DMD Fast Forward. Published on August 6, 2009 as doi:10.1124/dmd.109.028530
This article has not been copyedited and formatted. The final version may differ from this version.

DMD 28530

# Expression and Characterization of CYP4V2 as a Fatty Acid ω-Hydroxylase

Mariko Nakano, Edward J. Kelly and Allan E. Rettie

Departments of Medicinal Chemistry (M.N., A.E.R.) and Pharmaceutics (E.J.K.), School of Pharmacy, University of Washington, WA 98195, USA.

**Running title:** CYP4V2 Substrate Specificity

**Corresponding author:**

Allan E. Rettie

Department of Medicinal Chemistry, Box 357610

School of Pharmacy, University of Washington

Seattle, WA 98195-7610

E-mail: rettie@u.washington.edu

Number of Text Pages: 15

Number of Tables: 1

Number of Figures: 3

Number of References: 15

Number of Word in Abstract: 160

Number of Words in Introduction: 293

Number of Words in Discussion: 562

**Abbreviations:**

P450, cytochrome P450; BCD, Bietti's corneo-retinal crystalline dystrophy; HET0016 (N-hydroxy-N'-(4-n-butyl-2-methylphenyl formamidine).

ABSTRACT

Bietti's crystalline dystrophy is an ocular disease which is strongly associated with polymorphisms in the *CYP4V2* gene. CYP4 enzymes are typically microsomal fatty acid ω-hydroxylases that function together with mitochondrial and peroxisomal β-oxidation enzymes to degrade cellular lipids. Indeed, ocular and peripheral cells cultured from Bietti's patients have been reported to exhibit abnormal lipid metabolism. However, CYP4V2 possesses low sequence homology to other members of the CYP4 family. Therefore, we cloned and expressed CYP4V2 and analyzed the functional characteristics of this new P450 enzyme. We find that CYP4V2 is a selective ω-hydroxylase of saturated, medium-chain fatty acids with relatively high catalytic efficiency towards myristic acid. Moreover, HET0016 is a nanomolar inhibitor of the enzyme. Therefore, CYP4V2 exhibits catalytic functions typical of a human CYP4 enzyme, but with a distinctive chain-length selectivity coupled with high ω-hydroxylase specificity. Consequently, defective ω-oxidation of ocular fatty acids/lipids secondary to mutations in the *CYP4V2* gene appears to be a plausible mechanism underlying Bietti's crystalline dystrophy.

## INTRODUCTION

CYP4V2, a relatively new member of the pantheon of human cytochrome P450 enzymes, is termed an 'orphan P450' because its substrate specificity and physiological roles are unknown (Stark and Guengerich, 2007). The issue of CYP4V2's substrate specificity is important because an intriguing genetic association has emerged between *CYP4V2* and a rare ocular disorder known as Bietti's corneo-retinal crystalline dystrophy (BCD) (Bietti, 1937). BCD is a progressive disease that leads to atrophy of the retinal epithelium, constriction of the visual field and night blindness. Potentially disruptive exonic and intronic mutations in the *CYP4V2* gene were identified originally in nearly two dozen BCD patients, and subsequently many investigators have corroborated this gene defect (Li et al., 2004; Wada et al., 2005; Nakamura et al., 2006). Given the well recognized role of other CYP4 enzymes in fatty acid metabolism, a deficiency in this catalytic function of CYP4V2 in BCD patients is an attractive hypothesis.

The prototypic enzymatic reaction of the CYP4 enzymes is fatty acid ω-hydroxylation. However, CYP4V2 is an unusual CYP4 enzyme in that gene resides on human chromosome 4, separate from the CYP4ABXZ and CYP4F gene clusters on chromosomes 1 and 19 (Hsu et al., 2007), respectively, and has very low sequence identity (31-37%) to other CYP4 enzymes (Rettie and Kelly, 2008). These observations raise the question of how closely CYP4V2's catalytic capabilities resemble those of other human CYP4 enzymes, delineation of which is a first step towards elucidating the role of the enzyme in BCD. Therefore, the goals of the present study were to clone and express CYP4V2 and to characterize the enzyme's functional behavior towards saturated fatty acids and the formamidine derivative, HET0016, which is emerging as a high affinity inhibitor of many of the human CYP4 isoforms (Miyata et al., 2005).

