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(54) Title: QUINONE DERIVATIVES, PHARMACEUTICAL COMPOSITIONS, AND USES THEREOF

(57) Abstract: This application describes quinone derivatives which target the redox site of Ape1/Ref1. Also included in the invention are pharmaceutical formulations containing the derivatives and therapeutic uses of the derivatives.

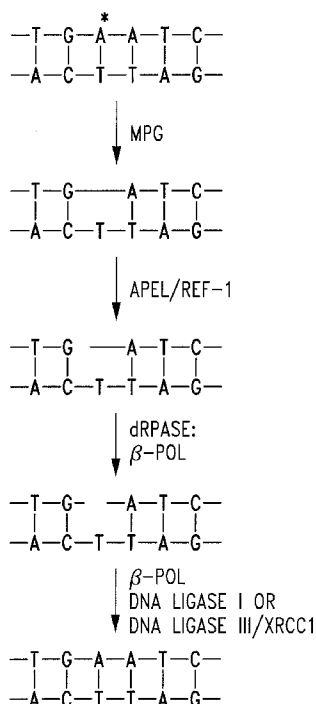


Fig. 1A



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QUINONE DERIVATIVES, PHARMACEUTICAL COMPOSITIONS, AND USES THEREOF

CROSS REFERENCE TO RELATED APPLICATIONS

- 5 This application claims priority to United States Provisional Patent Applications Nos. 60/989,566 filed on November 21, 2007, and 60/975,396 filed September 26, 2007, the complete disclosures of which are incorporated herein by reference.

FIELD OF INVENTION

- 10 The present invention relates generally to the fields of molecular biology, biochemistry, and pathology. More specifically, in certain aspects, the invention relates to quinone derivatives useful as Ape1/Ref-1 redox inhibitors.

BACKGROUND

- Apurinic/apyrimidic endonuclease (Ape1), also known as redox
15 effector factor (Ref-1) (hereinafter Ape1/Ref-1 or Ape1) is an enzyme with a dual role. In addition to its DNA base excision repair (BER) activity, Ape1/Ref-1 also functions as a redox effector maintaining transcription factors in an active reduced state. All X-ray structures currently available for Ape1 depict the base excision repair (BER) site, and little structural information is known about the redox site. Cysteine
20 65 is the critical residue for redox function, unfortunately it is not solvent accessible in any structure.

- Ape1/Ref-1 has been shown to stimulate the DNA binding activity of several transcription factors such as HIF-1 α , NF κ B, AP-1 and p53, and others known and unknown, which are related to tumor survival and progression (Evans *et al.*,
25 *Mutat Res* 2000, 461, 83). Ape1/Ref-1 expression has been shown to be altered in a variety of cancers including breast, cervical, germ cell tumors, adult and pediatric gliomas, osteosarcomas, rhabdomyosarcomas, non-small cell lung cancer, and multiple myeloma (Puglisi *et al.*, *Oncol Rep* 2002, 9, 11; Thomson *et al.*, *Am J Pediatr Hematol Oncol* 2001, 23, 234; Roberston *et al.*, *Cancer Res* 2001, 61, 2220;
30 Puglisi *et al.*, *Anticancer Res* 2001, 21, 4041; Koukourakis *et al.*, *Int J Radiat Oncol Biol Phys* 2001, 50, 27; Kakolyris *et al.*, *Br J Cancer* 1998, 77, 1169; Bobola *et al.*, *Clin Cancer Res* 2001, 7, 3510). High Ape1/Ref-1 expression has also been

associated with a poor outcome for chemoradiotherapy, poor complete response rate, shorter local relapse-free interval, poorer survival, and high angiogenesis (Koukourakis *et al.*, *Int J Radiat Oncol Biol Phys* 2001, 50, 27; Kakolyris *et al.*, *Br J Cancer* 1998, 77, 1169; Bobola *et al.*, *Clin Cancer Res* 2001, 7, 3510).

