Optimized Inhibitors of Soluble Epoxide Hydrolase Improve in Vitro Target Residence Time and in Vivo Efficacy

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ABSTRACT: Diabetes is affecting the life of millions of people. A large proportion of diabetic patients suffer from severe complications such as neuropathic pain, and current treatments for these complications have deleterious side effects. Thus, alternate therapeutic strategies are needed. Recently, the elevation of epoxy-fatty acids through inhibition of soluble epoxide hydrolase (sEH) was shown to reduce diabetic neuropathic pain in rodents. In this report, we describe a series of newly synthesized sEH inhibitors with at least 5-fold higher potency and doubled residence time inside both the human and rodent sEH enzyme than previously reported inhibitors. These inhibitors also have better physical properties and optimized pharmacokinetic profiles. The optimized inhibitor selected from this new series displayed improved efficacy of almost 10-fold in relieving pain perception in diabetic neuropathic rats as compared to the approved drug, gabapentin, and previously published sEH inhibitors. Therefore, these new sEH inhibitors could be an attractive alternative to treat diabetic neuropathy in humans.

INTRODUCTION

A recent survey from the Centers for Disease Control and Prevention indicates that diabetes affects 25.8 million people in the United States which is 8.3% of the U.S. population.1 Most diabetic patients will ultimately develop kidney failure, hypertension, and/or suffer stroke. In addition, about two-thirds of diabetic patients will develop peripheral neuropathy.2,3 People suffering from diabetic neuropathic pain experience spontaneous pain (pain sensation in the absence of stimulation), hyperalgesia (increased pain sensation to painful stimuli), and allodynia (pain sensation to innocuous stimuli), which greatly affect their quality of life. Hyperglycemia has been suggested to be the initiating cause of peripheral nerve fiber degeneration, which results in pain.4 However, aggressive glycemic control can only control the progression of neuronal degeneration but not reverse the neuropathy.4 Current treatments of diabetic neuropathy include tricyclic antidepressants, anticonvulsants, selective serotonin reuptake inhibitors, and opioids, however they often have side effects that limit their use.5 Therefore, an alternative therapy with no or greatly reduced side effects is still imperative for these patients often suffering multiple comorbid conditions.

Epoxy fatty acids (EpFAs), formed by cytochrome P450 (CYP450) from polyunsaturated fatty acids, are important lipid mediators.6 Epoxy-eicosatrienoic acids (EETs), epoxy-eicosatetraenoic acids (EpETEs), and epoxy-docosapentaenoic acids (EpoDPEs), from arachidonic acid, eicosapentaenoic acid, and docosahexaenoic acid, respectively, have analgesic properties in inflammatory pain models.7,8 Although these EpFAs are very potent lipid mediators, they are rapidly metabolized by soluble epoxide hydrolase (sEH EC 3.3.2.10) to their corresponding 1,2-diols and to a lesser extent by other enzymes in vivo.9 The in vivo biological activities of these natural chemical mediators appear limited by their rapid degradation. Stabilization of EpFAs through inhibition of sEH has shown anti-inflammatory, antihypertensive, and analgesic effects. Recent studies also indicate that sEH inhibition is analgesic in chronic diabetic

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neuropathic pain in animal models. In fact, it is more efficacious than gabapentin, a clinically approved drug for this condition. In nonmodel species, sEH inhibitors have reduced the inflammatory and devastating neuropathic pain in laminitis horses, reduced blood pressure in forearm blood flow studies in man, and reduced neuropathic pain in human diabetics (www.sphaerapharma.com). Thus, sEH is a potentially important pharmaceutical target.

Over the years, several groups have reported the synthesis and evaluation of sEH inhibitors with different central pharmacophores with potency varying from micromolar to nanomolar ranges. The 1,3-disubstituted urea is one of the more potent central pharmacophores being used to inhibit sEH because the urea forms tight hydrogen bonds with the active residue Asp335 and the chemistry is easily accessible. The physical properties of many of the most potent compounds are generally poor. Efforts to improve physical properties including water solubility, hydrophilicity, decreased clogP, and lowered melting point of sEH inhibitors have generally resulted in a decrease in potency and less desirable pharmacokinetics. These physical properties can also result in poor absorption and inferior pharmacokinetic properties and can demand heroic formulation. Therefore, it is necessary to further optimize the structures of the inhibitors and improve the oral bioavailability of the sEH inhibitors carrying a 1,3-disubstituted urea as a central pharmacophores.

Recent reports in drug discovery suggest that the residence time of a drug in its target is an important parameter to predict in vivo drug efficacy. Residence time is defined as the duration of time which the target, either enzyme or receptor, is occupied by the ligand. The traditional IC₅₀ and Kᵣ is determined in a closed in vitro system in which the concentrations of the ligand and the target are constant. However, an in vivo system is an open system, thus the target is exposed to a varying concentration of ligand after dosing because of circulation, metabolism, and excretion. Therefore, drug efficacy is no longer correlated with the in vitro potency (IC₅₀ or Kᵣ) that is determined in a closed system but rather depends on the duration the target is occupied by the ligand. This residence time can be calculated from the reciprocal of the dissociation rate constant (kᵦ) of the target–ligand complex.

In this report, inhibitors with improved potency have been designed and synthesized based on the holo-structure of the recombinant human sEH with published sEH inhibitor: TPPU (UC1770) (Figure 1B). Their residence times have been determined and their in vivo efficacies have been tested in a diabetic neuropathic pain model.

### RESULTS AND DISCUSSION

**Inhibitor Design and Synthesis.** Piperidyl-urea inhibitors of sEH were first described in 2006 and have the general scaffold shown in Figure 1A. It has been demonstrated that large amide substituents at R₂ improve the potency of the sEH inhibitors (Figure 1A). However, sEH inhibitors with large amide substituents at R₂ (Figure 1A) exhibit poor pharmacokinetic profiles in dogs. To further improve both the potency and pharmacokinetic profiles of the sEH inhibitors, we started with a published inhibitor having a small substituent at R₂: TPPU (inhibitor 18) (Figure 1B), which resulted in good potency and a good pharmacokinetic profile. Because of the favorable properties of inhibitor 18, an X-ray structure of human sEH with inhibitor 18 was obtained and used to predict structural modifications of inhibitors leading to improved...
potency and properties. The X-ray structure indicates that there is a small secondary binding site (valley) next to the α-carbon of the amide of inhibitor 18 (Figure 2A), which can provide additional binding possibilities. We therefore hypothesized that the potency of the inhibitors could be significantly improved by incorporating a small hydrophobic substituent at the α-carbon of the amide (Figure 2B). In addition, the 4-trifluoromethoxyphenyl− group on the urea of inhibitor 18 fits closely to the "right side" of the binding pocket with only a little room for additional binding (Figure 2C,D). Thus, only substituents which are similar to the size of the 4-trifluoromethoxyphenyl− group were used for inhibitor optimization. On the basis of these findings, a series of 30 piperidyl-ureas was made using four different methods described previously.34 These methods with slight modifications are summarized in Scheme 1 (detailed synthetic procedures are provided in the Supporting Information).

