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Letter

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Synthesis and Evaluation of Non-covalent Naphthalene-Based KEAP1-NRF2 Inhibitors

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Abstract: The oxidative stress response, gated by the protein-protein interaction of KEAP1 and NRF2, has garnered significant interest in the past decade. Misregulation in this pathway has been implicated in disease states such as multiple sclerosis, rheumatoid arthritis, and diabetic chronic wounds. Many of the known activators of NRF2 are electrophilic in nature and may operate through several biological pathways, rather than solely through the activation of the oxidative stress response. Recently, our lab has reported a non-electrophilic, monoacidic, naphthalene-based NRF2 activator which exhibited good potency *in vitro*. Herein, we report a detailed structure-activity relationship of naphthalene-based NRF2 activators, an X-ray crystal structure of our monoacidic KEAP1 inhibitor, and identification of an underexplored area of the NRF2 binding pocket of KEAP1.

Keywords: KEAP1, NRF2, Protein-protein interaction, Oxidative stress

Chronic oxidative stress is implicated in a number of disease states, such as chronic obstructive pulmonary disease (COPD), multiple sclerosis, diabetic chronic wounds, and chronic kidney disease.[1-6] Upregulating cellular defenses against oxidative stress may be a viable pathway for treatment or management of such diseases.[7-9] NRF2 (Nuclear factor (erythroid-derived 2)-like 2), a basic leucine zipper protein, regulates transcription of many antioxidant proteins. This oxidative stress response is gated primarily by the protein KEAP1 (Kelch-like ECH-associated protein 1), which sequesters NRF2 and, through a multi-protein assembly, poly-ubiquitinates it, marking it for proteosomal degradation.[10] If the KEAP1-NRF2 protein-protein interaction is inhibited, NRF2 can no longer be sequestered and tagged for degradation. Inhibiting KEAP1 in this manner allows cytoplasmic NRF2 concentrations to increase, translocate into the nucleus, and promote the transcription of genes associated with the antioxidant response, such as NADPH quinone oxidoreductase 1 (NQO1), heme oxygenase 1 (HO1), and glutamyl cysteine ligases-C and -M. (Figure 1).[10-14]

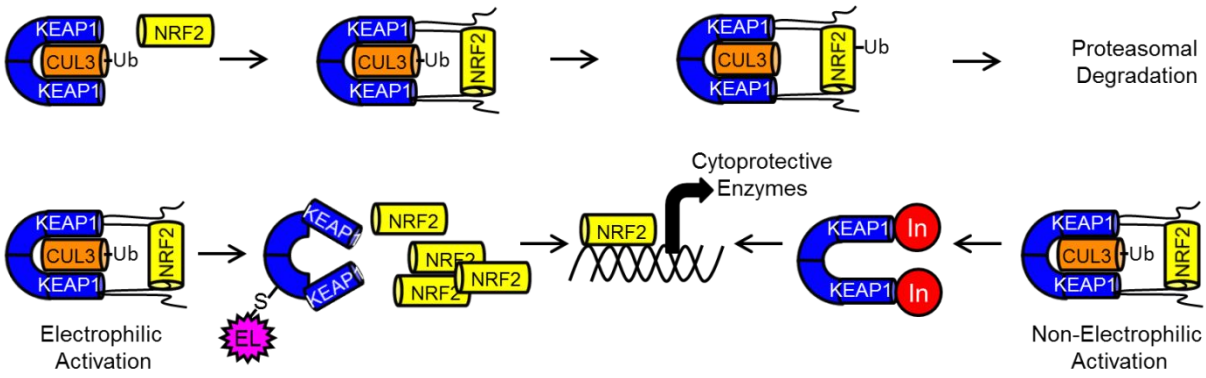
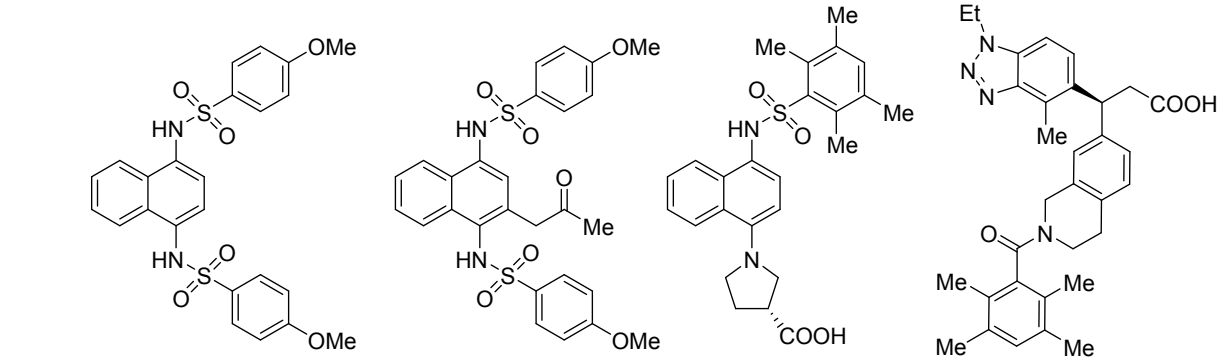


Figure 1. Top: KEAP1-NRF2 interaction under basal conditions. Bottom: Mechanism of NRF2 via electrophilic and non-electrophilic pathways.