5 Angiogenesis is an important component of cancer growth and metastasis. The formation of new blood vessels at the site of a cancerous tumor provides a source of nutrients for accelerated tumor growth and expansion as well as a path for tumor cells to enter the bloodstream and spread to other parts of the body. Thus, effective inhibition of angiogenesis is a useful mechanism to slow or prevent
10 the growth and spread of cancer. An increase in Ape1/Ref-1 activity has been associated with angiogenesis. Vascular endothelial growth factor (VEGF) is an important signaling protein involved in both vasculogenesis and angiogenesis. Ape1/Ref-1 is a component of the hypoxia-inducible transcriptional complex formed on the vascular endothelial growth factor (VEGF) gene's hypoxic response element
15 (Ziel *et al.*, *Faseb J* 2004, 18, 986).

 In addition to cancer, altered angiogenesis contributes to pathological conditions related to, among others, cardiovascular disease, chronic inflammatory disease, rheumatoid arthritis, diabetic retinopathy, degenerative maculopathy, retrolental fibroplasias, idiopathic pulmonary fibrosis, acute adult respiratory distress
20 syndrome, asthma, endometriosis, psoriasis, keloids, and systemic sclerosis. Inhibition of angiogenesis is a desirable clinical outcome for the amelioration or prevention of diseases involving altered angiogenesis.

 Given the role the redox site looks to play in pathologies, it is desirable to design and synthesize compounds which preferably selectively inhibit
25 the redox pathway.

SUMMARY OF INVENTION

 This application describes quinone derivatives which target the redox site of Ape1/Ref1. Also included in the invention are pharmaceutical formulations containing the derivative and therapeutic uses of the derivatives.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1: Pathways of BER following either simple or complex glycosylase activity

Figure 2: Point mutation T58C to introduce derivativeous cysteine into zebrafish Ape1.

Figure 3: EMSA data for wildtype Ape1 (C65) and C65A/C65A mutants.

Figure 4: Distribution of redox and repair domains (top) as well as the nuclear localization sequence in Ape1.

Figure 5: A. Surface rendering of the 1DEW pdb crystal for Ape1.⁹ Cysteine 65 is indicated by the arrow. B. Representation of the BER active site on the same pdb structure.

Figure 6: Inhibitors of the Ape1 protein.

Figure 7: Proposed mechanism for intramolecular esterification during nitric acid oxidation of (Z)-44a.

Figure 8: Simple amide derivatives.

Figure 9: HPLC spectra of oxidation and coupling reactions to synthesize quinone 92.

Figure 10: EMSA data for E3330 (1) and derivatives 10a (unsubstituted double bond) and 64 (methoxyethyl substituted double bond).

Figure 11: EMSA data for E3330 (1) and derivative 10e (nbutyl substituted olefin).

Figure 12: A. Crystal of inhibitor 43a used for X-ray diffraction study. B. Structure generated from data collected from X-ray diffraction studies on 43a.

Figure 13: Structure derived from X-ray diffraction study.

Figure 14: HMQC spectra of A. *E*-42a; B. *Z*-42a; C. 9f; and D. 79.

Figure 15: nOe spectra of A. *E*-42a; B. *Z*-42a; C. 9f; and D. 79.

Figure 16: Analysis of *Z* and *E* isomers (*Z*)-77 and (*E*)-77, respectively, by direct comparison of ¹H NMR spectra (A/B), HMQC spectra (C/D), nOe enhancement from irradiation of allylic protons (E/F), and nOe enhancement from irradiation of vinyl protons (G/H). A/B.

Figure 17: Direct comparison of Z and E isomers (Z)-81 and (E)-81, respectively, by their corresponding ¹H NMR spectra (A/B), HMQC spectra (C/D), and nOe enhancement from irradiation of vinyl protons (E/F).

DETAILED DESCRIPTION

5 The most important regulatory processes for the genome are sustaining the fidelity and integrity of DNA, as well as appropriately expressing the genes contained therein. More than 130 genes are directly involved in maintaining fidelity within DNA, and potentially more than 2000 transcription factors regulate the expression of genes.¹ Human apurinic endonuclease-1/redox-enhancing factor-1 (Ape1/Ref1) functions in two capacities. The first function plays an integral role in 10 the base excision repair (BER) pathway. BER is extremely important in regulating DNA fidelity as well as repairing DNA damage from exogenic and endogenic sources, such as alkylating agents and reactive oxygen species (ROS) respectively.² The BER pathway proceeds via the removal of a purine or pyrimidine base by either a 15 simple or complex glycosylase, resulting in the formation of an apurinic site (AP site). (Figure 1) AP sites form on the order of 10⁴ times per cell per day through spontaneous glycosidic bond hydrolyses alone, and when combined with bases damaged by alkylating agents, ROS, genotoxins, etc., the barrage of genetic damage is monumental.³ Abasic sites pose detrimental consequences for the cell including 20 single and double strand breaks, mutations, and ultimately apoptosis.² Ape1 is able to counter this genetic onslaught by being the only endonuclease capable of nicking the phosphate backbone 5' to the AP site in the case of a simple glycosylase, or excising a 3'-deoxyribose phosphate (dRP) in the case of a complex glycosylase (Figure 1A and Figure 1B, respectively).²