DMD Fast Forward. Published on August 6, 2009 as DOI: 10.1124/dmd.109.028530
This article has not been copyedited and formatted. The final version may differ from this version.



## METHODS

*Chemicals.* NADPH, BSTFA, octanoic acid, lauric acid, myristic acid, palmitic acid, 8-hydroxy octanoic acid, 12-hydroxy lauric acid, 16-hydroxy palmitic acid, 14-hydroxytetradeca-10, 12-diynoic acid, Ex-Cell 420 media and δ-aminolevulinic acid were obtained from Sigma-Aldrich (St. Louis, MO). The ω-1, ω-2 and ω-3 hydroxy lauric acid, -myristic acid and -palmitic acid metabolites were generated biologically using recombinant CYP102 that was kindly provided by Dr. Rheem Totah (University of Washington, Seattle). ω-1 Hydroxy octanoic acid was generated from recombinant rabbit CYP4B1. 14-Hydroxy myristic acid was synthesized as described previously (Lillemin et al., 1984) and the product confirmed by GC-MS and NMR. HET0016 was obtained from Cayman Chemicals (Ann Arbor, MI).

*CYP4V2 cloning and baculovirus production.* The cDNA for *CYP4V2* (I.M.A.G.E. clone ID 30333559) was purchased from ATCC, and a recombinant baculovirus containing *CYP4V2* with a hexahistidine tag was generated using the Bac-to-Bac® Baculovirus expression system (Invitrogen, Carlsbad, CA). Briefly, to obtain the full length cDNA with the hexahistidine tag, *CYP4V2* was amplified by PCR with the specific primers, 5'-GCG CGA ATT CAT GGC GGG GCT CTG GCT GGG G-3' and 5'-GCG CGT CGA CTT AAT GAT GAT GAT GAT GAT GGC GTT CAT CTG C-3'. This PCR product was double digested and subcloned into the pFastBac1 vector via the cloning sites, EcoRI and Sal1 to generate the construct, pFastbacCYP4V2HIS. DH10Bac *E. coli* was transfected with pFastbacCYP4V2HIS to obtain the recombinant bacmid DNA. Recombinant baculovirus was produced in sf9 cells (*Spodoptera frugiperda)* by transformation with bacmid DNA. The presence of *CYP4V2* in both bacmid and recombinant baculovirus was confirmed by PCR and sequence analysis.

*Baculovirus expression of CYP4V2.* Hexahistidine-tagged CYP4V2 was expressed in sf9 cells following infection with the recombinant baculovirus. Mock-infected cells were also prepared as a control. Sf9 cells were grown the suspension culture using Ex-Cell 420 media containing 2.5% FBS and antibiotics-antimycotics. The expression culture was supplemented with 0.3 mM δ-aminolevulinic acid and 0.2 mM ferric citrate 24 hours after infection with the recombinant virus. Cells were harvested 72 hours after infection. The microsomal fraction of cells was prepared by differential ultracentrifugation and CYP4V2 expression confirmed by SDS-PAGE analysis (9%) with Coomassie blue staining and Western blotting with an hexa-histidine antibody (Qiagen, Valencia, CA).

*Reduced CO-bound spectra.* Reduced, carbon monoxide (CO)-bound spectra were recorded on a Cary 300 UV/VIS Spectrometer. Briefly, dithionite and 1.2 μM methyl viologen were added to microsomal samples diluted in 100 mM potassium phosphate, pH 7.4, containing 0.5 mM EDTA and 20% glycerol. After bubbling with CO gas, holo-P450 concentrations were measured using an extinction coefficient of 91 $mM^{-1}cm^{-1}$ (450-500nm).