Optimization of the Potency (K) of sEH Inhibitors. A new series of sEH inhibitors was synthesized with various substituents at R2 on the amide (Table 1) while maintaining R1 as a 4-trifluoromethylphenyl− group. In general, as the size of the substituent increases, the potency of the inhibitors against human sEH increases. As we hypothesized, addition of a methyl− group on the α-carbon of the amide (Figure 1A) greatly improves the potency by almost 5-fold (inhibitors 2 vs 4 and inhibitors 3 vs 6). Interestingly, replacing the isopropyl− (4) with cyclopropyl− group (5) also results in a slight increase in potency, an increase in water solubility, and a decrease in melting point. The elongation of the aliphatic chain by one carbon (inhibitors 2 vs 3) slightly enhances (30%) the potency (Table 1). To investigate whether the enhanced potency of inhibitor 6 is stereospecific, we tested the corresponding S−isomer (inhibitor 7), which is 2-fold more potent than its racemic mixture (Table 1), suggesting that the R−isomer is less active. The related inhibitor 8 is less potent than inhibitors 6 and 7, which indicates that the addition of methyl− group not only is stereospecific but is also regiospecific. An X-ray structure of human sEH with inhibitor 4 shows that the methyl− group on the α-carbon of the amide of inhibitor 4 effectively fits into the additional binding site on the right side of the binding pocket (Figure 3). This additional binding site was predicted from the crystal structure of human sEH with inhibitor 18 (Figure 2B).

Although the addition of an alkyl group enhances the potency of this series of sEH inhibitors, their metabolic stability will likely decrease because the added alkyl group at the α-position is expected to be metabolized faster. This also increases the lipophilicity of the inhibitors, which may increase their affinity to CYP450 enzymes that are responsible for drug oxidation.35 Because fluoride replacement is known to decrease metabolism,36 we synthesized inhibitor 9,37 and it shows potency similar to inhibitor 8. The size of the CF3− group is similar to the size of the isopropyl− group and the potency of inhibitor 9 is maintained. This could provide an approach to increase the stability of the inhibitors without hampering the potency of the inhibitors.

We then further optimized the potency of sEH inhibitors by modifying the substituent at R1 while maintaining the 2-methyl butanoyl group at R2 (Table 2). The binding pocket is very hydrophobic (Supporting Information, Figure S2) with limited space (Figure 2C,D). Therefore, the size of R1 was modified slightly in order to test if increasing the hydrophobic surface of the inhibitors could enhance their potency. Consequently, inhibitors 11 and 12 were synthesized (Table 2). The result indicates that there is steric hindrance within the right binding pocket (Figure 2C,D). Thus, the potency of the inhibitor dropped when the size of the substituent at R1 (Figure 1A) was increased from a 4-isopropylphenyl group to a 4-tert-butylphenyl− group (inhibitors 11 and 12) (Table 2). It is interesting that the inhibitor 6, which has CF3− group in place of an iso-propyl− and tert-butyl− group,37 is more potent as an inhibitor when compared to inhibitors 11 and 12. To
investigate whether the enhanced potency of inhibitor 6 is due to fluorine induced interactions or better occupancy of the binding pocket, the 4-t-butylphenyl− group of inhibitor 12 was replaced by its isostere: a 4-heptafluoro-iso-propyl-phenyl group at R₁ of inhibitor 13.37 This compound is 20-fold more potent than inhibitor 6, which indicates that the fluorine induced interactions in the left binding pocket are very strong (Table 2). These data suggest that the left side of the binding pocket is likely fluorophilic. Interestingly, replacement of the 4-trifluoromethylphenyl− at R₁ of inhibitor 6 by a 4-trifluoromethoxyphenyl− group (inhibitor 14) did not alter potency, but the replacement improved solubility by 10-fold (Table 1). Furthermore, inhibitors with a cycloalkyl− group at R₁ were synthesized, and the addition of carbon atoms (inhibitor 15 to 17) enhances the binding toward human sEH by more than 4 times (Table 2) and placement of cycloalkyl− group at R₁ greatly enhances their solubility.

It has been reported that inhibitors with 4-trifluoromethoxyphenyl− at R₁ are more potent than inhibitors with 4-trifluoromethylphenyl− at R₁ and have better physical properties.33 To investigate whether such substitution could enhance the potency of the inhibitors and improve physical properties in general,38 a series of inhibitors with 4-trifluoromethylphenyl group at R₁ was replaced with a 4-trifluoromethoxyphenyl− group (Figure 1A). The results suggest that substitution of 4-trifluoromethylphenyl− with 4-trifluoromethoxyphenyl− enhances the potency of certain inhibitors (2 vs 18 and 4 vs 19 in Tables 1 and 3), but there is no substantial improvement with inhibitors with the 2-methyl butanoyl group at R₂ (6 vs 14 and 7 vs 21 in Table 1−3) or the cyclopropyl group at R₂ (5 Vs 20). This may be due to the possibility of different binding orientations than the one shown in Figure 2A and in previous crystallography.39 Therefore, two inhibitors which are structurally similar to 21 but with urea substituted by the amide (22 and 23) were synthesized. In general, structure−activity relationships developed with the urea central pharmacophore are predictive of enzyme inhibition with amide and carbamate. Both inhibitors 22 and 23 are less potent than their corresponding urea (21) (Table 3). Compound 22, which has amide nitrogen (N′) on the piperidine side (Figure 1A), is far less potent than the amide 23, which has an amide nitrogen (N′H) on the R₁ side (Figure 1A) (Table 2). It indicates that the urea N′H−Asp(O) interaction is stronger than the urea N″H−Asp(O) interaction by 5.7 kJ mol⁻¹, calculated based on the Kᵢ of both inhibitors. This result is consistent with the crystal structure where the distance between urea N′H and Asp(O) is shorter than the distance between urea N″H and Asp(O) hydrogen bonding (Figure 2A). In some cases, the placement of 4-trifluoromethoxyphenyl− at R₁ (Figure 1A) enhances the potency of sEH inhibitors, but in
all cases, this substitution decreases the melting point and improves the solubility of the inhibitors (Tables 1–3). These improvements of physical properties ease the drug formulation process.

It was reported that replacement of amide with sulfonamide at R2 was shown to enhance the potency of the inhibitors. However, such observations were based on very few comparisons.23,34 Therefore, a new series of inhibitors with a different sulfonamide at R2 was synthesized for a more detailed study (Table 4). In general, the potency of the inhibitors increases with the size of R2 (7-fold better potency from a methyl to a butyl). However, unlike the inhibitor with an amide at R2 (Table 1), the placement of an iso-propylsulfonamide at R2 (29 vs 26) does not significantly enhance the potency against human sEH. This is probably because the sulfonamide exists as a tetrahedron while amide is trigonal planar and the S(O)2−C bond is at least 0.28 Å longer than the C(O)−C bond.40 These data further indicate that the enhanced potency of the methyl substitution at the α-position of the amide is structurally specific. Overall, unlike previously reported, the inhibitors with a sulfonamide at R2 are less potent than the inhibitors with amides at R2. In addition, the physical properties (solubility and melting point) of inhibitors with a sulfonamide at R2 are generally poor as compared to inhibitors with amides at R2.

Here, we have identified several structural changes that can significantly enhance the potency and improve the physical properties of the inhibitors. We have also demonstrated that the sulfonamide at R2 is less attractive than the corresponding amide.