25 Figure 1: Pathways of BER following either simple or complex glycosylase activity. A. Following base removal by a simple glycosylase (MPG) the phosphate backbone is still intact bearing an apurinic site. Ape1 acts as the 5' to 3' endonuclease, cleaving the backbone 5' to the abasic site, leaving a 5' phosphate and a 3' hydroxyl. β-polymerase then acts as the phosphodiesterase, removing the abasic 30 site. B. Base removal by a complex glycosylase (OGG, NTH) results in an abasic site flanked by a 3' nick bearing a phosphate attached to the 3' hydroxyl. Ape1 then performs 3' to 5' exonuclease activity to remove the abasic site, preparing for base

replacement by β -polymerase. C. Infrequently the sugar at the abasic site can become either reduced or oxidized, and Ape1 is then responsible for nicking 5' to the abasic site. Long Patch BER then takes place where multiple nucleotides are joined 5' to the AP site and then ligated to the damaged strand.²

5 The portion of genetic information that ultimately becomes transcribed into mRNA for processing into proteins needs to be regulated as tightly as the fidelity of the DNA. The second function of Ape1 controls the oxidation state of a multitude of transcription factors responsible for cell cycle progression, cell proliferation, and apoptosis, including activator protein-1 (AP1), hypoxia-inducible factor-1 α (HIF-1 α),
10 and nuclear factor- κ B (NF κ B).^{2,4} These transcription factors all contain cysteine residues that bind a specific promoter region in a DNA, and after a cycle of transcription activation these factors become oxidized. It is hypothesized that cysteine 65 of Ape1 performs the reduction of oxidized transcription factors.⁵ The significance of C65 is supported by both the loss of redox activity in the C65A
15 mutant, as well as gain of function in the corresponding zebrafish model where a critical cysteine residue is introduced in the T58C mutant (Figure 2)⁶ Conflicting data also exist that suggest C65 is not necessary for redox function. (Figure 3)⁷ Even though a majority of research seems to support a role for C65 in the redox regulation of transcription factors, a redox mechanism is not readily apparent because cysteine
20 65 is buried within the protein and therefore not solvent accessible (Figure 5A).

Figure 2: Point mutation T58C to introduce derivativeous cysteine into zebrafish Ape1 affects redox abilities in the zebrafish model as measured by luciferase assay. ⁶

Figure 3: EMSA data for wildtype Ape1 (C65) and C65A/C65A
25 mutants. The C64A point mutation does not affect redox function in human Ape1 suggesting this cysteine is not necessary for redox regulation of transcription factors. Lanes: 1) dilution buffer alone; 2) 10 mM DTT; 3 to 5) 10, 25, and 50 ng of wild-type lung extract, respectively; 6 to 8) 10, 25, and 50 ng of C64A/C64A lung extract, respectively; 9 to 11) 10, 25, and 50 ng of wild-type heart extract, respectively; 12 to
30 14) 10, 25, and 50 ng of C65A/C64A heart extract, respectively. C64 in murine Ape1 corresponds to C65 in human Ape1. The arrow indicates free DNA probe.⁷

The BER and redox functions of Ape1 were discovered separately which led to the belief that they existed in two different proteins; this codiscovery is

responsible for the Ape1/Ref1 dual name. Only years after the identification of both functions was it determined that they belonged to two slightly-overlapping domains of the same protein (Figure 4).⁸ Distribution of redox and repair domains (top) as well as the nuclear localization sequence in Ape1. Phosphorylation sites (bottom) located
5 throughout the Ape1 sequence.²

Figure 5: A. Surface rendering of the 1DEW pdb crystal for Ape1.⁹ Cysteine 65 is indicated by the arrow. B. Representation of the BER active site on the same pdb structure.