*Metabolic incubations.* Microsomal CYP4V2 was mixed with purified NADPH-cytochrome P450 reductase and cytochrome $b_5$ at a molar ratio of 1:2:1, respectively in a total volume of 500 μL of 100 mM potassium phosphate buffer (pH 7.4). Saturated fatty acids, dissolved in DMSO, were added followed by pre-incubation for 2 min at 37˚C in a water bath. Metabolic reactions were initiated by the addition of 1 mM NADPH and allowed to proceed for 20 minutes. Reactions were quenched with 500 μL of cold 10% hydrochloric acid. Samples were spiked with 2.5 μg of the internal standard (15-hydroxy pentadecanoic acid for lauric acid, myristic acid and palmitic acid metabolite assays, or 12-hydroxy lauric acid for the octanoic acid metabolite assay) and extracted twice with ethyl acetate. Pooled organic extracts were dried

under $N_2$ stream and reconstituted with ethyl acetate (50 µl). The same volume of BSTFA [(N,O-bis(trimethylsilyl)trifluoroacetate] was added to the samples which were heated at 90°C for 45 min and analyzed by GC-MS.

*GC-MS analysis.* Derivatized extracts were analyzed on a Shimadzu GCMS-QP5050A or HP5986 GC-FID fitted with a fused silica capillary column coated with a DB-1 stationary phase. Lauric acid metabolism were assayed as described previously (Guan et al., 1998). Myristic acid and palmitic acid incubation extracts were injected at a temperature of 100ºC. After 2 minutes, the oven temperature was raised at 40ºC/min to 200ºC, held for 1 min, then raised at 4ºC/min to 245ºC, and finally at 30ºC/min to 290ºC. Under these conditions, the derivatized ω, ω-1, ω-2 and ω-3 hydroxylated metabolites of myristic acid (and palmitic acid) eluted at 12.4 (15.3), 11.3 (14.2), 11.0 (13.9) and 10.6 (13.5) min respectively. Derivatized extracts from octanoic acid incubations were also injected at an initial temperature of 100ºC. After 2 minutes, the oven temperature was raised at 40ºC/min to 130ºC, held for 2 min, then raised at 4ºC/min to 210ºC, and finally at 30ºC/min to 290ºC. Under these conditions, the derivatized ω and ω-1 hydroxylated metabolites of octanoic acid eluted at 12.9 and 11.2 min respectively. Rate data were calculated from standard curves generated with authentic ω-hydroxy metabolites.

*Kinetic analysis.* Kinetic parameters for CYP4V2-dependent fatty acid ω-hydroxylation were obtained by nonlinear regression analysis of rate data generated from substrate concentrations between 1.6 and 300 µM using GraphPad Prism®.

*Inhibition by HET0016.* Reconstituted microsomal CYP4V2 was incubated, as described above, with lauric acid (100 µM) and NADPH in the presence of 1-1000 nM HET0016 (N-hydroxy-N'-(4-n-butyl-2-methylphenyl formamidine). The $IC_{50}$ of HET0016 for CYP4V2-dependent lauric acid ω-hydroxylation was also determined using GraphPad Prism®.

RESULTS and DISCUSSION

CYP4V2 was successfully expressed in insect cell microsomes as evidenced by the protein band near 55 kDa that is visualized by Coomassie-staining in Figure 1a and by immunoblotting with an anti-His6 antibody in Figure 1b. The presence of holo-CYP4V2 was confirmed spectrophotometrically by the carbon monoxide difference spectrum obtained in Figure 1c. The specific content of CYP4V2 insect cell microsomes was 0.2 nmol/mg protein, and total expression levels of holo-CYP4V2 in culture were estimated at ~50 nmol/litre.

The catalytic activity of CYP4V2 was first evaluated against lauric acid because ω-hydroxylation of this substrate is the prototypical reaction of the CYP4A family of enzymes (Okita and Okita, 2001). Figure 2 demonstrates that CYP4V2 is an NADPH-dependent lauric acid hydroxylase with high selectivity for ω-hydroxylation. Kinetic parameters ($K_M$ and Vmax) for 12-hydroxy lauric acid formation by CYP4V2 were 140±20 μM and 3.7±0.27 pmol/pmol/min, respectively.