The KEAP1-NRF2 interaction is inhibited in the presence of electrophiles, reactive oxygen species, or reactive nitrogen species, leading to a cytoprotective response in the cell.[15] Some therapies which inhibit the KEAP1-NRF2 interaction utilize KEAP1's sensitivity to electrophiles to increase cellular NRF2 levels. Some electrophiles may be promiscuous binders, and their lack of selectivity may make identification of mechanism of action more challenging.[16-17]

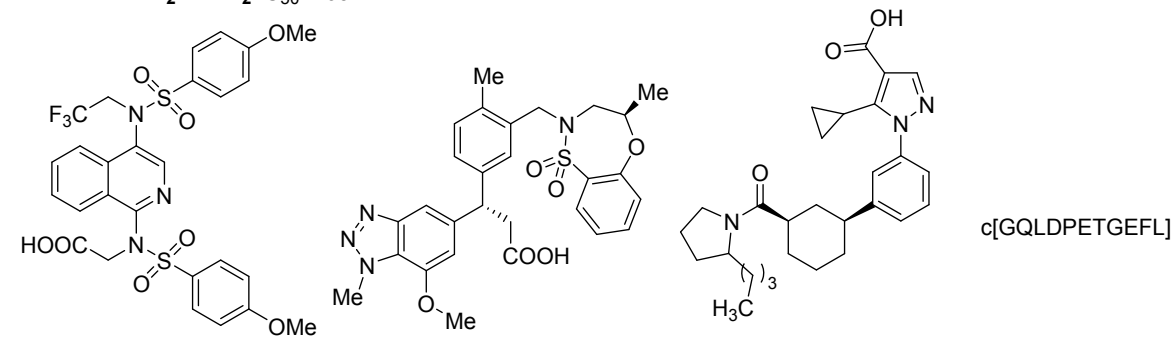


1a: R^1=R^2 = H IC_{50} = 2.7 μM
1b: R^1=R^2 = CH_2COOH IC_{50} = 29 nM
1c: R^1= H R^2 = CH_2COOH IC_{50} = 61 nM
1d: R^1=R^2 = CH_2CONH_2 IC_{50} = 63 nM

1e
IC_{50} = 6.2 μM

1f (RA-839)
IC_{50} = 140 nM

1g
KEAP1 K_d = 0.7 nM



1h
IC_{50} = 73 nM

1i
IC_{50} = < 15 nM

1j
IC_{50} = 63 nM

1k
c[GQLDPETGEFL]
IC_{50} = 18 nM

Chart 1. Representative examples of known KEAP1 inhibitors[18-27]

There have been multiple reports in recent years of non-electrophilic KEAP1-NRF2 inhibitors with significant structural diversity, including various small molecules (**1a-1j)** and peptides (**1k)** (Chart 1). Most of these molecules possess anionic character at physiological pH. Due to the relative ease of modifying compounds such as naphthalene **1a**, we and others have developed an

SAR of these compounds via scaffold-hopping approaches and modification to the flanking benzenesulfonamide arms; however, comparatively little investigation has been done to probe variations in the regions that link the naphthalene core to the benzensulfonamides.[20, 28] In this letter, we present structural modifications, informed by a crystal structure of mono-acid inhibitor **1c** (Figure 2), that provide valuable insights into the key interactions governing the potency and binding affinities of these 1,4-disubstituted naphthalene inhibitors.

Previously, we were unable to obtain a suitable co-crystal structure of **1c** with the KEAP1 Kelch domain, so we analyzed the potential binding mode of mono-acidic inhibitor **1c** *in silico*.[20] Docking experiments predicted that the carboxylate would likely interact with R483 and R415. We have now achieved success in co-crystallization of mono-acidic inhibitor **1c** with the Kelch domain of KEAP1 from a sodium formate solution. The co-crystal structure that we obtained contained a unit cell comprised of four Kelch domains, each possessing **1c** in slightly different orientations. Two Kelch domains contained a formate ion interacting with the unsubstituted sulfonamide, while the remaining two displayed water molecules in this position. While these two variations contained slightly different orientations, the overall interactions between **1c** and the Kelch domain remained similar (Figure 2a and 2b). Interestingly, we observed that the carboxymethyl functionality is engaged in a hydrogen bond network and dipolar interactions with R415, N414, N382, S363, and a water molecule, which was contradictory with our docking experiments, which showed interactions with R415, R483.[20] In the crystal structure, key interactions appear to be made between the sulfonamide oxygen atoms and S363, S508, Y525, S555, S602 and two water molecules. With these data in hand, we set forth to determine which of these interactions are critical for inhibitor binding.