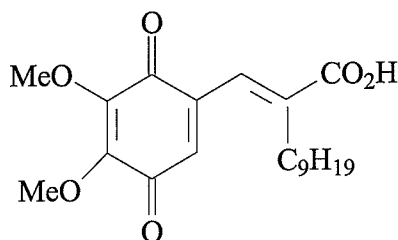
Ape1 has been found upregulated in small-cell lung, head and neck,
10 prostate, cervical, germ cell, colon, and ovarian cancers.² AP sites caused by DNA damaging agents are efficiently repaired by Ape1, thus overexpression of Ape1 in cancer confers resistance to drugs that modify DNA. The redox function of overexpressed Ape1 also aids the tumor cell, where the unregulated redox-cycling of transcription factors enables the cancer cell to bypass fundamental cell-cycle
15 checkpoints. Ape1 becomes an attractive target for drug design because of these two inherently important functions, but the salient questions that arise are which function should be inhibited and how?

Structurally there is significant information regarding the repair site, with a crystal structure of the protein bound to an abasic site on a short segment of
20 double stranded DNA.⁹ There is still very little known about the structure of the redox site. As previously mentioned the apparent redox cysteine is buried in all known crystal structures, and a redox active conformation may exist that has yet to be captured by crystallography. This leads to a great deal of ambiguity for a rational drug design approach, and thus inhibitor design requires a structure activity
25 relationship (SAR) approach to determine preferences of the active site.

Presently there are only a few compounds shown to inhibit Ape1. Lucanthone, a natural product discovered and synthesized in the early 1950's, appears to act through an intercalative mechanism to inhibit the repair function of Ape1.¹⁰ (Compound 3, Figure 6) Methoxyamine also acts to inhibit the BER function;
30 methoxyamine condenses with the aldehyde present in the hemiacetal of the abasic sugar, and Ape1 can no longer recognize the AP site for repair.¹¹ (Compound 2, Figure 6) Both of these compounds act in an indirect way to inhibit the BER function of Ape1, but to date nothing has been shown to interact directly with the BER site on

the Ape1 protein. Affinity chromatography and western blotting with radio-labeled drug were used to show E3330 (Compound 1, Figure 6) was specific for only Ape1 from a crude cell lysate.¹²

The redox function of Ape1/Ref-1 was found to be selectively
5 inhibited by 3-[(5-(2,3-dimethoxy-6-methyl,4-benzoquinoyl)]-2-nonyl-2-propionic acid, below (hereinafter "E3330", also referred to as "RN3-3").



10

Further information on E33300 may be found in Abe *et al.*, U.S. Patent 5,210,239, fully incorporated herein by reference. Further, it has been determined with E3330 that selective inhibition of the redox function of Ape1/Ref-1 results in the inhibition of altered angiogenesis and cancer.

15

Based on the findings related to E3330, an effort was made to synthesize a range of quinone derivatives (benzoquinones and naphthoquinones) to determine their effect on the redox active site of Ape1. Another desire was to conjugate the derivatives to biotin in order to provide molecular tools for determining specificity and dissociation constants (K_D).

20

As the quinone E3330 has been shown to selectively inhibit the redox site of Ape1, this provided a starting point for further synthetic efforts. Without structural information regarding the redox active site on Ape1 the project began with a SAR approach, first examining the structure of E3330 to determine what aspects were important, and later applying this knowledge to the quinone derivatives.