Next, we evaluated the chain-length specificity over the range C8-C16 for CYP4V2-dependent metabolism of saturated fatty acids (Table 1). Only trace amounts of internally hydroxylated metabolites were detected. Octanoic acid was not detectably ω-hydroxylated by CYP4V2, but palmitic acid, like lauric acid, was selectively ω-hydroxylated by CYP4V2 at a comparable rate, but with a three-fold higher Km. Likewise, myristic acid was selectively ω-hydroxylated by CYP4V2, a reaction that proceeded with the highest catalytic efficiency of all the substrates examined (Table 1). This metabolic profile differs from CYP4B1 and CYP4F enzymes which show a preference for shorter chain (Fisher et al., 1998) and longer-chain (Hardwick, 2008) fatty acids, respectively. CYP4V2 displays a similar chain-length specificity to CYP4A11 (Hardwick, 2008), but differs from this latter isoform in its selectivity for ω-

hydroxylation of myristic acid and palmitic acid. These data demonstrate that CYP4V2 is a saturated fatty acid hydroxylase with regioselectivity and chain-length specificities that distinguish the enzyme from other well characterized human CYP4 isoforms.

The P450 inhibitor, HET0016, has been used extensively in renal P450 physiology for its ability to inhibit 20-HETE, a metabolite of arachidonic acid that regulates renal vascular function (Maier and Roman, 2001). HET0016 is a potent and selective inhibitor of CYP4A and CYP4F isoforms exhibiting IC50s in the low nanomolar region (Miyata et al., 2005). This compound also inhibits CYP2C9, CYP2D6 and CYP3A4, but with ~1000-fold lower potency (Miyata et al., 2001). Therefore, we evaluated the inhibitory potency of HET0016 towards CYP4V2-mediated lauric acid metabolism for further evidence of a ligand selectivity indicative of a CYP4 family enzyme. Inhibition of 12-hydroxylauric acid metabolite formation was concentration dependent with an $IC_{50}$ of 38 nM (Figure 3). This finding extends the array of P450 CYP4 sub-families susceptible to potent inhibition by HET0016.

In summary, we report the first functional analysis of recombinant human CYP4V2. Despite its low sequence homology to other members of the CYP4 family, CYP4V2 displays catalytic properties that are characteristic of other members of the human CYP4 family in that the enzyme is a selective fatty acid ω-hydroxylase and is potently inhibited by HET0016. EST tag analysis reveals that CYP4V2 is widely distributed and present in the eye (http://www.ncbi.nlm.nih.gov/UniGene/ESTProfileViewer.cgi?uglist=Hs.237642). Collectively, these observations suggest that ocular CYP4V2 may play a role in fatty acid homeostasis in the eye. Moreover, it seems plausible that defective ω-oxidation of ocular fatty acids/lipids secondary to mutations in the *CYP4V2* gene could contribute to the etiology of BCD. Functional studies with polyunsaturated fatty acids, found at high concentrations in the eye, are underway.

REFERENCES

Bietti G (1937) Ueber familiaeres vorkommen von 'retinitis punctata albescens' (verbunden mit dystrophia marginalis cristallinea corneae), glitzern des glaskoerpers und anderen degenerativen augenveraenderungen. *Klin Mbl Augenheilk* **99:**737-757.

Fisher MB, Zheng YM and Rettie AE (1998) Positional specificity of rabbit CYP4B1 for omega-hydroxylation1 of short-medium chain fatty acids and hydrocarbons. *Biochem Biophys Res Commun* **248:**352-355.

Guan X, Fisher MB, Lang DH, Zheng YM, Koop DR and Rettie AE (1998) Cytochrome P450-dependent desaturation of lauric acid: isoform selectivity and mechanism of formation of 11-dodecenoic acid. *Chem Biol Interact* **110:**103-121.

Hardwick JP (2008) Cytochrome P450 omega hydroxylase (CYP4) function in fatty acid metabolism and metabolic diseases. *Biochem Pharmacol* **75:**2263-2275.

Hsu MH, Savas U, Griffin KJ and Johnson EF (2007) Human cytochrome p450 family 4 enzymes: function, genetic variation and regulation. *Drug Metab Rev* **39:**515-538.

