Hydrolysis of cis- and trans-Epoxyeicosatrienoic Acids by Rat Red Blood Cells

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ABSTRACT
Erythrocytes serve as reservoirs for cis- and trans-epoxyeicosatrienoic acids (EETs). Incubation of rat red blood cells (RBCs) with cis- and trans-EETs produces threo- and erythro-dihydroxyeicosatrienoic acids, respectively. The V_max of EET hydrolysis by rat intact RBCs (2.35 ± 0.24 pmol/min/10^8 RBCs for 14,15-trans-EET) decreased by approximately 2 to 3-fold sequentially from 14,15-, 11,12- to 8,9-EETs for both cis- and trans-isomers. The V_max of trans-EET hydrolysis by RBCs is approximately 2 to 3 times that of the corresponding cis-EETs. Incubation of RBCs with recombinant murine soluble epoxide hydrolase (sEH) yielded the same geometric and regio preferences of EET hydrolysis as with rat intact RBCs. The principal epoxide hydrolase activity for EET hydrolysis (approximately 90%) is present in the erythrocyte cytosol. Western blots of sEH suggested a concentration of sEH protein to be approximately 2 μg/mg protein or 0.4 μg/10^8 RBCs. The apparent K_m values of EETs were between 1 and 2 μM, close to the K_m for purified sEH as reported. Erythrocyte hydration of cis- and trans-EETs was blocked by sEH inhibitors, 1,3-dicyclohexylurea and 4-[4-(3-adamantan-1-ylreido)cyclohexyloxy]benzoic acid. Erythrocyte sEH activity was inhibited more than 80% by 0.2% bovine serum albumin in the buffer. Preferred hydrolysis of 14,15-EETs and trans-epoxides characterizes sEH activity in RBCs that regulates the hydrolysis and release of cis- and trans-EETs in the circulation. Inhibition of sEH has produced antihypertensive and antiinflammatory effects. Because plasma trans-EETs would increase more than cis-EETs with sEH inhibition, the potential roles of trans-EETs and erythrocyte sEH in terms of circulatory regulation deserve attention.

Epoxide hydrolases convert EETs to threo-DHETs and trans-EETs to erythro-DHETs. Cytochrome P450 epoxygenases generate cis-EETs, whereas EETs in vivo include both cis- and trans-EETs. "Epoxyeicosatrienoic acids (EETs) are arachidonic acid (AA)-derived vasoactive, antithrombotic, antiplatelet, and anti-inflammatory lipids mediators (Larsen et al., 2006; Fleming, 2007) that are inactivated by soluble epoxide hydrolase (sEH), producing dihydroxyeicosatrienoic acids (DHETs) (Inceoglu et al., 2007). Formation of EE is catalyzed by cytochrome P450 epoxygenases (Capdevila et al., 1991), hemoglobin (Jiang et al., 2007), and lipid peroxidation (Nakamura et al., 1997). The substrate preferences for cis- and trans-epoxides by sEH vary according to cell type (Seidegård et al., 1984) and species (Morisseau and Hammock, 2005). sEH is a therapeutic target for control of blood pressure (Sinal et al., 2000; Loch et al., 2007; Zhang et al., 2007) vascular inflammation (Davis et al., 2002; Schmelzer et al., 2005; Smith et al., 2005), and cancer progression (Morisseau and Hammock, 2005), as well as for cardiac (Seubert et al., 2006) and renal protection (Igig, 2005) by augmenting the levels of EETs in vivo. Inhibition of sEH also increases EET incorporation into phospholipids, thereby modulating endothelial function in the coronary vasculature" (Weintraub et al., 1999). Increases in sEH activity have been associated with diabetes (Rodriguez and Clare-Salzler, 2006) and hypertension (Igig et al., 2002; Ai et al., 2007).