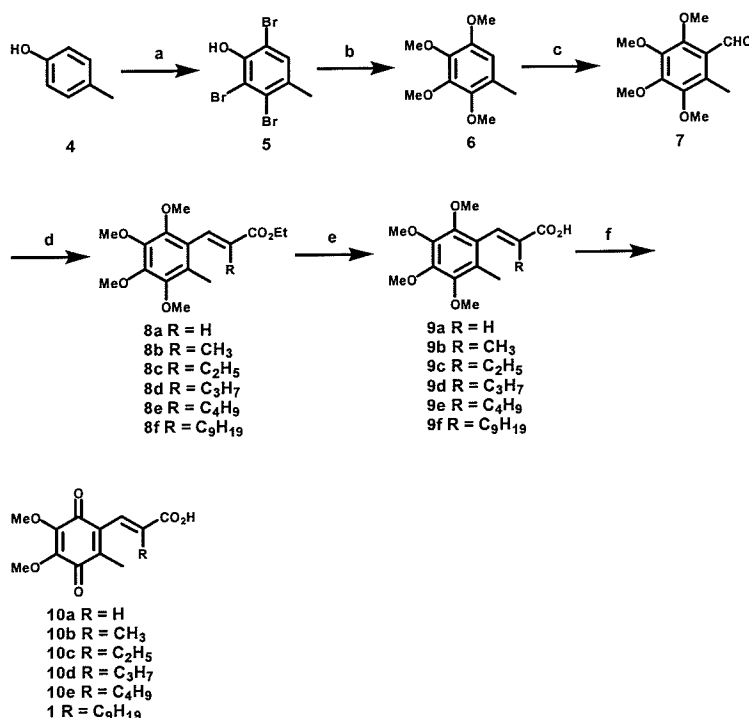
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The Emmons condensation of 6-methyl-2,3,4,5-tetramethoxybenzaldehyde (Compound 7, Scheme 1) was performed with a variety of alkylated phosphonoacetates. To make E3330 more druggable the n-nonyl sidechain needed to be truncated significantly, but it was equally important to ensure that reducing the size of the chain did not have less desirable effects on activity. The
30 nonyl sidechain was replaced with n-butyl, n-propyl, ethyl, and methyl substituents, as well as an unsubstituted derivative. A methoxyethyl sidechain was also included to

compare to the aliphatic sidechains. In order to modify the methyl substituent of the ring the des-methyl aldehyde (Compound 19, Scheme 1) was synthesized. The 2-chloro derivative was chosen because it presented a facile synthesis and would further develop knowledge regarding electronics of the benzoquinone ring. The chlorine
5 substituent would be isosteric to the methyl group of E3330, while electronically different. Observations from the benzoquinone series would then be utilized to generate a series of naphthoquinone inhibitors.

Naphthoquinone inhibitors with a variety of substituents in the 3 position were synthesized, while maintaining a group of sidechains. Methyl
10 substitution was first examined to correlate to the E3330 series. The halogenated derivatives (bromo, chloro, fluoro) were next synthesized to examine the effects of electronegative substituents replacing the ring methyl group. Then methoxy and methylthio derivatives were tested to observe the affect of including substituents that are electronegative, but significantly larger than the parent methyl compound.

15 Also, the epoxidation and reduction of the double bond, as well as synthesis of the Z isomer, were employed. The carboxylate functional group was modified by preparation of the methyl ester and hydroxyethylamide. These final derivatives shed light upon the importance regarding the entire unsaturated acid moiety of the naphthoquinone derivatives.

E3330 Derivatives

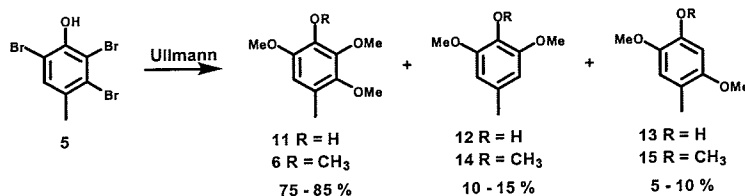
a) CH₂Cl₂, Br₂, rt 3 h, 89 - 100%; b) i. CuI, NaOMe, DME, DMC, reflux 20 h; ii. H₂O, Me₂SO₄, 4h, 40 - 65%; c) TiCl₄, CHCl₂OCH₃, CH₂Cl₂, 0 °C to rt 4 h, 89%; d) NaH, (EtO)₂P(O)CHRCO₂Et, THF, rt 12 h, 42 - 88%; e) KOH, EtOH, reflux 30 min, 78 - 100%; f) HNO₃, AcOH, EtOAc, rt 4 h, 31 - 59%

Scheme 1: Synthesis of E3330 and derivatives.

5 First, E3330 was synthesized. The synthesis of E3330 (1) was performed based on a 1993 Japanese patent as shown in Scheme 1.¹³ The first step of the synthesis requires the tribromination of 4-methylphenol (4) which proceeds rapidly at room temperature.^{13,14} The reactions result in approximately a 90% yield of a white crystalline solid that can be readily separated from 2,6-dibromo-4-methylphenol via recrystallization from hexane.