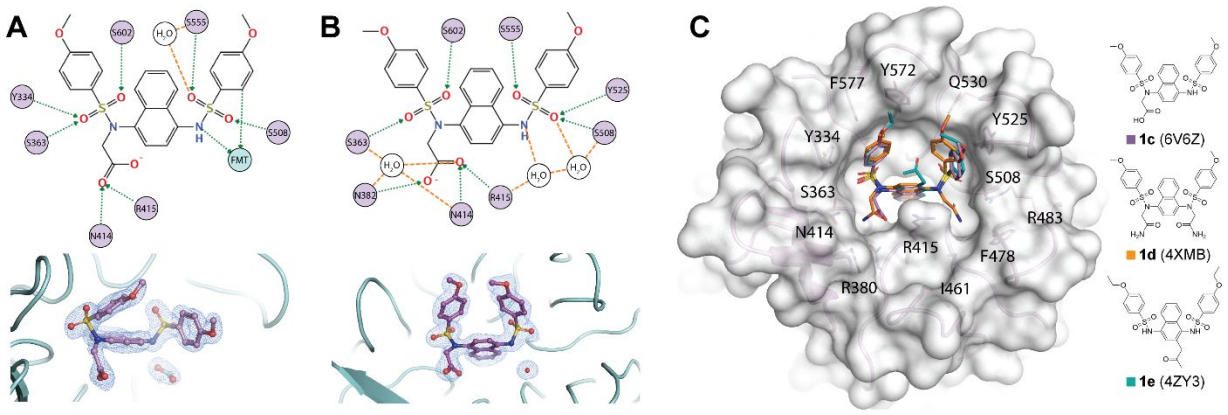
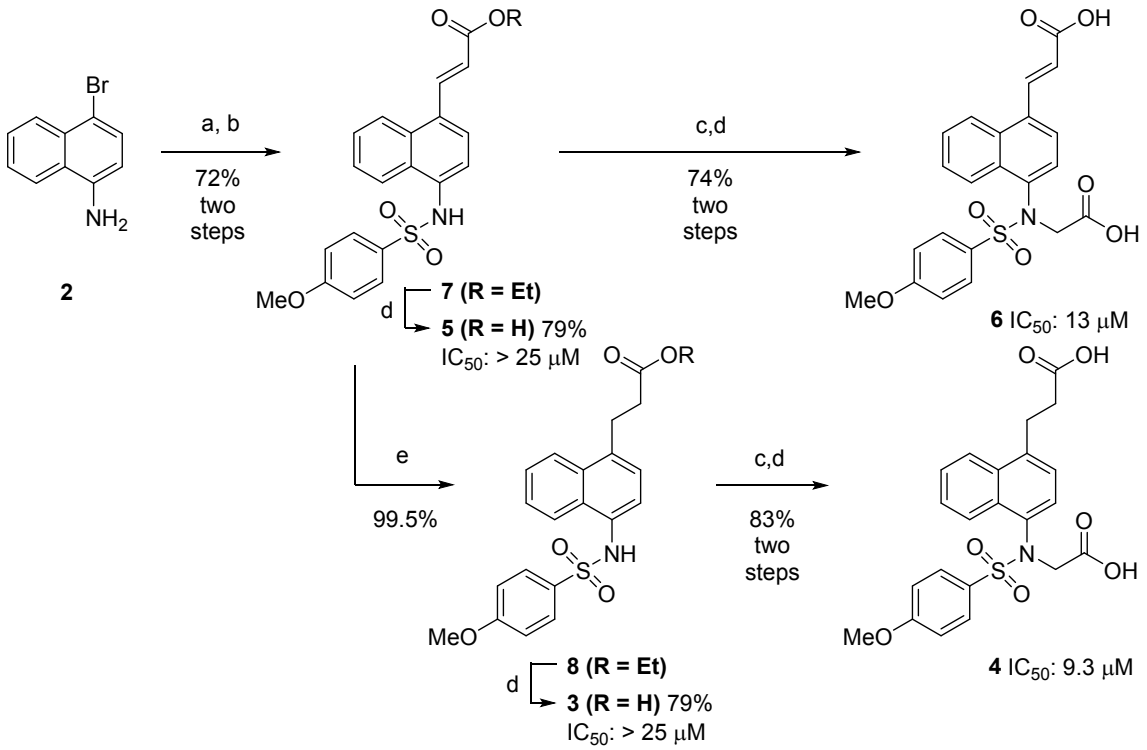