Epoxy hydrolysates convert cis-EETs to threo-DHETs and trans-EETs to erythro-DHETs (Fig. 1). Cytochrome P450 epoxygenases generate cis-EETs, whereas EETs in vivo include both cis- and trans-EETs (Jiang et al., 2005). The 5,6-erythro-DHET was more potent in dilating preconstricted renal interlobar arteries than the 5,6-cis-EET,
whereas, unlike cis- and trans-EETs, it did not inhibit platelet aggregation (Jiang et al., 2004). Red blood cells (RBCs) are reservoirs for both cis- and trans-EETs that can be released by ATP stimulation of erythrocyte P2X7 receptors (Jiang et al., 2007). The hydrolysis of EETs by erythrocytes may represent an important mechanism involved in circulatory regulation.

Human erythrocytes were originally discovered to possess a sEH that hydrates leukotriene A4 (LTA4) and, to a much lesser degree, hydrates cis-EETs (McGee and Fitzpatrick, 1985). Because epoxide hydrolases occur in multiple forms and possess individual substrate specificities (Ota and Hammock, 1985; Thomas et al., 1990), an additional form of sEH was demonstrated preferred hydrolysis for cis- and/or trans-EETs that can be released by ATP stimulation of erythrocyte P2X7 receptors (Jiang et al., 2007). The hydrolysis of EETs by erythrocytes may represent an important mechanism involved in circulatory regulation.

Materials and Methods

Animals. All animal procedures were approved by the Institutional Animal Care and Use Committee of New York Medical College and conformed to the Institute of Laboratory Animal Resources (1996). Eight-week-old male Sprague-Dawley rats were purchased from Charles River Laboratories (Wilmington, MA). Rats were maintained at 22°C with alternate light/dark cycles and fed ad libitum with standard rat chow and water.

Blood Cell Preparation. Sprague-Dawley rats (9–12 weeks old) were anesthetized with pentobarbital (65 mg/kg i.p.), and 10 ml of blood was drawn from the inferior vena cava after midline laparotomy using heparin-rinsed syringes and transferred to Vacutane heparin tubes (PAX, W. Fisher Scientific, Waltham, MA). After inverting four to six times, the blood was centrifuged at 800 × g for 10 min. The supernatant was removed by aspiration, and the buffy layer was collected in some experiments. Packed RBCs were washed four times in an ice-cold physiological salt solution (PSS) with centrifugation at 400 g for 10 min, and the washing buffer and any residual buffy layer were discarded after each wash. The PSS contained 5.0 mM KCl, 1.2 mM CaCl2, 1.2 mM MgSO4, 128 mM NaCl, 20 mM HEPES, 5 mM dextrose, and 2 mg/ml bovine serum albumin (BSA), and pH was adjusted to 7.4. Washed RBCs were suspended in PSS, examined, and counted using hemacytometers under the microscope.

Separation of Membrane and Soluble Fractions. Washed rat erythrocytes (4 ml) were lysed hypotonically in ice-cold sterile water and vortexed for 2 min. After restoration to isotonic buffer conditions, the crude lysate was centrifuged at 100,000 × g for 1 h with a Beckman Ultracentrifuge (Beckman Coulter, Fullerton, CA) at 4°C. The supernatant was filtered through a 0.45-μm nylon syringe filter to obtain the cytosol fraction of RBCs. Both the pellet and the cytosol were diluted in PSS buffer without BSA under the same conditions.

To determine the proportion of EET hydrolysis by RBCs in blood, 100 μl of plasma, theuffy layer diluted in phosphate-buffered saline (PBS), and diluted RBCs in PBS were incubated with trans-EETs (1 μM) for 5 min at 37°C, respectively. EET and DHET extraction for electrospray ionization (ESI)-liquid chromatography (LC)/mass spectrometry (MS) analyses were performed as described previously (Jiang et al., 2004).

Separation of Membrane and Soluble Fractions. Washed rat erythrocytes (4 ml) were lysed hypotonically in ice-cold sterile water and vortexed for 2 min. After restoration to isotonic buffer conditions, the crude lysate was centrifuged at 100,000 × g for 1 h with a Beckman Ultracentrifuge (Beckman Coulter, Fullerton, CA) at 4°C. The supernatant was filtered through a 0.45-μm nylon syringe filter to obtain the cytosol fraction of RBCs. Both the pellet and the cytosol were diluted in PSS buffer without BSA to correspond to a cellular concentration of 2 × 109 RBCs/ml.

