolates

Drugs	IC_{50} (μM)	
	KT1 isolate	KT3 isolate
Pyronaridine	0.006	0.02
Amsacrine	8.0	10.8
Etoposide	97.0	95.0
Norfloxacin	> 100	> 100
Primaquine	0.8	2.1

number of asexual parasites. Pure gametocyte cultures of *P. falciparum* KT1 and KT3 isolates were obtained on day 11 with an average number of gametocytes of 305 and 392 per 10 000 erythrocytes, respectively. These gametocytes consisted of 19% stage II, 60% stage III and 21% stage IV and were used in the drug treatment studies.

3.4. *In vitro gametocytocidal effects of pyronaridine and DNA topoisomerase II inhibitors against P. falciparum KT1 and KT3 isolates*

Gametocytes of *P. falciparum* KT1 and KT3 isolates could be inhibited by pyronaridine and eukaryotic DNA topoisomerase II inhibitors (amsacrine and etoposide) whereas norfloxacin did not have any effect on gametocytes even when the concentration was raised to 100 μM (Table 3). Pyronaridine was the most potent inhibitor against gametocytes in cultures (IC_{50} of 6 and 20 nM against KT1 and KT3, respectively), being approximately 3×10^3–3×10^4 times more effective than amsacrine and etoposide. Moreover, IC_{50} of pyronaridine was lower than IC_{50} of primaquine.

4. Discussion

Gametocyte-producing *P. falciparum* KT1 and KT3 isolates used in this study can be looked upon as multidrug-resistant parasites because of their resistance to chloroquine, pyrimethamine and cycloguanil. Both isolates were still sensitive to mefloquine.

The study of topoisomerases has expanded into the realm of pharmacology and clinical medicine through identification of bacterial topoisomerase II (DNA gyrase) as a target of antibitotics and toxins and of eukaryotic DNA topoisomerase II as a target of a large number of anticancer agents [16]. In vitro activities of pyronaridine and DNA topoisomerase II inhibitors against the asexual stage of recently acquired *P. falciparum* KT1 and KT3 isolates were investigated and the results showed that both prokaryotic and eukaryotic DNA topoisomerase II inhibitors could inhibit asexual parasite growth, similar to previous studies conducted on the established multidrug-resistant *P. falciparum* K1 strain [11]. Pyronaridine was the most potent inhibitor with IC_{50} values for both KT1 and KT3 isolates of 2 nM, not significantly different from that for *P. falciparum* K1 strain (IC_{50} = 2.7 nM) [11]. The present results indicate that chloroquine-, pyrimethamine- and cycloguanil-resistant *P. falciparum* showed no cross resistance to pyronaridine whereas pyronaridine-resistant *P. falciparum* exhibits cross resistance to chloroquine and piperaquine [17].

Divo et al. [18] have reported on the antimalarial activity of fluoroquinolones against asexual stage of chloroquine-sensitive and -resistant *P. falciparum*. Previous study showed that the decatenation activity of *P. falciparum* DNA topoisomerase II is inhibited by fluoroquinolones [19]. Growth inhibition of asexual stages of *P.*

falciparum KT1 and KT3 isolates by norfloxacin is consistent with these observations. Mitochondrial DNA topoisomerase II of *P. falciparum* may be a possible target for DNA gyrase inhibitors.

Gametocytocidal activity of pyronaridine was very much higher than that of the other DNA topoisomerase II inhibitors tested (amsacrine, etoposide and norfloxacin). Since the gametocytes used in this study were predominantly stage III, in which only RNA and protein synthesis occur, it is not surprising that known DNA topoisomerase II inhibitors showed very low gametocytocidal efficacy because their target plays a role in DNA synthesis which occurs only in stage I and II gametocytes.

Although we have shown that pyronaridine can inhibit *P. falciparum* DNA topoisomerase II in vitro, it now appears that DNA topoisomerase II is not the specific target of pyronaridine based on two lines of evidence. Firstly, pyronaridine strongly inhibited gametocyte growth in spite of the lack of DNA synthesis in this stage. Secondly, using an assay for detection of DNA cleavage, we have shown that pyronaridine was not able to inhibit asexual *P. falciparum* topoisomerase II in situ [20]. Pyronaridine has recently been demonstrated to inhibit malaria parasite heme polymerization as well [21].

This is the first report of the gametocytocidal effect of pyronaridine on *P. falciparum*. It is 100 times more effective than primaquine which is the only gametocytocidal antimalarial in clinical use. The dual role of pyronaridine as a schizontocidal and gametocytocidal drug should make it highly attractive for clinical application.

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