Li A, Jiao X, Munier FL, Schorderet DF, Yao W, Iwata F, Hayakawa M, Kanai A, Shy Chen M, Alan Lewis R, Heckenlively J, Weleber RG, Traboulsi EI, Zhang Q, Xiao X, Kaiser-Kupfer M, Sergeev YV and Hejtmancik JF (2004) Bietti crystalline corneoretinal dystrophy is caused by mutations in the novel gene CYP4V2. *Am J Hum Genet* **74:**817-826.

Lillemin D, Cadiot P and Kuetagan P (1984) A new synthesis of w-hydroxyalkanoic acids via copper catalysis. *Synthesis* **3:**230-231.

Maier KG and Roman RJ (2001) Cytochrome P450 metabolites of arachidonic acid in the control of renal function. *Curr Opin Nephrol Hypertens* **10:**81-87.

Miyata N, Seki T, Tanaka Y, Omura T, Taniguchi K, Doi M, Bandou K, Kametani S, Sato M, Okuyama S, Cambj-Sapunar L, Harder DR and Roman RJ (2005) Beneficial effects of a new 20-hydroxyeicosatetraenoic acid synthesis inhibitor, TS-011 [N-(3-chloro-4-morpholin-4-yl) phenyl-N'-hydroxyimido formamide], on hemorrhagic and ischemic stroke. *J Pharmacol Exp Ther* **314:**77-85.

Miyata N, Taniguchi K, Seki T, Ishimoto T, Sato-Watanabe M, Yasuda Y, Doi M, Kametani S, Tomishima Y, Ueki T, Sato M and Kameo K (2001) HET0016, a potent and selective inhibitor of 20-HETE synthesizing enzyme. *Br J Pharmacol* **133:**325-329.

Nakamura M, Lin J, Nishiguchi K, Kondo M, Sugita J and Miyake Y (2006) Bietti crystalline corneoretinal dystrophy associated with CYP4V2 gene mutations. *Adv Exp Med Biol* **572:**49-53.

Okita RT and Okita JR (2001) Cytochrome P450 4A fatty acid omega hydroxylases. *Curr Drug Metab* **2:**265-281.

Rettie AE and Kelly EJ (2008) The CYP4 Family, in: *Cytochrome P450:Role in the metabolism and toxicity of drugs and other xenobiotics.* (C. I ed), Royal Society of Chemistry, London.

Stark K and Guengerich FP (2007) Characterization of orphan human cytochromes P450. *Drug Metab Rev* **39:**627-637.

Wada Y, Itabashi T, Sato H, Kawamura M, Tada A and Tamai M (2005) Screening for mutations in CYP4V2 gene in Japanese patients with Bietti's crystalline corneoretinal dystrophy. *Am J Ophthalmol* **139:**894-899.

FOOTNOTES

This work was supported in part by the National Institutes of Health [Grant GM 49054)].

LEGENDS TO FIGURES

Figure 1. Analysis of CYP4V2 expressed in insect cells by (a) SDS-PAGE with Coomassie staining, (b) Western blotting with an anti-His6 antibody. Lane 1. Molecular Weight markers. Lane 2: Microsomes from mock-infected Sf9 cells. Lane 3: Microsomes from Sf9 cells infected with baculovirus containing CYP4V2. Lanes 2 and 3 were loaded with 10 μg protein. (c) Carbon monoxide difference spectrum of CYP4V2-containing insect cell microsomes demonstrating absorbance of holo-P450 at ~450nm.

Figure 2. GC-MS analysis of lauric acid metabolites. (a) bis-TMS derivatives of hydroxy lauric acid standards monitored at *m/z* 345, 117, 131, 145 for 12-, 11-, 10- and 9-hydroxy lauric acid, respectively. The derivatized internal standard (IS), 15-hydroxypentadecanoic acid, was monitored at m/z 387. (b) Metabolites produced from CYP4V2 microsomes in the absence of NADPH. Similar data were obtained with NADPH and mock-transfected insect cells (c) Metabolites produced from CYP4V2 microsomes in the presence of NADPH. A trace amount of 11-hydroxy lauric acid was formed, but this is not evident in the chromatographic traces because the ion current intensities are normalized to the major product.