Western Blots of Erythrocyte sEH. Total protein concentration was quantified with the Pierce BCA assay (Pierce, Rockford, IL), using Fraction V BSA as the calibrating standard. After thawing the frozen erythrocyte cytosol, sEH activity was measured using radiometric [3H]trans-1,3-diphenylpropene oxide as described previously (Moriseau and Hammock, 2007). For each cytosolic sample, 50 μg of protein was loaded on a 12% SDS-polyacrylamide gel electrophoresis. The separated proteins were then transferred onto a polyvinylidene difluoride membrane, and sEH was detected using a rabbit serum raised against recombinant mouse sEH (Davis et al., 2002). Detection was done using a goat antibody raised against rabbit IgG labeled with horseradish peroxidase. Bands were revealed using the ECL kit (Amersham, Piscataway, NJ). Recombinant purified mouse sEH (500 ng) was used as a positive control.

Kinetic Studies of EET Hydrolysis. Because BSA was found to have inhibitory effects on EET hydrolysis, PSS buffer without BSA was used in the last wash of rat RBCs, and RBCs were diluted to 2 × 109 RBCs/ml in PSS without BSA. To achieve substrate saturation, 14,15-, 11,12-, and 8,9-cis- or trans-EETs (0.1–4 μM) in 30 μl of RBCs or cellular fractions were hydrolyzed at 37°C for 10 min. Endogenous EETs and DHETs released from 1 × 109 RBCs in a buffer without BSA were negligible (Jiang et al., 2007), which was
confirmed by the insignificant alternative EET/DHET peaks in LC/MS analyses. Freshly prepared rat intact RBCs were used for the incubations because freeze-thawing of RBCs reduced EET hydrolysis by 50% as tested. After incubation, 2 ml of ice-cold ethyl acetate/ hexanes (1:1) was added to each tube to stop the reaction, the mixtures of which were extracted after adding internal standards of EET-d8 and DHET-d8 and adjusting pH to 4 with 10% acetic acid. The kinetics of 5,6-EET were not measured because of nonenzymatic conversion to 5,6-DHET (Jiang et al., 2004).

IC$_{so}$ Assay. IC$_{so}$ of sEH inhibitors were determined based on National Institute of Health Chemical Genomics Center enzymatic assay guidance manual. Rat erythrocyte cytosol (corresponding to $5 \times 10^{8}$ RBCs) was incubated with cis- and trans-4-[4-(3-adamantan-1-ylureido)cyclohexyloxy]benzoic acid (AUCB) (Hwang et al., 2007) as well as 1,3-dicyclohexylurea (DCU), respectively, for 5 min in PBS, pH 7.4, at 37°C before substrates of 1 $\mu$M 14,15-, 11,12-, and 8,9-trans-EETs were added. Activity of sEH was assessed by analyzing erythro-DHETs formed with LC/MS after ethyl acetate extraction. Assays were performed in triplicate. IC$_{so}$ and S.E. were determined by regression of at least eight data with a minimum of two points in the linear region of the curve on either side of the IC$_{so}$.

ESI LC/Tandem Mass Spectrometry Analyses. ESI LC/tandem mass spectrometry (MS/MS) analyses of EETs and DHETs were carried out as described previously (Jiang et al., 2005). In brief, a Finnigan LCQ Advantage quadrupole ion-trap mass spectrometer (Thermo Fisher Scientific) equipped with ESI source run by Xcalibur software was used. Reversed-phase high-performance liquid chromatography (HPLC) was run with a Luna C18(2) 250 × 2.0-mm column (Phenomenex, Torrance, CA) maintained at 30°C with an isocratic eluent of acetonitrile/water/methanol/acetic acid (60:30:10:0.05) at a flow rate of 0.30 ml/min. For EET hydrolysis kinetic studies, the isocratic eluent was kept for 5 min and followed by a gradient to a final composition of acetonitrile/water/methanol/acetic acid (75:15:10:0.05) in 15 min. ESI was carried out at an ion transfer tube temperature of 260°C, a spray voltage of 4.5 kV, a sheath gas flow of 34 units, and an auxiliary gas flow of 20 units (units refer to arbitrary values set by the LCQ software). MS/MS breakdown for $m/z$ 337 was at an energy level of 30% set by the instrument, and a 7-point Gaussian smoothing was applied in the mass data processing.