Figure 2. Structure of KEAP1 Kelch domain bound to compound **1c**. A, B) Diagram of interactions between KEAP1 Kelch residues (depicted as violet circles) and compound **1c.** Of the four KEAP1 Kelch:**1c** complexes crystallized in the asymmetric unit, two subunits contain a formate ion (FMT, shown in teal) within hydrogen bonding distance of **1c** (A), and two subunits contain a water molecule (B). $2f_o$-f_c electron density of **1c** and formate (A) and **1c** and bridging water (B) is shown in blue mesh contoured at 1σ. C) Superposition of KEAP1 Kelch:**1c** complex with the structures of KEAP1 bound to two other naphthalene-based compounds (**1d**, orange and **1e**, teal) previously reported in the literature. Associated PDB codes (6V6Z, 4XMB, 4ZY3) are shown at right. Amino acids in close proximity to bound ligands are labeled on the protein surface.

Our investigation into the structure-activity relationship began by probing the necessity of the bis-sulfonamide motif. In previous work, we showed that mono-acidic analogs of **1b** still maintained significant potency; however, no di-carboxyl-mono-sulfonamide analogs were synthesized. We sought to determine if protein binding was driven more by the sulfonamide oxygens or the interactions of the carboxylates. A series of these mono-sulfonamide compounds

were easily accessed through a Heck reaction of 1-bromo-4-aminonaphthalene (**2**) and subsequent derivatization (Scheme 1). Although these mono-sulfonamide compounds are structurally similar to reported mono-sulfonamide compound RA-839 (**1f**), none of these compounds retained nanomolar affinities for the Kelch-domain of KEAP1, as determined by fluorescence anisotropy (FA).[21, 29] This difference in affinity may be due to the rigidity of the acid in RA-839, versus the more freely rotating carboxylate groups in **3** and **4**. Even though compounds **5** and **6** contained an electrophilic α,β-unsaturated carbonyl, the activity of these compounds in the FA assay would be solely dependent on non-electrophilic inhibition since we used a truncated version of the KEAP1 protein which does not contain the previously mentioned electrophilic cysteine residues.

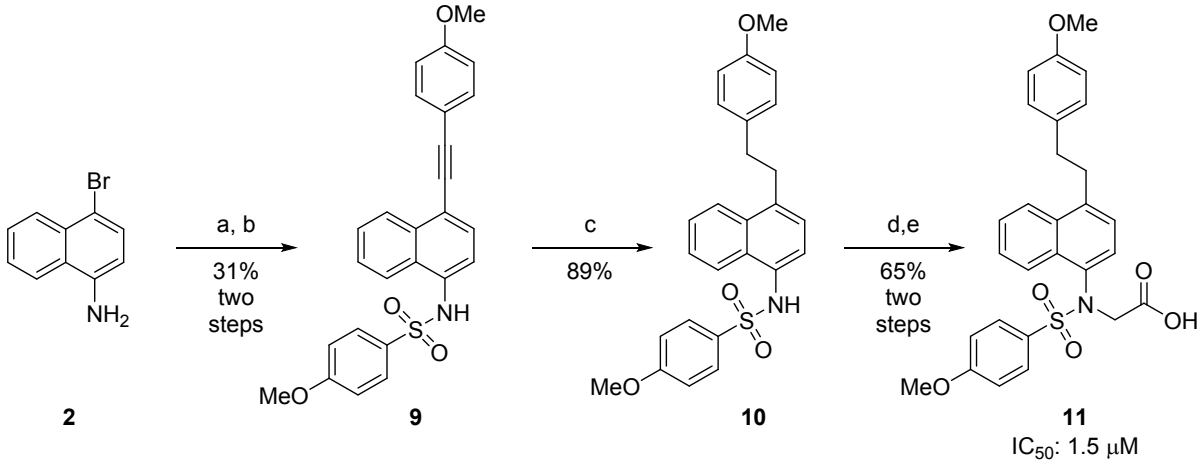
Scheme 1. Synthesis of mono-sulfonamide analogs of 1b and 1c[a]



[a](a) $Pd(OAc)_2$, P(*o*-tolyl)$_3$, K_2CO_3, ethyl acrylate, dioxane, 100 °C 16h; (b) 4-methoxybenzenesulfonyl chloride, pyridine; (c) ethyl bromoacetate, K_2CO_3, MeCN, rt, 16h; (d) 15% $NaOH_{(aq)}$, MeOH, rt, 4h; (e) 10 wt. % Pd/C, H_2 (40 PSI), EtOH, rt.