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**Table 1. Physical Properties and Potency of sEH Inhibitors against Human sEH (Modification of R2)**

| Inhibitor | Physical Properties | Human sEH |
|-----------|---------------------|-----------|
|           | Solubility (µg/mL) | Melting Point (°C) | eLogP | Ki (nM) |
| 1 R₂:     | 8.95               | 244.0-248.7 (246.4) | 2.74 | 14.6±1.70 |
| 2         | N.D. b             | 224.0-228.0 (226)  | N.D. b | 2.96±0.60 |
| 3         | N.D. b             | 192.3-197.6 (193.6) | N.D. b | 2.23±0.71 |
| 4         | 7.20               | 234.1-235.4 (234.9) | 3.37 | 0.66±0.10 |
| 5         | 19.7               | 193.4-194.2 (193.7) | 3.18 | 0.49±0.08 |
| 6         | 2.63               | 225.2-226.3 (225.9) | 3.83 | 0.37±0.04 |
| 7         | 9.20               | 221.3-225.6 (221.6) | 3.84 | 0.22±0.04 |
| 8         | N.D. b             | 220-223 (221.5)    | 3.86 | 0.49±0.12 |
| 9         | 3.22               | 209.2-210.7 (210.3) | 3.99 | 0.43±0.06 |
| 10        | N.D. b             | 198.0-202.3 (199.6) | 3.66 | 1.2±0.1 |

*Solubility was measured with sodium phosphate buffer (0.1 M, pH 7.4) according to the method described by Tsai et al. and described in detail in Supporting Information.34 N.D. means "not determined". eLogP was determined by HPLC method calibrated with eLogP of six selected inhibitors determined by the shake-flask method (Supporting Information, Figure S3). Kᵢ was determined by FRET-based displacement assay described by Lee et al.38 The results are the average of duplicates with ±SEM. Abbreviation: eLogP stands for experimental Log P.*
Table 2. Physical Properties and Potency of sEH Inhibitors against Human sEH (Modification of R1)\(^c\)

| Inhibitor | R1 | Solubility (ug/mL)\(^a\) | Melting Point (°C) | elogP\(^b\) | Ki (nM)\(^d\) |
|-----------|----|--------------------------|--------------------|------------|-------------|
| 6         | R1: | 2.60                     | 225.2-226.3 (225.9) | 3.83       | 0.37±0.04   |
| 11        |     | 2.60                     | 174.0-174.9 (174.5) | 4.21       | 1.17±0.27   |
| 12        |     | 0.02                     | 213.2-216.6 (214.3) | 5.12       | 2.44±0.30   |
| 13        |     | 0.17                     | 182.2-183.2 (182.8) | 4.96       | 0.02±0.01   |
| 14        |     | 22.5                     | 170.9-171.6 (171.3) | 3.98       | 0.36±0.09   |
| 15        |     | 923                      | 127.7-130.5 (128.5) | N.D. \(^b\) | 4.23±0.07   |
| 16        |     | 278                      | 122.4-124.2 (122.9) | N.D. \(^b\) | 0.99±0.06   |
| 17        |     | 39.5                     | 149.8-150.8 (150.4) | N.D. \(^b\) | 0.23±0.07   |

\(^a\)Solubility was measured with sodium phosphate buffer (0.1 M, pH 7.4) according to the method described by Tsi et al. and described in detail in Supporting Information.\(^b\)N.D. means "not determined". \(^c\)elogP was determined by HPLC method calibrated with elogP of six selected inhibitors determined by the shake-flask method (Supporting Information, Figure S3). \(^d\)Ki was determined by FRET-based displacement assay described by Lee et al.\(^38\) The results are the average of duplicates with ± SEM. \(^e\)Abbreviation: elogP stands for experimental Log P.

New sEH Inhibitors Have Improved Dissociation Rate Constants (k\(_{\text{off}}\)) against Human sEH. Recent studies have suggested that k\(_{\text{off}}\), a kinetic parameter on enzyme inhibition, from the enzyme is a better indicator for in vivo potency than K\(_i\).\(^33\) This is because inhibitors are only effective in blocking catalysis when the target proteins are occupied by the inhibitors. The k\(_{\text{off}}\) can provide more detailed information, about the duration of time the inhibitors are bound to the target enzyme (target occupancy) than the K\(_i\), an equilibrium parameter on enzyme inhibition, and ultimately this translates into in vivo efficacy.\(^30\) Therefore, a small set of new potent inhibitors together with several potent published inhibitors (Figure 1C) were selected to determine their k\(_{\text{off}}\) against sEH using a recently developed FRET-based assay.\(^38\)

The result indicates that the k\(_{\text{off}}\) of inhibitors decreases with the size of R\(_2\) increased (Table 5 and Figure 1C, inhibitor 4 < 7; TPAU < 18 (TPPU) < 19 < 21; and TUPS < 32). However, the k\(_{\text{off}}\) does not substantially change when the R\(_1\) was varied among a 4-trifluoromethylphenyl group (inhibitor 6), a 4-trifluoromethoxyphenyl group (inhibitor 14), and a 4-isopropylphenyl group (inhibitor 11) (Table 5). The 4-heptafluorisopropylphenyl group at R\(_1\) (inhibitor 13 and inhibitor 24) significantly decreased the k\(_{\text{off}}\) of the inhibitors. This further supports our hypothesis that the pocket is fluorophilic and the added fluorines can induce several interactions with the nearby residues within the binding pocket. The k\(_{\text{off}}\) of new inhibitors are slower overall, indicating a longer residence time in the target and have at least a 2-fold slower off rate than any of the previously published inhibitors (Table 5 and Figure 1C, APAU, TPAU, 18 (TPPU), TUPS, t-TUCB).

To investigate relationship of k\(_{\text{off}}\) with K\(_i\) and other physical properties of the inhibitors, correlation graphs of k\(_{\text{off}}\) with these parameters were plotted (Supporting Information, Figure S1A). The results show no correlation (R\(^2\) = 0.21) between the number of non-hydrogen atoms and k\(_{\text{off}}\). However, there is a trend showing (R\(^2\) = 0.52) that an increase in elogP results in a decrease of k\(_{\text{off}}\) (Supporting Information, Figure S1B). This may due to the fact that the binding pocket of the human sEH is hydrophobic (Supporting Information, Figure S2). An increase of hydrophobicity of the ligand increases the lipophilic interactions with the binding pocket. Therefore, it requires higher activation energy to break up the interactions between protein and the bound inhibitors. In addition, a correlation between K\(_i\) and k\(_{\text{off}}\) was plotted (Supporting Information, Figures S1C, S1D). The plot indicates that there is a good correlation between K\(_i\) and k\(_{\text{off}}\) (R\(^2\) = 0.88) over a wide range of potencies (from 0 to 20 nM). However, when we focused on a narrower range of potencies (from 0 to 1.4 nM), the correlation is moderate (R\(^2\) = 0.44). Because K\(_i\) is a ratio of k\(_{\text{off}}\) over k\(_{\text{on}}\), K\(_i\) should be inversely proportional to k\(_{\text{off}}\). Therefore, the poor correlation over a moderate range K\(_i\) values suggests that the differences are due to the k\(_{\text{on}}\). These results indicate that it is possible to specifically modulate k\(_{\text{off}}\) without greatly affecting K\(_i\).