Statistical Analysis. Results are presented as mean ± S.E.M. Parameters of $V_{\text{max}}$, $K_{m}$, and IC$_{50}$ were analyzed with GraphPad Prism 5 software (GraphPad Software Inc., San Diego, CA) using Michaelis-Menten kinetics. One-way analysis of variance followed by a Bonferroni test for selected groups were used to analyze for differences. A $P$ value less than 0.05 was regarded as statistically significant.

Reagents. Standard cis-EETs and LTA$_{4}$, hydrolyses were purchased from Cayman Chemical (Ann Arbor, MI). Standard racemic trans-EETs were synthesized by Dr. John R. Falck (Falck et al., 2003; Jiang et al., 2004). Potent sEH inhibitors, cis- and trans-AUCB, were prepared as described previously (Hwang et al., 2007). SC22716, DCU, and AA were ordered from Sigma-Aldrich (St. Louis, MO). AA was used immediately after HPLC purification. Fatty acid-free BSA and HPLC grade organic solvents were obtained from Thermo Fisher Scientific, and EET-d8 standards were from Biomial Research Laboratories (Plymouth Meeting, PA). Recombinant murine sEH was produced in a baculovirus expression system (Grant et al., 1993) and purified by affinity chromatography. The preparations were at least 97% pure as judged by SDS-polyacrylamide gel electrophoresis and scanning densitometry. No detectable esterase or glutathione transferase activity, which can interfere with this sEH assay, was observed.

Results

Hydrolysis of EETs by Rat RBCs in PSS. Incubation of 6 ng of each cis- and trans-EETs with $4 \times 10^{9}$ rat RBCs in 2 ml of PSS at 37°C for 2 min revealed conversion of EETs to corresponding DHETs (Fig. 2). LC/MS chromatography resulted in complete separation of individual EETs and DHETs when cis- or trans-EETs were incubated separately (Fig. 2, A and B). cis-EETs were converted to threeo-DHETs (Fig. 2A), whereas trans-EETs were converted to erythro-DHETs (Fig. 2B). When eight EET isomers were incubated together with RBCs, the chromatogram was similar to a combination of individual incubations (Fig. 2C), indicating no inhibition of hydrolysis by EET isomers at 10 nM. The hydrolysis of cis- and trans-EETs by rat RBCs can be blocked by 10 $\mu$M DCU (Fig. 2D), a traditional sEH inhibitor, as well as by 100 nM cis- and trans-AUCB (similar to Fig. 2D), novel potent
sEH inhibitors. A cell-permeable LTA₄ hydrolase inhibitor, SC22716, did not inhibit EET hydrolysis by rat RBCs, and commercial LTA₄ hydrolase (25 μg/ml) did not hydrolyze cis- or trans-EETs when tested under similar conditions of incubation.

Selectivity of cis- and trans-EET Hydrolysis by Recombinant Murine sEH. When incubating recombinant murine sEH (0.5 μg/ml) with cis- or trans-EETs, preferred hydrolysis for trans- over cis-EETs and for 14,15-EETs over other regioisomers similar to the hydrolysis of RBCs (Fig. 3) was also observed. Comparative hydration rates are 121.4 ± 18.2, 55.6 ± 9.6, and 29.6 ± 4.7 nmol/min/mg protein for 14,15-, 11,12-, and 8,9-cis-EET, respectively, and 230.6 ± 35.1, 174.3 ± 31.4, and 85.8 ± 13.7 nmol/min/mg protein for 14,15-, 11,12-, and 8,9-trans-EET, respectively, for 1 μM EETs in PBS at 37°C as averaged from at least three incubations.