Next, we sought to determine the extent to which the affinity of these compounds was driven by interactions stemming from the aryl groups appended to the sulfonamides. Alkynyl sulfonamide **9** was obtained via a Sonogashira coupling of 1-bromo-4-aminonaphthalene (**2**) and 4-ethynylanisole, followed by sulfonylation of the amine. Hydrogenation of the alkyne yielded the saturated analog **10**, and subsequent alkylation of the sulfonamide and saponification of the resulting ester produced phenethyl derivative **11** (Scheme 2). The affinity of this compound was determined by an FA assay, and it displayed reduced affinity for the Kelch-domain of KEAP1, which indicated that the benzenesulfonamide groups may be a major contributor to the activities of these compounds.

Scheme 2. Synthesis of phenethyl analog 11[a]



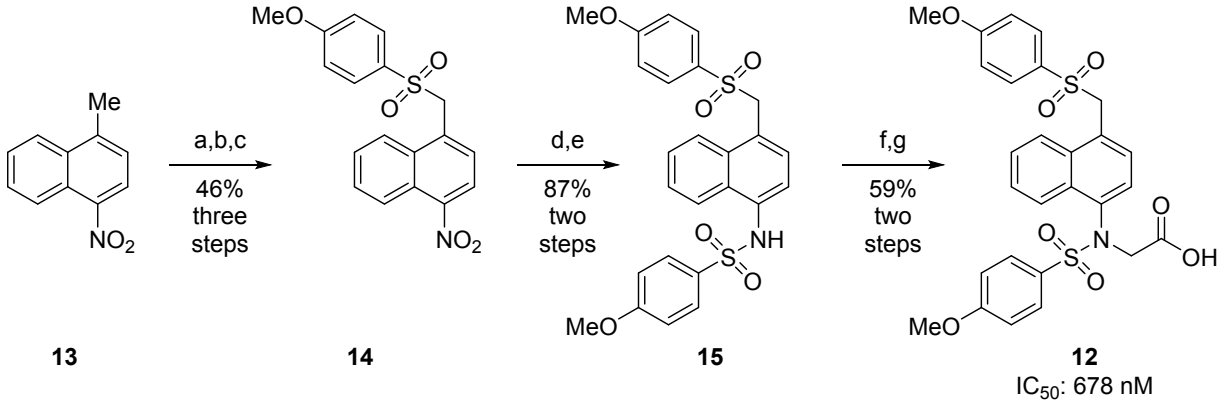
2 **9** **10** **11**

IC_{50}: 1.5 μM

[a](a) $Pd(PPh_3)_4$, CuI, 4-ethynylanisole, NEt_3, DMF, 80 °C, 20 h; (b) 4-methoxybenzenesulfonyl chloride, pyridine, rt, 18 h; (c) 5 wt. % Pd/C, H_2 (40 PSI), EtOAc, rt, 18 h; (d) ethyl bromoacetate, K_2CO_3, MeCN, rt, 18 h; (e) 15% $NaOH_{(aq)}$, MeOH, rt, 5 h

To test the hypothesis of the sulfonamide groups' key interactions, we synthesized analog **12**, in which a sulfone rather than a sulfonamide moiety was installed. Synthesis of these analogs began with a nitration of 1-methylnaphthalene to yield 1-nitro-4-methylnaphthalene **13**. Benzylic bromination with azabisisobutyronitrile/*N*-bromosuccinimide, followed by substitution with 4-methoxybenzenethiol, yielded the thioether, which was oxidized with H_2O_2 to the corresponding sulfone **14**. Reduction of the nitro group and sulfonylation produced the sulfone analog of **1a**, which then underwent alkylation, and saponification to yield the desired monoacidic sulfone analog **12** (Scheme 3).

Scheme 3.[a]