An Improved Pharmacokinetic Profile of New Series of sEH Inhibitors. To investigate the oral bioavailability of sEH inhibitors, we determined the pharmacokinetic profiles post oral administration. Cassette dosing was used as a...
screening tool to select the compounds for more detailed study to allocate limited resources to the most promising compounds. There are cautions with cassette dosing including changes in pharmacokinetic behavior due to competition for xenobiotic metabolism. The high potency and thus low doses used in this study make this artifact less likely. A comparison of pharmacokinetic profiles of sEH inhibitors between the cassette dose and single dose carried out in nonhuman primate. The results show that there was no statistically significant difference in the pharmacokinetic behaviors between cassette and individual dosing of sEH inhibitors; therefore, cassette dosing was predictive for the compounds reported here.41

The pharmacokinetic profiles of this series of selected potent compounds also determined the effect of the position or addition of aliphatic carbons on the inhibitors. In general, the results indicate that the sEH inhibitors with a 4-trifluoromethylphenyl− or a 4-trifluoromethoxyphenyl− group at R1 (Figure 1A) have good drug exposure levels based on the area under the curve of the pharmacokinetic profile (PK-AUC) after oral administration (Table 6). As we replaced the 4-trifluoromethoxyphenyl− group at R1 with a 4-isopropylphenyl− group (inhibitors 6 or 14 vs 11), the potency of inhibitor 14 decreases (Table 2). As we anticipated, the pharmacokinetic T1/2 (PK-T1/2) and oral drug exposure level estimated by PK-AUC also decreases (Table 6). Further replacement of the phenyl group at R1 with a cycloalkyl− group (inhibitors 16 and 17) greatly decreases the oral drug exposure level (Table 6, Supporting Information, Figures S6, S8, and S9). It is likely that each addition of an aliphatic carbon renders the molecule more susceptible to metabolism by CYP450 enzymes.42 Such a phenomenon was also observed as the alkyl chain length varied at R2. A similar result was obtained with the sulfonamide inhibitor. Inhibitor 30 shows at least a 20-fold better bioavailability based on oral PK-

### Table 3. Physical Properties and Potency of sEH Inhibitors against Human sEH (Modification of R1)ε

| Inhibitor | Physical Properties | Human sEH |
|-----------|---------------------|-----------|
| 18 (TPPU) | Solubility (µg/mL) 60 | 198.2-200.8 (199.5) | 3.23 | 0.91±0.13 |
| 19 | Melting Point (°C) 179.1-180.3 (179.6) | 3.56 | 0.31±0.18 |
| 20 (TPCU) | 4.6 | 193.4-194.2 (193.8) | 3.28 | 0.55±0.10 |
| 21 | 21.3 | 168.0-169.3 (168.7) | 3.97 | 0.19±0.04 |
| 22 | N.D. b | 91.2-92.6 (91.7) | N.D. b | 111±13 |
| 23 | N.D. b | Gel-like | N.D. b | 11.2±0.42 |
| 24 | 12.3 | 131.8-135.8 (133.8) | 4.89 | <0.02 |

εSolubility was measured with sodium phosphate buffer (0.1 M, pH 7.4) according to the method described by Tsai et al. and described in detail in Supporting Information.44 bN.D. means “not determined.” celogP was determined by HPLC method calibrated with elogP of six selected inhibitors determined by the shake-flask method (Supporting Information, Figure S3). dK was determined by FRET-based displacement assay described by Lee et al.38 The results are the average of duplicates with ± SEM. eAbbreviation: elogP stands for experimental Log P.
AUC with a substantially longer PK-$t_{1/2}$ as compared to inhibitors 31 and 32 (Table 6). These data support the hypothesis that the CF$_3$ substitution effectively blocks metabolism at $R_2$. However, addition of fluorne to the fluorinated substituents could not further enhance the stability of the inhibitors. When the inhibitors with 4-trifluoromethyl-
groups at R₁ were substituted by a heptfluoro-isopropyl group (inhibitor 6 vs 13), both the PK-T₁/₂ and bioavailability decreased (Table 6). This is probably due to the fact that the increase of eLogP enhances the affinity toward xenobiotic metabolizing enzymes and cell membranes. These results suggest that in order to enhance the stability of the inhibitors, addition of fluorine should be carefully positioned.35,43

In general, inhibitors with 4-trifluoromethylphenyl−, 4-trifluoromethoxyphenyl−, and 4-(heptfluoro-isopropyl)phenyl− groups at R₁ with amide substituents at R₂ showed only minor inhibition of both CYP450 enzymes is observed at 1 μM of the sEH inhibitors (Table 7). These data suggested that Kᵦ against recombinant human sEH, have more potent plasma protein binding and nonspecific binding at 1 μM (%).44,45 However, modulating plasma protein binding can help drug solubilization and drug distribution.46 Therefore, the plasma protein binding of the selected inhibitors were measured with an assay carried out with a rapid equilibrium dialysis device based on manufacturer’s protocol (Table 7). These new inhibitors demonstrated a moderate level of plasma protein binding ranging from 85 to 96%. This level of plasma protein binding is unlikely to alter their bioavailability. Given the inhibitors had Kᵦ approaching the subnanomolar range, the plasma proteins could be considered as carrier proteins that facilitate the effect in vivo and 0.31 nM Kᵦ except for inhibitors 5 and 19 (Table 7). However, even inhibitors 5 and 19, which have 0.49 and 0.31 nM Kᵦ against recombinant human sEH, have more than an 10000-fold selectivity over the hERG channel. Therefore, these selected inhibitors are considered not to present a risk with hERG inhibition.

### Table 6. Pharmacokinetic Parameters of Selected sEH Inhibitors after Oral Dosing on Mice

| inhibitor | PK-AUC (nM·h) | Cmax (nM) | T₁/₂ (h) | Tmax (h) |
|-----------|---------------|-----------|----------|----------|
| APAU      | 183           | 30        | 3        | 1        |
| TUPS      | 5300          | 370       | 15       | 3.3      |
| 18 (TPPU) | 10650         | 495       | 12.1     | 8        |
| 4         | 19650         | 1160      | 6        | 4        |
| 5         | 24630         | 960       | 17       | 6        |
| 6         | 3295          | 320       | 6        | 0.5      |
| 7         | 4940          | 435       | 5        | 1        |
| 9         | 8845          | 330       | 15.4     | 8        |
| 11        | 200           | 90        | 2        | 0.5      |
| 13        | 1600          | 135       | 4.5      | 2.5      |
| 14        | 3300          | 235       | 6        | 2        |
| 16        | 75            | 3         | 8.4      | 0.5      |
| 17        | 37            | 5         | 12       | 0.5      |
| 19        | 19500         | 900       | 9        | 5        |
| 21        | 2530          | 195       | 7.7      | 4        |
| 24        | 9600          | 365       | 18.9     | 8        |
| 25        | 4675          | 130       | 22       | 8        |
| 30        | 4270          | 100       | 25       | 8        |
| 31        | 245           | 30        | 7.4      | 1        |
| 32        | 220           | 65        | 2        | 1.2      |

"The mice (n = 4) were treated by oral dosing with a cassette of 3 to 5 compounds (0.3 mg/kg per each compounds dissolved in 20% PEG-400 in oleic acid rich triglycerides). The pharmacokinetic profiles of the inhibitors were calculated by Winonlin based on the model of one compartmental analysis. The pharmacokinetic profiles of the inhibitors were calculated by Winonlin based on the model of noncompartmental analysis.