Active Formation and Hydrolysis of EETs by Rat RBCs. The presence of erythro-DHETs in vivo was expected as trans-EETs were identified in plasma and phospholipids (Jiang et al., 2005). LC/MS/MS spectra of erythro-DHETs produced with the hydrolysis of trans-EETs by RBCs (Fig. 3) provided the starting point for individual identification of erythro-DHETs. Incubation of AA (20 μM) with 4 x 10⁸ RBCs in 2 ml of PSS produced both threeo- and erythro-DHETs as

![Fig. 4. LC/MS/MS spectra of erythro (e)-DHETs](image)

![Fig. 5. Incubation of AA (20 μM) with 4 x 10⁸ RBCs in 2 ml of PSS for 20 min resulted in the formation and release of cis- and trans-EETs as well as threeo- and erythro-DHETs from rat RBCs. Identification of threeo- and erythro-DHETs was shown by the LC/MS/MS breakdown of ion m/z 337, [M - 1]⁺ for DHETs, A, m/z 337 → m/z 319; B, m/z 337 → m/z 207; C, m/z 337 → m/z 197; D, m/z 337 → m/z 185; and E, m/z 337 → m/z 145. DHET peaks from left to right in each duplex from B to E represent erythro- and threeo-DHET, respectively, consistent with peaks of standards in Fig. 2. LC/MS/MS analyses were carried out as described under Materials and Methods, and identification of HETEs and EETs was as reported (Jiang et al., 2007).](image)
as hydroxyeicosatetraenoic acids (HETEs) and cis-/trans-EETs (Fig. 5), suggesting that erythrocytes function as a potential source of AA-derived eicosanoids in plasma. Identification of individual erythro-DHETs by LC/MS/MS is shown in Fig. 5, whereas identification of HETEs and cis-/trans-EETs was as reported previously (Jiang et al., 2007). Breakdown of m/z 337 to m/z 237 is ideal for the MS/MS identification of 14,15-DHETs (Fig. 4). The selection of m/z 207 for the identification of 14,15-DHETs (Fig. 5) is based on the observation that MS/MS product ions with weaker abundances, such as m/z 237 for 14,15-DHETs and m/z 207 for 11,12-DHETs, do not show up in the analysis of barely detectable amounts of DHETs. Using the same method of analysis, both free erythro- and three-DHETs were identified in rat plasma with the total amount at 1.0 ± 0.2 ng/ml; erythro-DHETs accounted for approximately one fourth of the total free DHETs (n = 3).

**EET Hydrolysis by Rat RBCs Compared with Other Blood Fractions.** Comparison of EET hydrolysis by rat plasma, buffy layer, and RBCs revealed predominant EET hydrolysis by RBCs in blood. EETs were not hydrolyzed by plasma, particularly when there was no hemolysis. The buffy layer containing most of the leukocytes and platelets in blood hydrolyzed EETs, approximating 9.1 ± 2.2% (n = 4) of the hydrolysis by rat RBCs as calculated from the hydrolysis of 14,15-, 11,12-, and 8,9-cis- or trans-EETs (1 µM) for 5 min at 37°C.

**Localization of Epoxide Hydrolases in Rat RBCs.** Localizing the specific epoxide hydrolase for EET hydrolysis in rat RBCs disclosed its major existence in the cytosol of RBCs. The rat RBC membrane residue accounted for 11.9 ± 5.1 and 9.4 ± 4.5% (n = 4) of the total hydrolysis of trans- and cis-EETs by RBCs, respectively, as identified by the conversion of 1 µM 14,15-EETs to their respective DHETs. When 0.2% BSA was included in the buffer for the study, the specific activity of rat RBCs or cytosol to hydrolyze EETs at 1 µM fell to an approximately 10 to 20% level (n = 4), indicating considerable inhibition of EET hydrolysis by BSA binding of EETs.

**Protein Analysis of Erythrocyte sEH.** Total protein concentration of the prepared cytosol of rat RBCs corresponding to 2 or 4 × 10⁸ RBCs/ml was 4.8 ± 0.6 mg/10⁸ RBCs (n = 6), indicating less than 50% recovery of hemoglobin in the prepared cytosol after centrifugation and filtration. Whereas a dense band was detected for the positive control in Western blots of sEH (Fig. 6), weaker bands were observed for the samples, suggesting a concentration of sEH protein to be approximately 2 µg/mg protein or 0.4 µg/10⁸ RBCs based on densitometry comparisons. The last rat erythrocyte cytosol (sample 3) was freshly prepared and frozen, whereas samples 1 and 2 had been stored and frozen at −20°C for 5 months, which may explain the lighter sEH band than the one observed for sample 3.