Figure 3. Effect of HET0016 (1-1000 nM) on CYP4V2-catalyzed ω-hydroxylation of lauric acid (100 μM). HET0016 is a potent inhibitor of CYP4V2, as evidenced by the $IC_{50}$ value of 38 nM.

DMD Fast Forward. Published on August 6, 2009 as DOI: 10.1124/dmd.109.028530
This article has not been copyedited and formatted. The final version may differ from this version.



Table 1. CYP4V2-dependent Metabolism of Saturated Fatty Acids

| Fatty acid | Metabolite* | $K_M$ (μM) | Vmax (nmol/nmol/ min) | $V_{max}/K_M$ (μl/nmol/ min) | ω/ ω -1** |
|---|---|---|---|---|---|
| Octanoic acid | 8-OH octanoate | —* | <0.1 | —* | —* |
| Lauric acid | 12-OH laurate | 140 ± 20 | 3.7 ± 0.27 | 26 | >20:1 |
| Myristic acid | 14-OH myristate | 65 ± 7.4 | 2.3 ± 0.07 | 35 | >20:1 |
| Palmitic acid | 16-OH palmitate | 430 ± 89 | 3.5 ± 0.26 | 8.1 | >10:1 |

* ω-Hydroxy metabolites of the C8-C16 substrates were detected as the molecular ions of the TMS derivatives at *m/z* 289, 345, 373 and 401, respectively.

** Reaction velocities were below quantifiable levels.

*** Regioselectivity was determined by GC-FID analysis of the TMS derivatives, assuming an equal detector response for the ω and ω-1 metabolites.

Figure 1.