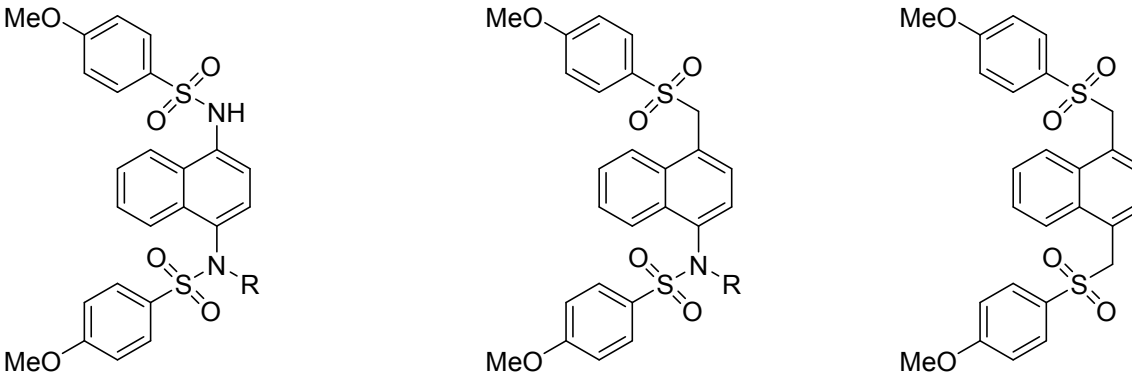
13 **14** **15** **12**

IC_{50}: 678 nM

[a](a) *N*-bromosuccinimide, azabisisobutyronitrile, MeCN, rt, 6 h; (b) 4-methoxybenzenethiol, 1M $NaOH_{(aq)}$, dioxane, rt, 18 h; (c) 30% H_2O_2, AcOH, Ac_2O, rt, 5 h; (d) 10 wt. % Pd/C, H_2 (40 PSI), EtOAc; (e) 4-methyoxybenzenesulfonamide, pyridine, rt, 18 h; (f) ethyl bromoacetate, K_2CO_3, MeCN, rt, 18 h; (g) 15% $NaOH_{(aq)}$, MeOH, rt, 5 h.

Additionally, we attempted to synthesize analogs in which the carboxymethyl group was attached to the carbon alpha to the sulfone, and where both sulfonamides were replaced with sulfones; however, we were unable to successfully isolate the desired products due to β-elimination of a sulfinate to give α,β-unsaturated compounds. Comparison of intermediates **15** and **16** to bis-sulfonamide **1a** showed that monosulfone **15** had comparable activity to **1a**, yet

bis-sulfone **16** was inactive (Chart 2). When comparing the sulfone monoacid **12** and diamino monoacid **1c**, sulfone monoacid **12** showed about a 10-fold drop in affinity. This loss of binding affinity may be due to an unfavorable increase of hydrophobicity in the Arg-rich area of the binding pocket.



1a R = H; IC_{50}: 2.7 μM
1c R = CH_2COOH; IC_{50}: 0.06 μM

15 R = H; IC_{50}: 3.0 μM
12 R = CH_2COOH; IC_{50}: 0.678 μM

16 IC_{50}: > 25 μM

Chart 2. Sulfone Analogs of Compounds **1a** and **1c**

We were also interested in probing the ability of the binding pocket to accommodate substitutions alpha to the carboxylate group. Recently, a report by Lu *et al.*, outlined an exploration of various alpha substituents based on amino acid side chains producing compounds of structure **17** (Chart 3).[28] Due to the lack of activity of our mono-sulfonamide analogs, we opted to explore the activity of bis-sulfonamide compounds with structure **18**. We hypothesized that the more congested nature of the substituents in **18** may constrain the three-dimensional structure, leading to enhanced interactions and binding affinity compared to the less constrained compounds with structure **17**.

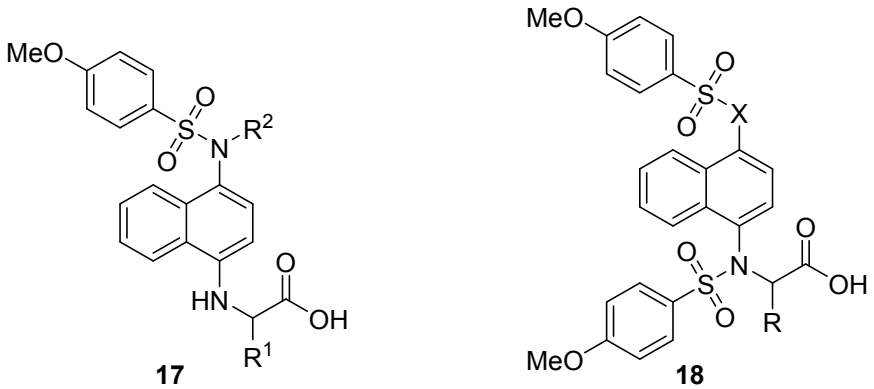


Chart 3. Structural variations explored by Lu *et al.* vs. this work

Not only would α-substituents potentially lead to the development of an SAR for an underexplored area of these molecules, substitution in this position introduces chirality into this framework. Due to **12** being the best inhibitor in the series we synthesized methyl analog **19** and phenyl analog **20** by substituting ethyl bromoacetate with ethyl-2-bromopropionate and benzyl-2-bromo-2-phenylacetate, respectively, for the alkylation step. Use of benzyl-2-bromo-2-phenylacetate was required because basic saponification of the α-phenyl carbonyl resulted in decomposition of the material.