**Kinetics of Erythrocyte sEH on EET Hydrolysis.** Kinetic studies of the sEH activities of rat RBCs were tested using 50 µl of RBCs (2 × 10⁸ RBCs/ml) in PSS without BSA for 0.1 to 4 µM 14,15-, 11,12-, and 8,9-cis- or trans-EETs (Fig. 7). The specific EET hydrolysis at 4 µM were excluded in the kinetic analysis (Table 1) because of distortion of the kinetic parameters caused by apparent inhibition of the hydrolysis of

![Fig. 6. Western blots of sEH in the cytosol of rat RBCs. Recombinant marine sEH (C, 500 ng) and 50 µg of protein of the rat erythrocyte cytosolic samples were loaded for analysis. The last rat erythrocyte cytosol (sample 3) was freshly prepared and frozen, whereas samples 1 and 2 had been stored and frozen at −20°C for 5 months. Western blots were carried out as described under Materials and Methods.](image)

![Fig. 7. Representative LC/MS chromatograms (m/z 337 + m/z 319) of the kinetic analysis of rat RBCs on the hydrolysis of 14,15-, 11,12-, and 8,9-cis-EETs (A) and 14,15-, 11,12-, and 8,9-trans-EETs (B). Insets in the middle are the Michaelis-Menten data. Studies were carried out as described under Materials and Methods.](image)

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Kinetics of EET (0.1–2 µM each in groups of trans- or cis-EETs) hydrolysis by rat intact RBCs (n = 8–15)</th>
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<tr>
<td>EETs</td>
<td>Vₘₐₓ</td>
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<tr>
<td>14,15-trans-EET</td>
<td>2.35 ± 0.24</td>
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<tr>
<td>11,12-trans-EET</td>
<td>1.48 ± 0.21</td>
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<tr>
<td>8,9-trans-EET</td>
<td>0.68 ± 0.39</td>
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<tr>
<td>14,15-cis-EET</td>
<td>0.86 ± 0.23</td>
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<td>11,12-cis-EET</td>
<td>0.26 ± 0.08</td>
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<td>8,9-cis-EET</td>
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<th>Table 2</th>
<th>Kinetics of EET (0.2–4 µM individually) hydrolysis by rat erythrocyte cytosol (n = 7–11)</th>
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<tr>
<td>EETs</td>
<td>Vₘₐₓ</td>
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<tr>
<td>14,15-trans-EET</td>
<td>3.59 ± 0.37</td>
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<tr>
<td>11,12-trans-EET</td>
<td>2.72 ± 0.22</td>
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<tr>
<td>8,9-trans-EET</td>
<td>1.24 ± 0.24</td>
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<tr>
<td>14,15-cis-EET</td>
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<td>11,12-cis-EET</td>
<td>0.77 ± 0.10</td>
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<tr>
<td>8,9-cis-EET</td>
<td>0.53 ± 0.06</td>
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*Values were obtained by analyzing substrate concentrations from 0.2 to 2 µM. Hydrolysis of 14,15-cis-EET at 4 µM by erythrocyte cytosol was greatly enhanced, not conforming to Michaelis-Menten kinetics possibly due to further hydrolysis by LTA₄ hydrolase (McGee and Fitzpatrick, 1985).*
8,9-EETs by 14,15-EETs that have a greater affinity for the sEH in RBCs. The $V_{\text{max}}$ of rat RBCs for trans-EET hydrolysis was greater by 3-fold or more than the $V_{\text{max}}$ for cis-EETs.