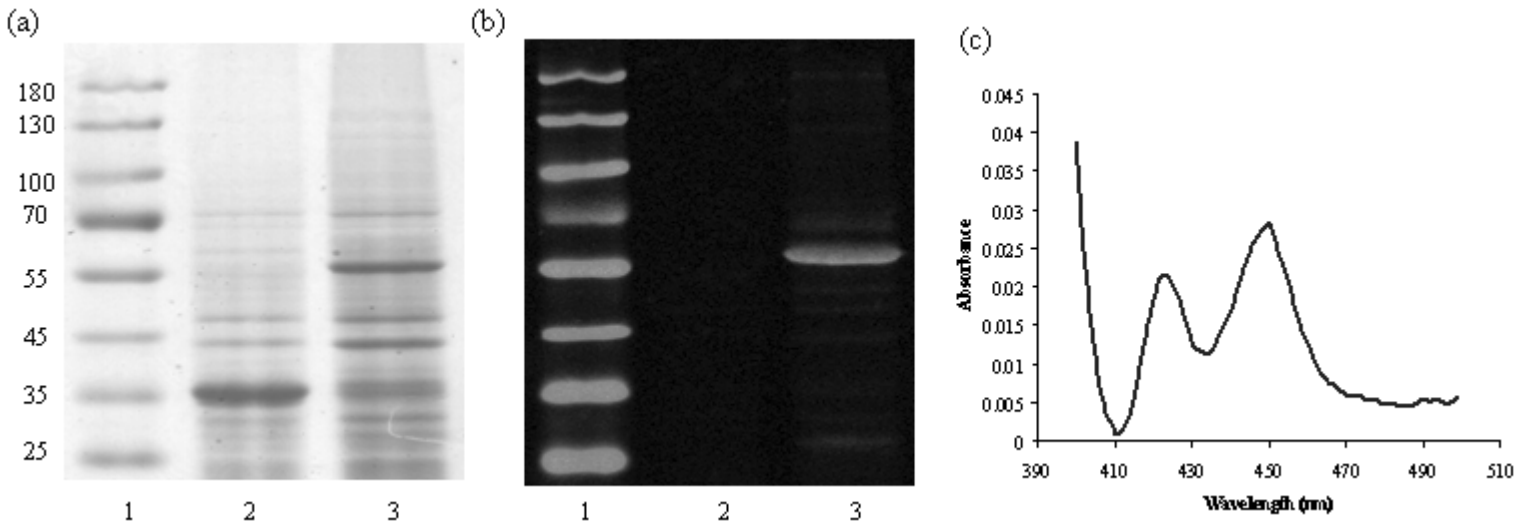

Figure 2

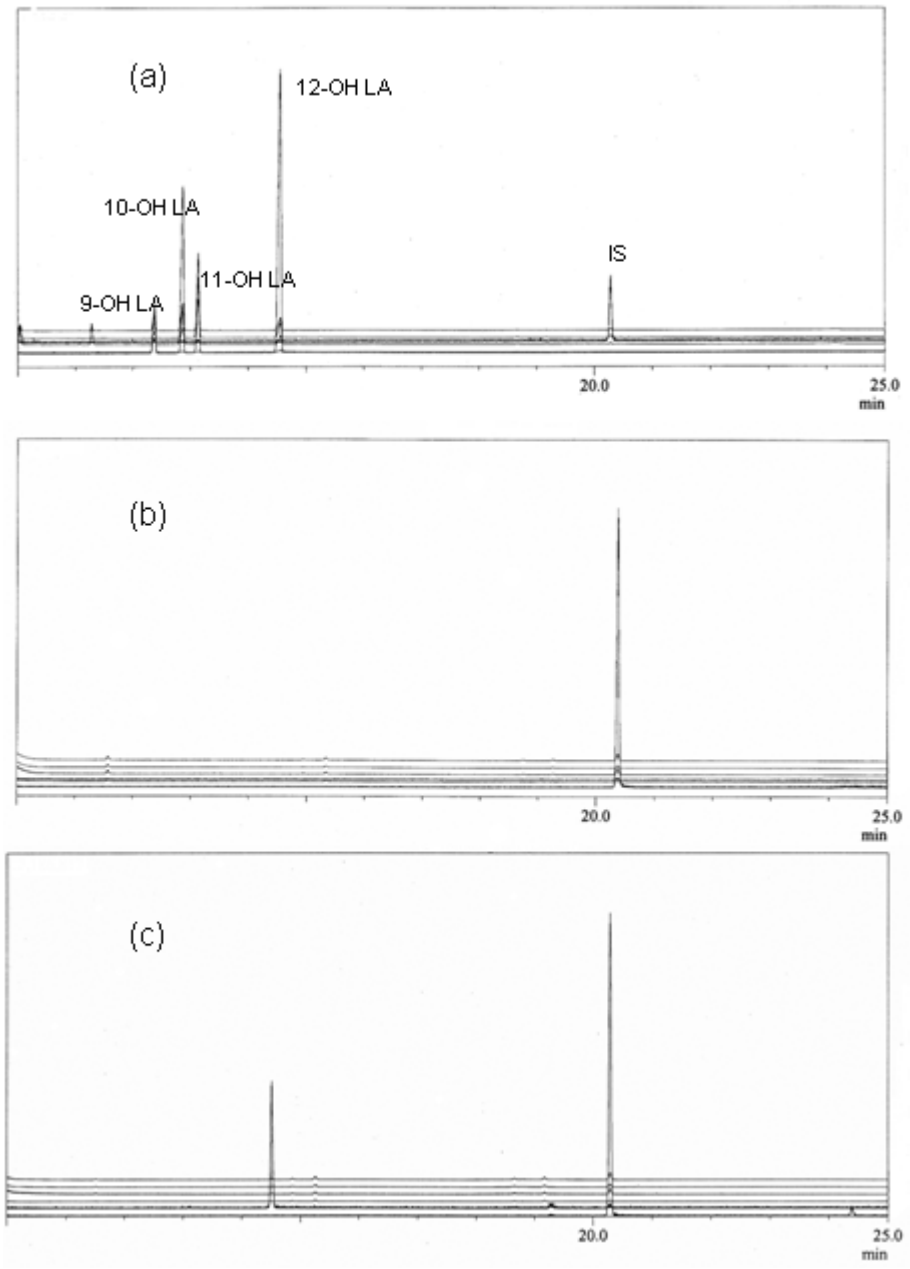

Figure 3.