### Table 7. Testing for Nonspecific Protein Binding with Selected sEH Inhibitors

| inhibitor | hERG channel inhibition at 50 μM (%) | human plasma protein binding at 1 μM (%) | human CYP2C remaining activity at 10 μM (%) | human CYP2J remaining activity at 10 μM (%) |
|-----------|--------------------------------------|----------------------------------------|-------------------------------------------|-------------------------------------------|
| APAU      | 45 ± 0.5                             | 50.0 ± 2.0                             | 140.0 ± 5.0                               | 104.0 ± 1.0                               |
| 18 (TUPS) | 26.0 ± 1.0                           | 79.0 ± 1.0                             | 91.9 ± 2.2                                | 118.0 ± 2.4                               |
| 4         | 16.5 ± 1.5                           | 85.0 ± 0.5                             | 81.6 ± 3.0                                | 110.0 ± 2.0                               |
| 5         | 41.5 ± 1.5                           | 95.1 ± 0.5                             | N.D.                                      | N.D.                                      |
| 7         | N.D.                                 | 96.3 ± 0.2                             | 82.6 ± 3.1                                | 107.0 ± 3.0                               |
| 19        | 32.5 ± 1.5                           | 89.0 ± 2.5                             | 73.4 ± 0.3                                | 103.0 ± 1.0                               |
| 21        | N.D.                                 | 92.4 ± 0.1                             | 60.6 ± 8.2                                | 108.0 ± 1.0                               |

"The result is the average of duplicates with standard error shown. b"The result is the average of triplicates with standard derivation shown. N.D. means "not determined". The experiments were conducted according to the Graves et al. procedure.46

### New Series of sEH Inhibitors Show No Significant Nonspecific Binding toward Other Pharmacologically Important Proteins.

Several of the newly synthesized sEH inhibitors selected for potency and good oral drug exposure levels were tested against a set of proteins to evaluate potential off-target side effects and nonspecific binding. Inhibitor 24 was excluded because of its relatively high eLogP (Table 3), which was suspected to lead to high nonspecific binding. High lipophilicity is avoided when possible in medicinal chemistry because it is associated with poor pharmacokinetic behavior and nontargeted related side effects. Although not conclusive, the pharmacokinetic studies indicated that the 4-(heptfluoro-isopropyl)-phenyl group likely enhances the affinity of inhibitors toward xenobiotic metabolizing enzymes and cell membranes, potentially leading to the poor oral drug exposure of inhibitor 13 (Table 6).

It was reported that very high plasma protein binding can not only hamper the efficacy of drugs or signaling molecules but also can alter their pharmacokinetic profile.44,45 However, modulating plasma protein binding can help drug solubilization and drug distribution.46 Therefore, the plasma protein binding of the selected inhibitors were measured with an assay carried out with a rapid equilibrium dialysis device based on manufacturer’s protocol (Table 7). These new inhibitors...
In summary, we have demonstrated that our sEH inhibitors having $K_i$ values in the lower subnanomolar are unlikely to induce unanticipated side effects due to nonspecific binding to other pharmacologically important proteins. However, this does not completely rule out idiosyncratic off-target effects.

sEH Inhibitors Are Effective against an Animal Model of Type 1 Diabetic Neuropathic Pain. Several new potent sEH inhibitors with good pharmacokinetic profiles and no significant nonspecific binding on human proteins and enzymes were selected for further in vitro testing prior to in vivo studies. Because the in vivo studies were to be conducted in rat, we determined the potency ($K_i$ and $k_{off}$) against the recombinant rat sEH (Table 8). The data suggest that the inhibitors have a slightly different structure—activity relationship (SAR) on the recombinant rat sEH compared to human sEH. The inhibitors with a 4-trifluoromethoxyphenyl—group at R1 are less potent than the inhibitors with a 4-trifluoroethylphenyl—group at R1 by at least 10-fold (Table 8). These results are opposite to the SAR obtained from the human recombinant sEH (Table 1 and 3). In addition, there is not a clear SAR based on the $k_{off}$ of the inhibitors (Table 8). However, the results indicate that the new inhibitors are more potent, both in $IC_{50}$ and $k_{off}$ than the previously published inhibitors 18 (TPPU) and TPAU (Figure 1C and Table 8). Additionally, the pharmacokinetic profiles in rat were obtained for this new set of inhibitors (Supporting Information, Figure S11). All of the selected inhibitors show good oral bioavailability (PK-AUC) except inhibitor 21, which demonstrated at least 2× lower blood concentration than the other inhibitors (Table 9). Elimination is an important parameter of overall pharmacokinetics, and it has been previously reported that inhibitors with short elimination PK-$T_{1/2}$ are not well suited to use for chronic treatment.1,2 Several of the new inhibitors demonstrate good pharmacokinetic profiles with moderate elimination PK-$T_{1/2}$ ($\geq$ 5 h) in both mice and rats. Therefore, these inhibitors were selected for further in vivo efficacy test on rat.

Because inhibitor 7 has the best in vitro potency ($IC_{50}$ and $k_{off}$) against rat sEH with a good pharmacokinetic profile (Table 8 and 9), it was tested in a model of type 1 diabetic neuropathic pain. At as low as 0.1 mg/kg, inhibitor 7 effectively increases mechanical withdrawal thresholds (reduces pain) in neuropathic rats (Figure 4A). Importantly, this reduction in pain behavior increases dose dependently from 0.1 to 0.3 mg/kg (Figure 4AB, $p < 0.05$). In addition, there is a good correlation between the blood concentration of inhibitor 7 and increased withdrawal thresholds (Figure 4C,D).

Our data indicate that inhibitor 7 shows better in vivo efficacy in terms of both $IC_{50}$ and $k_{off}$ than the previously published inhibitor TPAU (Figure 1C) as well as having good pharmacokinetic profiles in both mouse and rat (Table 6 and 9). Therefore, we compared the in vivo efficacy of inhibitor 7 as previously reported results for TPAU in the same model. Our results indicate that using a 10-fold lower dose of inhibitor 7 is as efficacious as TPAU in the nociceptive bioassay (Figure 5). It is also reassuring that the relative in vivo potency of these two sEH inhibitors in the nociceptive assays correlates with their relative in vitro potency on the target enzyme. These pain assays in the rat appear valuable for broad ranking of the analgesic activity of sEH inhibitors. However, the differences in pharmacokinetic and target site affinities caution against extrapolating these data to predict the fine ranking of the potency of different sEH inhibitors in man.