Erythrocyte EETs were mostly esterified in RBC membranes; the presence of cytosolic EETs and DHETs was minimal. Kinetic analyses of individual EETs were carried out using 50 μl of RBC cytosol corresponding to $1 \times 10^8$ RBCs to exclude factors affecting EET uptake and DHET release, as well as endogenous EETs. A more accurate exclusion of factors affecting EET uptake and DHET release, as well as endogenous EETs. A more accurate

Discussion

The preferred hydrolysis of 14,15-EETs and trans-epoxides characterizes sEH activities in rat RBCs. Incubation of rat RBCs with 10 nM EETs in PSS demonstrated that hydration of trans-EETs by RBCs was at rates that differ by more than three folds from hydration rates of the corresponding cis-EETs (Fig. 3). The rates of EET hydrolysis by rat RBCs decreased at approximately 2 to 3-fold sequentially from 14,15-, 11,12-, and 8,9- to 5,6-EETs for both the cis- and trans-isomers. The results are in accord with the report that 14,15-cis-EET was found to be hydrolyzed faster than other cis-regiosomers by sEH (Zeldin et al., 1995). 5,6-EETs are hydrolyzed the least by rat RBCs, consistent with the inability of the 5,6-EET to serve as a suitable substrate for liver sEH (Chacos et al., 1983).

The 3 to 5-fold greater specific hydrolysis of trans- relative to cis-EET by rat RBCs at 10 nM (Fig. 2 and 3) presumably is a combined result of sEH, membrane epoxide hydrolase, membrane transport, inhibition by albumin, as well as contributions of endogenous EETs. Nevertheless, the result may reflect de facto EET hydrolysis by RBCs in vivo. The RBC LTA₄ hydrolyase that has a $K_m$ of 20 μM for 14,15-cis-EET (McGee and Fitzpatrick, 1985) will probably not play a significant role in hydrolyzing EETs at low nanomolar concentrations. Hydrolysis of EETs by RBCs was immediate (Fig. 2), indicating rapid uptake of EETs and rapid release of DHETs by RBCs. The uptake of trans-EETs by RBCs may be faster than that of cis-EETs, considering that trans-EETs are more hydrophobic than cis-EETs as was also evidenced by the later elution of trans-EETs than cis-EETs, respectively, in reversed-phase HPLC separations (Fig. 2). We have reported that the cystic fibrosis transmembrane conductance regulator and panexrin-1 are involved in the secretion of EETs from rat RBCs (Jiang et al., 2007). Fatty acid-binding proteins are known to inhibit hydrolysis of EETs by sEH (Widstrom et al., 2003), as was manifested by inclusion of 0.2% fatty acid-free BSA in the incubations that resulted in over 80% inhibition of the rate of EET hydrolysis.

The $V_{\text{max}}$ for trans-EET hydrolysis is approximately 3-fold or greater than that of cis-EETs, respectively, when testing incubations of 0.1 to 2 μM of the three cis- or trans-EETs together with rat intact RBCs (Table 1). The diminution of the hydrolysis of 8,9-EETs when incubating the three cis- or trans-EETs together at 4 μM, respectively, suggested substrate saturation and greater affinity of 14,15- and 11,12-EETs than 8,9-EETs for the sEH, as was also confirmed by individual EET kinetics obtained with the erythrocyte cytosol (Table 2). Nonconformance to the Michaelis-Menten kinetics for the hydrolysis of 14,15-cis-EET at concentrations of 4 μM is probably caused by involvement of LTA₄ hydrolyase in the erythrocyte cytosol (McGee and Fitzpatrick, 1985).

The highly similar regio and geometric selectivity of EET hydrolysis by recombinant murine sEH and rat erythrocyte cytosol suggests either identity or close similarity of erythrocyte and hepatic sEH. Western blots of sEH suggested that a concentration of sEH protein is approximately 2 μg/mg protein or 0.4 μg/10⁹ RBCs (Fig. 6). The apparent $K_m$ of 1 to 2 μM EETs for rat RBCs is comparable with the $K_m$ of 3 to 5 μM EETs for the purified mouse liver sEH (Zeldin et al., 1995). The apparent $K_m$ and $V_{\text{max}}$ of rat erythrocyte for the hydrolysis of cis-EETs approximate those of the sEH in human leukocytes for the hydrolysis of cis-stilbene oxide (Seidegård et al., 1984). Purification of enzymes involves procedures that can increase or decrease specific activities of an enzyme. Thus, it may not be appropriate to compare the $V_{\text{max}}$ of erythrocyte cytosol with $V_{\text{max}}$ of purified sEH.