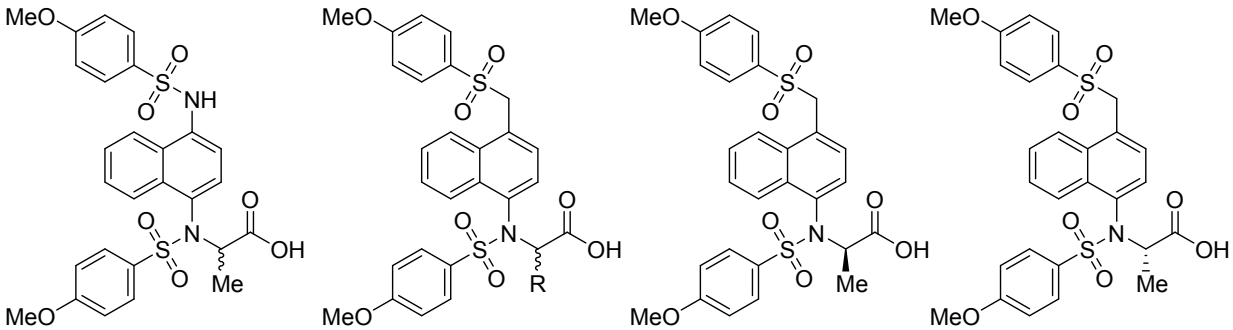


Chart 4. Propionate and phenylacetic acid analogs of **1c** and **12**

The addition of an R group alpha to the carbonyl did indeed constrain the orientation of the substituents; the constraint is evident from this modification due to the formation of

atropisomers, which displayed a 2:1 ratio of the major vs. minor conformer. A variable temperature NMR experiment, from 20 °C to 70 °C, was performed in an effort to observe the interconversion of the atropisomers; however, no substantial shift or coalescence of the signals was observed. Attempts to separate the atropisomers were unsuccessful. Interestingly, the addition of the methyl group increased binding affinity of sulfone **19** 5-fold compared to the unsubstituted sulfone **12**, while addition of the phenyl ring severely diminished the activity. These results can be rationalized by examination of the crystal structure of **1c** (Figure **1c**), in which there is a small hydrophobic pocket where the methyl group may fit. It is likely that this pocket is unable to accommodate much larger substituents, like phenyl. When comparing the α-methyl compound **21** and unsubstituted mono-acid **1c**, we observe a 2-fold reduction in binding affinity. The reason for this slight decrease may be due to the methyl group inducing a less favorable binding pose for this series of compounds.

Because of the relatively high binding affinity of racemic propionate **19**, we moved to determine whether the individual enantiomers of **19** displayed a preference for the binding pocket. To synthesize each of the enantiomers, it was necessary to preclude basic saponification to avoid racemization of the stereocenter (See SI). We utilized enantiopure benzyl esters, which were subsequently deprotected by Pd/C-catalyzed hydrogenation to afford the individual enantiomers with >95% e.e. (determined by chiral HPLC). Testing each of the enantiomers for their binding affinity in the FA assay indicated that there was a negligible eudysmic ratio (i.e., the ratio of the IC_{50} values of the high-affinity and low-affinity binder), indicating that further probing is warranted to determine the proper substituent for this area of the molecule. The results of the structural modifications detailed above are summarized in Table 1.

Table 1. IC_{50} ± standard deviation, retention times (see SI for HPLC method), and $cLogD_{7.0}$ of tested compounds.

Compound	IC_{50} ± standard deviation (nM)[a]	Retention Time (min)	$cLogD_{7.0}$[b]
1b	29[c]	n.d.	3.56
1c	63[c]	n.d.	-3.81
3	>25000	5.184	-0.39
4	9300 ± 560	5.008	-3.15
5	>25000	5.254	0.25
6	13000 ± 3700	5.071	-3.30
11	1500 ± 18	6.737	2.07
12	678 ± 29	5.886	0.13
15	3000 ± 120	6.072	3.07
16	>25000	6.184	4.08
19	189 ± 9	5.995	1.19
20	14000 ± 1060	6.312	2.08
21	126 ± 20	5.910	0.44
22	151 ± 20	5.995	1.19
23	241 ± 8	5.995	1.19

[a]Standard deviation of two independent experiments. [b]Values calculated with ChemAxon's LogD Predictor.[30] [c]values taken from Jain *et al.* and compounds were run in parallel as standards in the FA assay.[20]

Overall, using a combination of X-ray crystallographic analysis and experimental structure-activity relationship development, we have determined key features of naphthalene-based KEAP1–NRF2 inhibitors that are responsible for the binding affinity to the Kelch domain of KEAP1 (Chart 5).