Overall, our data show that the new inhibitor 7 exhibits a strong correlation between in vivo efficacy with dose and drug level in blood, is more efficacious than the previously reported TPAU, and has promise as a therapy for use in treating chronic pain conditions.

| Table 9. Pharmacokinetic Parameters of Selected sEH Inhibitors Followed by Oral Dosing on Rat$^a$ |
|-----------------|---------|---------|---------|---------|
| structure       | PK-AUC (nM·h)$^{b}$ | $C_{max}$ (nM)$^{b}$ | $T_{1/2}$ (h) | $T_{max}$ (h)$^{b}$ |
| 4               | 7304    | 510     | 5.4     | 4       |
| 7               | 5716    | 790     | 4.9     | 1       |
| 19              | 12000   | 890     | 3.5     | 1       |
| 21              | 2590    | 297     | 4.2     | 4       |

$^a$The rat (n = 3 or 4) were treated by oral dosing with a cassette of four compounds (0.3 mg/kg per each compound dissolved in 20% PEG400 in oleic acid rich triglycerides). The pharmacokinetic profiles of the inhibitors were calculated by Winonlin based on the best fit model of one compartmental analysis.

| Table 8. In Vitro Potency of Selected sEH Inhibitors against Rat sEH |
|-----------------|---------|---------|
| inhibitor       | $IC_{50}$ (nM)$^{a,b}$ | $k_{off}$ ($\times 10^{-4}$ s$^{-1}$)$^{c,d}$ |
| 18 (TPPU)       | 29.1 ± 4.5 | 8.52 ± 0.47 |
| TPAU            | 79 ± 2.5 | 9.70 ± 0.14 |
| 4               | 1.8 ± 0.1 | 3.26 ± 0.72 |
| 7               | <1.25    | 3.57 ± 0.45 |
| 19              | 13.3 ± 1.5 | 6.87 ± 0.11 |
| 21              | 20 ± 0.1 | 4.89 ± 0.28 |

$^a$The result is the average of triplicates with standard derivation (SD) shown. $^b$IC$_{50}$ is determined by radiometric assay using $[^{3}H]$-t-DPPO (50 μM) as a substrate and rat sEH (2.5 nM) incubated at 30 °C for 10 min $k_{off}$ was determined by FRET-based displacement assay described by Lee et al.$^b$ Briefly, a preincubated rat sEH—inhibitor complex (8 μM) was diluted by 240 times by fluorescent reporter—APCU (2 μM, 0.1 M sodium phosphate, pH 7.4). The fluorescent enhancement ($λ_{em} = 280$ nm, $λ_{ex} = 450$ nm) was measured over time (500 s). The results are the average of triplicates with ± SD. $^c$t$_{1/2}$ = ln(2)/$k_{off}$ which describes the half-life of enzyme—inhibitor complex. $^d$The result is the average of triplicates with standard derivation (SD) shown. |
Inhibiting sEH has been demonstrated to be more efficacious than gabapentin and celecoxib in alleviating modeled diabetic neuropathic pain in rat with no apparent side effect such as impaired mobility, cognition, or motor skill. However, the sEH inhibitors reported in those studies had either poor physical properties (poor water solubility and high melting point) or poor in vivo stability. In this report, the new more potent sEH inhibitors are close to 10 times more efficacious than TPAU in a diabetic neuropathic pain model. In addition, the selected inhibitor 7 demonstrated strong correlation between drug level in blood and dose with in vivo efficacy. This new series of inhibitors has demonstrated enhanced potency with slow $k_{\text{off}}$, improved pharmacokinetic profiles (moderate to long elimination $T_{1/2}$ and high AUC), and more importantly, improved efficacy against diabetic neuropathic pain in a rat model. With increased potency and bioavailability, there are decreases in the required effective dose and greatly simplified formulation. The new sEH inhibitors are good candidates for chronic treatment of diabetic neuropathic pain.

## EXPERIMENTAL SECTION

### General

All reagents and solvent were purchased from commercial suppliers and were used directly without further purifications. All syntheses were carried out in a dry nitrogen atmosphere unless otherwise specified. Reactions were monitored by thin-layer chromatography (TLC) on Merck F254 silica gel 60 aluminum sheets, and spots were either visible under light or UV light (254 nm) or deuterated. $^1$H NMR spectra were recorded on a Varian QE-300 spectrometer with deuterated chloroform ($\text{CDCl}_3$; $\delta = 7.24$ ppm) or deuterated dimethyl sulfoxide ($\text{DMSO-d}_6$) containing TMS as an internal standard. $^13$C NMR spectra were recorded on a Varian QE-300 spectrometer at 75 MHz.

The purity of the inhibitors reported in this manuscript was determined either by (1) HPLC-UV using Agilent 1200 series HPLC equipped with Phenomenex Luna2 C18 reverse phase column (C18, 4.6 mm × 150 mm, 5 μm) coupled with Agilent G1314 UV–vis detector (detection at 230 nm) with isocratic flow at methanol:water (2:1 by volume) for 90 min, or by (2) H NMR. The lowest obtained purity was reported. The inhibitor was dissolved in EtOH at 100 μM and 10 μL was injected on HPLC. Purity was based on the percent of total peak area at 230 nm using HPLC-UV. This purity estimate was

Figure 4. (A) Inhibitor 7 ($IC_{50}$ rat sEH = 1.25 nM) improves mechanical withdrawal thresholds in a model of diabetic neuropathy. Oral dosing of 0.1 and 0.3 mg/kg dose dependently increased MWT, indicating pain relief ($n$ = 5, mean ± SEM). The neuropathic baseline is normalized to 100% to show the response to a single dose of sEH inhibitor over the time course. The response to treatments depended on the time, but when the treatments were compared, there was a statistically significant increase from the 0.1 to the 0.3 mg/kg dose (Mann–Whitney rank sum test, $U$ = 454.5, $n_1 = n_2 = 45$, $p$ = 0.001). (B) Inhibitor 7 shows dose dependent pain relief in diabetic rats. AUC describes an area under the curve of the MWT post-oral dosing of the inhibitor vs time. The bar chart depicts the AUC of MWTs after oral dosing of inhibitor 7. An increased in AUC of MWT is interpreted as an increase in pain relief. When the AUC for these doses were compared, this relationship maintained statistical significance (Mann–Whitney rank sum test, $U$ = 2.00, $n_1 = n_2 = 5$, $p$ = 0.032). (C) Efficacy in nociceptive responses relates to blood concentration. A plot of the nociceptive responses ($n$ = 5, mean ± SEM) vs blood concentration ($n$ = 4, mean ± SEM) reveals increasing efficacy with increasing blood concentration. (D) The efficacy of inhibitor 7 is dependent on blood concentration. When compared, the nociceptive responses ($n$ = 5, mean ± SEM) and the pharmacokinetic profile after oral dosing ($n$ = 4, mean ± SEM) of 7 follow the same trend while revealing a slight delay to in the behavioral assay. The graphics and statistics were prepared by KaleidaGraph version 4.1 (Synergy Software, Reading, PA).

Figure 5. Newly optimized inhibitor 7 shows better in vivo efficacy in disease model. AUC describes an area under the curve of the withdrawal threshold post-oral dosing of the diabetic rat with sEH inhibitors vs time. A comparison of the newly synthesized sEH inhibitor 7 ($IC_{50}$ rat sEH = 1.25 nM, $t_{1/2} = 21.6$ min) to previously published analogue TPAU ($IC_{50}$ rat sEH = 79 nM, $t_{1/2} = 11.9$ min) showed a significantly higher response of inhibitor 7 at 0.3 mg/kg compared to the same 0.3 mg/kg dose of TPAU in a model of diabetic neuropathy ($t$ test, $t$ = 2.31 with 9 degrees of freedom, $p$ = 0.046, * shows significant difference to 0.3 mpk of inhibitor 7). However, there was no significant difference between the 10-fold lower dose of inhibitor 7 at 0.3 mg/kg and TPAU at 3 mg/kg (Mann–Whitney rank sum test, $U$ = 14.00, $n_1 = 5$ $n_2 = 6$, ns $p$ = 0.931). The graphic and statistics were prepared by SigmaPlot (SysTat Software, San Jose, CA).
 compared with that from the H NMR. The presence of anilines in the final product was estimated from H NMR. The lowest obtained purity was reported. The purity was also further supported as described in the Supporting Information by LC/MS with monitoring of total ion current, TLC in several systems, a sharp melting point, and occasional other technique. The elemental analysis was conducted by MIDWESTMICRO lab, LLC.