The divergent abilities of LTA₄ hydrolyse to hydrolyze LTA₄ and cis-EETs seem to preclude erythrocyte LTA₄ hydrolyse as an effective sEH that hydrolyzes cis-EETs (McGee and Fitzpatrick, 1985). This is consistent with the inability of the LTA₄ hydrolyase inhibitor, SC22716, to affect EET hydrolysis as well as the inability of commercial LTA₄ hydrolyse to hydrolyze EETs as tested in the present study. The LTA₄ sEH purified from human erythrocytes hydrolyzes 14,15-cis-EET with a $K_m$ of 20 μM (McGee and Fitzpatrick, 1985), which is 20-fold greater than the $K_m$ of sEH for 14,15-cis-EET in our study. Despite LTA₄ and trans-EETs sharing the trans-epoxide configuration, sEH demonstrated extraordi-

Fig. 8. Concentration-response curves of sEH inhibitors, cis-AUCB and trans-AUCB as well as DCU on the hydrolysis of trans-EETs (1 μM). Each point is the mean ± S.E.M. of $n = 3$ to 4.
nary specificity for substrate selection. The presence of sEH in RBCs is further supported by inhibition of EET hydrolysis by sEH inhibitors, cis- and trans-AUCB (Fig. 8).

This study mainly addressed the comparison of added cis- and trans-EET hydrolysis by rat erythrocytes because comparable amounts of cis- and trans-EETs are present in plasma and erythrocyte phospholipids (Jiang et al., 2005). The conversion of AA to EETs and HETEs by rat RBCs (Fig. 5) is a function of hemoglobin-activating oxygen in a monoxygenase-like fashion (Starke et al., 1984). Peroxy radicals of AA may mediate the formation of more trans- than cis-EETs in RBCs (Jiang et al., 2004). EETs in vivo demonstrate chiral prevalences (Wei et al., 2006), and regio- and enantioselectivity have been identified for the enzymatic hydration of cis-EET enantiomers (Zeldin et al., 1993, 1995). Analysis of the chirality of trans-EET isomers and their enantioselectivity for hydration has yet to be carried out.

It is a challenge to estimate the relative contributions to the hydrolysis of EETs by RBCs and by specific organs. However, the role of erythrocyte sEH in the regulation of circulating EETs may be particularly significant when considering potential effects of EETs on the rheological and hemodynamic determinants of the circulation, such as in cardiovascular and hematological diseases, as well as physiological implications for regulating blood flow in the microcirculation. Release of EETs from RBCs into the circulation in response to ATP stimulation of the erythrocyte P2X<sub>7</sub> receptor (Jiang et al., 2007) will contribute to activation of endothelial peroxisome proliferator-activated receptor γ transcription by EETs (Liu et al., 2005), which is magnified through elevating EETs at the blood-endothelial interface in response to inhibition of sEH in RBCs. Activation of peroxisome proliferator-activated receptor γ inhibits nuclear factor κB-mediated expression of adhesion molecules and endothelin that promotes vascular wall damage and atherosclerosis (Liu et al., 2005). Furthermore, localization of sEH in the RBC and the increase of EETs resulting from its inhibition presumably contributes to elevating the positive effects of EETs on regional blood flows to a greater degree than sEH localized “in the smooth muscle layers of the arterial wall” (Yu et al., 2004).

This study revealed preferential hydrolysis of trans- over cis-EETs and the presence of sEH in rat RBCs. Angiotensin II up-regulates sEH expression in the vascular endothelium (Ai et al., 2007); sEH inhibition greatly lowered systolic blood pressure in angiotensin II-induced hypertensive rats (Imig et al., 2002, 2005) and stroke (Zhang et al., 2007), as well as amelioration of inflammation (Schmelzer et al., 2005). Because plasma trans-EET levels would increase more than cis-EETs with sEH inhibition, the potential functional roles of trans-EETs and erythrocyte sEH in terms of contributing to the regulation of the circulation deserve attention.

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References


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