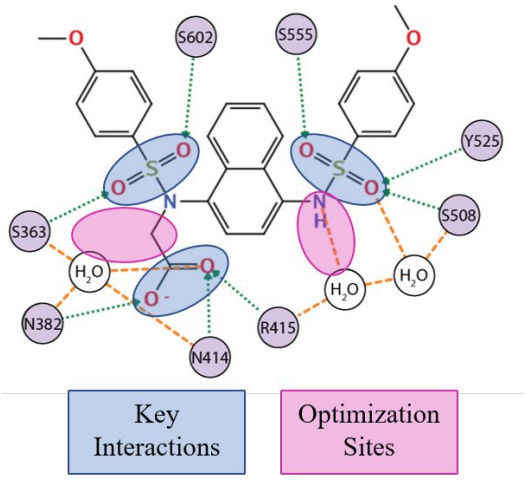


Chart 5. Key interactions and sites for optimization identified.

Key interactions are formed between serine residues within the Kelch domain and the oxygen atoms of either the sulfonamide or sulfone functionalities present within these inhibitors. Pairing the previously described serine–oxygen interactions with dipolar interactions between the carboxylate, asparagine, and arginine within the binding pocket appeared to be crucial for establishing strong protein–inhibitor interactions. Furthermore, we showed that one of the nitrogen atoms on the naphthalene ring could be replaced with a carbon atom and still maintain reasonable binding affinities. This substitution allows for the investigation of different geometries around this prochiral carbon, instead of being confined to an achiral nitrogen linker. Lastly, our observations agree with Lu *et al*. in having identified a region, alpha to the carbonyl of theses inhibitors where additional exploration may yield inhibitors with higher affinity. Further experiments are underway to determine the role these α-substituents play in inhibitor binding.

Associated Content:

Supporting Information

Experimental procedures of syntheses, biochemical assay protocols, and crystal structure parameters.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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Abbreviations:

KEAP1, Kelch-like ECH-associated protein 1; NRF2, Nuclear factor (erythroid-derived 2)-like 2; FA, Fluorescence anisotropy; SAR, Structure activity relationship; COPD, chronic obstructive

pulmonary disorder; DMF, dimethyl formamide; NQO1, NADPH quinone oxidoreductase 1; HO1, heme oxygenase 1

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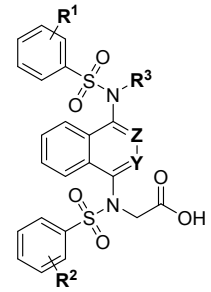

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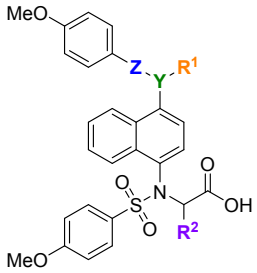

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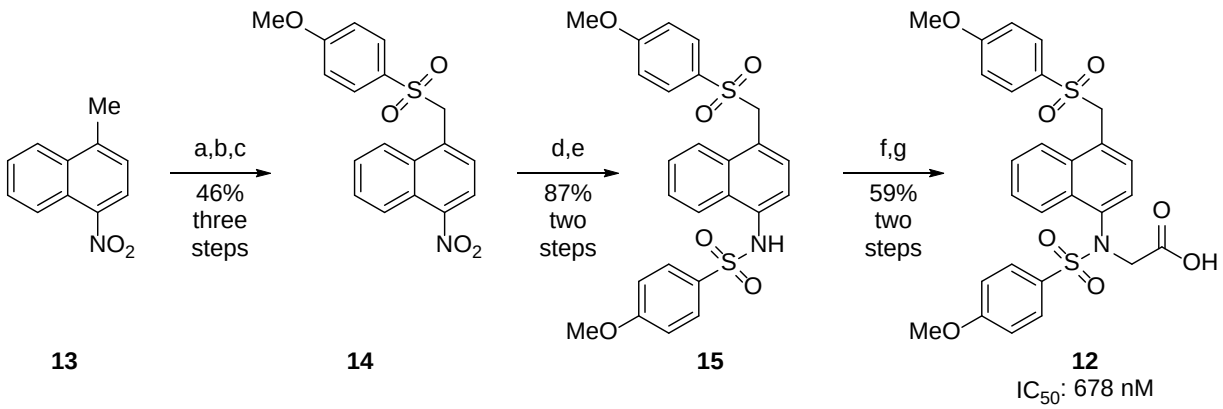

13 **14** **15** **12**

IC_{50}: 678 nM