The synthesis of tert-butyli 4-(3-(4-(triﬂuoromethyl)phenyl)ureido)-piperidine-1-carboxylate, 1-(piperidin-4-yl)-3-(4-(triﬂuoromethyl)-phenyl)urea, 1-(piperidin-4-yl)-3-(4-(triﬂuoromethoxy)phenyl)urea and tert-butyli 4-(3-(4-(triﬂuoromethoxy)phenyl)ureido)piperidine-1-carboxylic acid have been reported elsewhere. The synthesis of inhibitors 1,2,3,5,6,8,9 APAU,10 TPPU,13 18 (TPPU),13 20 (TFCU),13 and t-TUCB14 were reported elsewhere. Experimental of each individual inhibitor is described in Supporting Information in detail.

The experimental procedures of enzyme preparation, IC50 determination for sEH inhibitors, and Ki determination for sEH inhibitors followed the published procedures and are described in detail in Supporting Information.39,54–58

**Synthetic Method 1. Step 1.** Corresponding isocyanate (1 equiv) and 4-amino-1-Boc-piperidine (1.1 equiv) were dissolved in CH2Cl2 (50 mM, corresponding to isocyanate) and stirred at rt for 12 h. The reaction was quenched by addition of water. The organic layer was isolated, and the aqueous layer was extracted with EtOAc (EtOAc:aqueous layer/1:1) four times. The combined organic layer was dried over anhydrous magnesium sulfate and was concentrated under vacuo and was further puriﬁed by flash chromatography, yielding corresponding Boc-protected urea.

**Step 2.** The BOC protected urea from the step 1 was dissolved in HCl solution (2M, MeOH) to make reaction mixture (186 mM, BOC protected urea). The resulting solution was reﬁltered and dried under high vacuum. The product solution was dried over anhydrous magnesium sulfate and was concentrated in vacuo and further puriﬁed by TLC in several systems, a sharp melting point, and occasional other technique. The elemental analysis was conducted by MIDWESTMICRO lab, LLC.

**Step 3.** Unless speciﬁed, the unprotected urea (1 equiv) from step 2, EDCI (1.5 equiv), DMAP (1.5 equiv), and corresponding carboxylic acid (1.5 equiv) were dissolved in CH2Cl2 (8.3 mM, unprotected urea) and stirred overnight (12 h) at rt. The reaction was quenched by addition of HCl solution (1M). The organic layer was collected, and the aqueous layer was extracted with EtOAc (EtOAc:aqueous layer/1:1) four times. The combined organic layer was dried over anhydrous magnesium sulfate and was concentrated in vacuo and further puriﬁed by flash chromatography.

**Synthetic Method 2.** The corresponding isocyanate (1 equiv) was added to a suspension of targeted piperidine (1.1 equiv) in CH2Cl2 (20 mM, corresponding isocyanate). The reaction was stirred overnight (12 h) at rt. The reaction was quenched with the addition of HCl solution (2M). The organic layer was collected, and the aqueous layer was further extracted with EtOAc (EtOAc:aqueous layer/1:1) three times. The combined organic layer was washed with satd NaCl solution. The organic layer was dried over anhydrous magnesium sulfate and was concentrated in vacuo. The product was puriﬁed by flash chromatography.

**Synthetic Method 3.** Corresponding amine (1 equiv) and triethylamine (1.2 equiv) was dissolved in CH2Cl2 (54 mM corresponding to amine) and stirred at −78 °C. Triphosgene (0.37 equiv) dissolved in CH2Cl2 (20 mM, corresponding triphosgene) was added dropwise at −78 °C. The reaction was then warm to rt and was stirred for 30 min. The reaction was cooled to 0 °C. Corresponding piperidine (1.1 equiv) dissolved in CH2Cl2 (54 mM, corresponding piperidine) was added slowly, and the reaction was further stirred at rt for 12 h. The reaction was quenched with the addition of HCl solution (2M). The organic layer was collected, and the aqueous layer was further extracted with EtOAc (EtOAc:aqueous layer/1:1) three times. The combined organic layer was washed with satd NaCl solution. The organic layer was dried over anhydrous magnesium sulfate and was concentrated in vacuo. The product was puriﬁed by flash chromatography.

**Synthetic Method 4.** The first two steps are the same as synthetic method 1, steps 1 and 2, unless speciﬁed.

**Step 3.** The unprotected urea (1 equiv) and triethylamine (1.2 equiv) was dissolved in CH2Cl2 (8.3 mM, corresponding unprotected urea), and corresponding sulfonyl chloride was added dropwise at 0 °C and the reaction was stirred overnight (12 h) at rt. The reaction was quenched by addition of HCl solution (1M). The organic layer was collected, and the aqueous layer was extracted with EtOAc (EtOAc:aqueous layer/1:1) four times. The combined organic layer was dried over anhydrous magnesium sulfate and was concentrated in vacuo and further puriﬁed by flash chromatography.

**Protein Crystallization.** Crystals of the enzyme were obtained using the hanging drop vapor-diﬀusion method by mixing equal volumes of protein (8–12 mg/mL concentration in 100 mM sodium phosphate pH 7.4, 3 mM DTT) and the reservoir solution (30% PEG 3350, 0–10% sucrose) at 4 °C. The crystals grew in approximately 1 week and belonged to the hexagonal space group P622.

Complexes of sEH with inhibitors 8/UC1770 or 4 have been obtained by soaking sEH crystals grown as described above in modiﬁed mother liquor (35% PEG 3350, 50 mM sodium phosphate pH 7.4) supplemented with 1 mM solution of inhibitor for 1–7 days.

**Data Collection.** Prior to the data collection, a suitable crystal was dipped for 30 s in a modiﬁed mother liquor solution (35% PEG 3350) with the addition of 10% glycerol as a cryoprotectant. Diﬀraction data were collected at 100 K at the XP station at the Center for Advance Microstructures and Devices at Louisiana State University with a MAR charge-coupled device camera (structure TPPU/UC1770) or the NE-CAT beamline 24-ID-C at the Advanced Photon Source equipped with the Pilatus 6 M detector (structure 4). The images were processed and scaled using the HKL2000 (structure TPPU/UC1770) or Xia2 program suite (structure 4). Data collection and data processing statistics are given in Table 1.

**Crystal Structure Determination.** The molecular replacement procedure was applied to locate a solution using the program MOLREP. A monomer of human sEH (PDB accession code 1580) was used as a search model. The positioned MR model was reﬁned using the maximum likelihood reﬁnement in REFMAC5 with the TLS parameters generated by the TLSMD server. Program Coot was used for model building throughout the reﬁnement.

**HERG Patch Clamp Measurement.** Cell Culture for Channel Analysis. HEK-293 cells stably expressing hKv11.1 (hERG) under G418 selection were a generous gift from Craig January (University of Wisconsin, Madison). Cells were cultured in DMEM containing 10% fetal bovine serum, 2 mM glutamine, 1 mM Na+ pyruvate, 100 U/mL penicillin and 500 µg/mL G418. Before electrophysiological experiments, cells were grown to 60% conﬂuency and 100 mM asamizole was added to the culture for 24 h to increase Kv11.1 surface expression.

**Electrophysiology.** All experiments were conducted with an EPC-10 ampliﬁer (HEKA, Lambrecht/Pfalz, Germany) in the whole-cell conﬁguration of the patch-clamp technique with a holding potential of −80 mV. Pipette resistances averaged 2.0 MΩ. Compound solutions in Na+-Ringer were freshly prepared during the experiments from 10 mM stock solutions in DMSO. The ﬁnal DMSO concentration never exceeded 1%. The external solution contained in mM: 160 NaCl, 4 KCl, 2 CaCl2, 1 MgCl2, and 10 HEPES, pH 7.4, osmolality 300 mOsm/kg. The internal pipet solution contained in mM: 120 KCl, 10 HEPES, 4 NaATP, 10 EGTA, 5.374 CaCl2, 1.75 MgCl2, pH 7.2, osmolality 295 mmol/kg (free Ca2+ concentration 150 nM calculated with MaxChelator assuming a temperature of 25 °C, a pH of 7.2, and an ionic strength of 160 mM). HERG (Kv11.1) currents were elicited with a two-step pulse (applied every 10 s) from −80 mV ﬁrst to 20 mV for 1 s and then to −50 mV for 2 s, and the percent reduction of both peak and tail current by the drug were determined.

**Pharmacokinetic Study of Inhibitors Using Oral Dosing in Mice.** All the animal experiments were performed according to the protocols approved by the Animal Use and Care Committee of University of California—Davis. Male Swiss Webster mice (8 week old, 24–30 g) purchased from Charles River Laboratories were used for PK studies. Inhibitors for oral administration were dissolved in

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oleic acid-rich triglyceride containing 20% PEG400 (v/v) to give a clear solution. Blood (10 μL) was collected from the tail vein using a pipet tip rinsed with 7.5% EDTA(K₃) at 0, 0.5, 1, 1.5, 2, 4, 6, 8, 24, and 48 h after administration of the inhibitor in a cassette of 3–5 compounds (Supporting Information, Table S1) (0.3 mg/kg per compounds, 100–110 μL). Each group contained 3–4 animals. Each blood sample was immediately transferred to a tube containing 50 μL of water containing 0.1% EDTA. After being mixed strongly on a Vortex for 1 min, all samples were stored at −80 °C until analysis. The blood samples were prepared for the measurement of sEH inhibitors according to the previously reported method by Liu et al.18 The details LC/MS–MS methods are described in detail in the Supporting Information.

Pharmacokinetic Study of Inhibitors Using Oral Dosing in Rat. All the animal experiments were performed according to the protocols approved by the Animal Use and Care Committee of University of California—Davis. Male Sprague–Dawley rats (n = 4, 8 week old, 250–300 g) were used for pharmacokinetic study for sEH inhibitors. A cassette of four inhibitors (inhibitors 4, 7, 19, and 21, 0.3 mg/kg per inhibitor, 0.9–1.2 mL) was given by oral administration. Inhibitor was dissolved in oleic oil containing 5% polyethylene glycol 400 to form a clear solution. Blood (10 μL) was collected from the tail vein using a pipet tip rinsed with 7.5% EDTA(K₃) at 0, 0.5, 1, 1.5, 2, 4, 6, 8, and 24 h after oral dosing with the inhibitor. Each blood sample was immediately transferred to a tube containing 50 μL of water and mixed by vortex for 1 min, and all samples were stored at −80 °C until analysis. The blood samples were prepared for the measurement of sEH inhibitors according to the previously reported method by Liu et al. The details LC/MS–MS methods are described in detail in the Supporting Information.

Diabetic Neuropathic Pain Model. A diabetic neuropathic pain model was generated using streptozocin which targets and kills the pancreatic beta islet cells, rendering the animals with type I diabetes. The rats were acclimated for 1 h and tested for baseline thresholds before inducing diabetes. The baseline mechanical withdrawal thresholds were established using the von Frey mechanical nociceptive test with an electronic anesthesiometer (ITTC, Woodland Hills, CA). Subsequently, streptozocin (55 mg/kg) in saline was injected via tail vein per previously reported methods.84 After 5 days, the alldynia of diabetic rats was confirmed with the von Frey nociceptive assay. Rats were placed in clear acrylic chambers on a steel mesh floor. The hind paw of the rat was probed through the mesh with a rigid tip probe connected to the electronic readout pressure meter set to the maximum hold setting. The withdrawal thresholds per rat were measured 5 times at 1 min intervals for each time point. The baseline diabetic alldynia was quantified again at the beginning of all test days. The rats were then administered vehicle or sEH inhibitor via oral gavage and tested at 30 min, 1, 2, 3, 4, 5, 6, and 8 h for mechanical withdrawal thresholds. The reported scores are the grams of force required to elicit a hind paw withdrawal averaged with standard error of the mean (SEM) per a group of rats (n = 5). The baseline diabetic neuropathic scores were normalized to 100% to reflect the response to treatments which are reported as % of post diabetic neuropathic baseline.

ASSOCIATED CONTENT

Supporting Information
Correlation plot between Kᵅ against number of non-hydrogen atom, experimental log P and Kᵅ; plots of pharmacokinetic profiles of selected inhibitors in mice and rat; detailed experimental on chemistry, biochemistry, and animal studies; tables of optimized conditions for monitoring sEH inhibitors by MRM. This material is available free of charge via the Internet at http://pubs.acs.org.

Accession Codes
PDB accession codes: 4OD0 (human sEH with inhibitor 18 (UC1770/TPPU)) and 4OCZ (human sEH with inhibitor 4 (UC2389)).

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Notes
The authors declare the following competing financial interest(s): The University of California holds patents on the sEH inhibitors used in this study as well as their use to treat inflammation, inflammatory pain, and neuropathic pain. B.D. Hammock is a co-founder of Eicosis L.L.C., a start up company advancing sEH inhibitors into the clinic. All the others co-authors declare no competing financial interest.

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ABBREVIATIONS USED

sEH, soluble epoxide hydrolase; EpFAs, epoxy fatty acids; CYP450, cytochrome P450; EETs, epoxy-eicosatrienoic acids; EpETEs, epoxy-eicosatetraenoic acids; EpDPEs, epoxy-docosapentaenoic acids; Kᵅ inhibition constant; Kᵅ dissociation constant; TPPU, 1-trifluoromethoxyphenyl-3-(1-propionyl-piperidin-4-yl) urea; kᵅ dissociation rate constant; eloP, experimental Log P; PK-AUC, area under the curve of the pharmacokinetic profiles; TUPS, 1-(1-methylsulfonyl-piperidin-4-yl)-3-(4-trifluoromethoxyphenyl)-urea; TPAU, 1-trifluoromethoxyphenyl-3-(1-acetylpiperidin-4-yl)-urea; APAU, 1-(1-acetylpiperidin-4-yl)-3-adamantanylenurea; KMnO₄, potassium permanganate; t-TUCB, trans-4-[3-(4-trifluoromethoxyphenyl)-ureido]-cyclohexyloxycarbonylbenzoic acid; EDCl, 1-ethyl-3-(3- (dimethylamino)propyl)carbodiimide; EtOAc, ethyl acetate; MeOH, methanol; HCl, hydrochloric acid; NaOH, sodium hydroxide; DMAP, 4-dimethylaminopiperidin; MRM, multiple reaction monitoring; MWT, mechanical withdrawal thresholds.

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