10 The second step in the synthesis of E3330 is the most problematic, where the Ullmann-type methanolysis of 2,3,6-tribromo-4-methylphenol (5) results in multiple reduction byproducts that are not disclosed in the literature.^{13,14} The optimized Ullmann conditions in our hands result in a mixture of 4-methyl-2,3,6-trimethoxyphenol (11, 75 - 85%), 2,6-dimethoxy-4-methylphenol (12, 10 - 15%), and 2,5-dimethoxy-4-methylphenol (13, 5 - 10%). (Scheme 2) The resulting phenols are alkylated to generate 2,3,4,5-tetramethoxytoluene (6) and the two trimethoxytoluenes (14 and 15). The isolated yield is considerably lower than the observed conversion by

NMR, and removal of the two reaction sideproducts is necessary because both lead to E3330 derivatives missing crucial methoxy substituents.



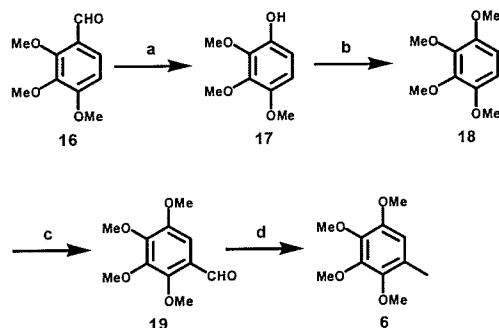
Scheme 2: Observed reduction products during the Ullmann reaction of 4-methyl-2,3,6-tribromophenol.

The Ullmann reaction can be quenched and worked up after the copper-mediated methanolysis of the aryl bromide to yield phenol 11, or subsequent *in situ* alkylation with methyl sulfate results in tetramethoxytoluene 6. The first option results in a decreased yield most likely resultant of the problematic workup with the Cu salts. The latter results in sideproduct 15 that is difficult to separate, and 14 with which separation is impossible. The first route provides a 50 – 60% yield of 6 following tedious chromatography. The second route results in 85% conversion by NMR and a mixture contaminated with 10% of 14.^{13,14}

Formylation of 2,3,4,5-tetramethoxytoluene (6) to generate aldehyde 7 has been reported and proceeds in high yield.¹⁵ The subsequent Emmons reactions with various alkylated phosphonoacetate reagents result in exclusive E-olefin formation at room temperature with 6-methyl-2,3,4,5-tetramethoxybenzaldehyde (8a-f; R = H, CH₃, C₂H₅, C₃H₇, C₄H₉, and C₉H₁₉). The hydrogen derivative (10a) represents complete removal of the sidechain, and the methyl derivative (10b) provides the shortest sidechain possible.

Hydrolysis of the ester is readily performed with KOH in EtOH and results in quantitative yield of the corresponding acid. Ring oxidation is the final transformation to quinone (10a-e, R = H, CH₃, C₂H₅, C₃H₇, C₄H₉; and 1, R = C₉H₁₉), where reported yields are below 50%.^{13,16} Ceric ammonium nitrate (CAN) oxidation results in comparable yield to the published nitric acid oxidation reaction; however, the resulting product from the nitric acid oxidation is much purer.^{13,16} Recrystallization is readily possible with the crude nitric acid oxidation product, whereas the CAN product typically needs chromatographic purification prior to recrystallization.

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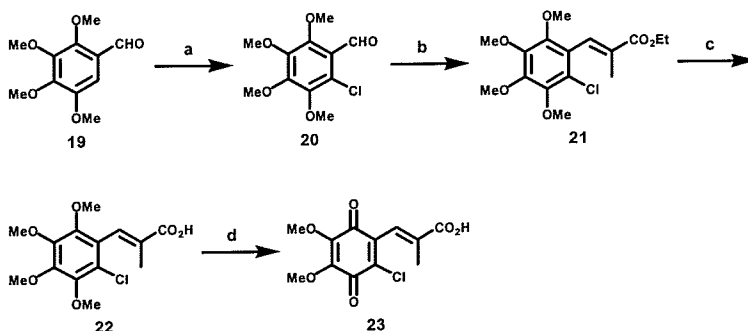


a) H_2O_2 , H_2SO_4 , MeOH, reflux 3 h, 98%; b) K_2CO_3 , MeI, acetone, reflux 2 d, 82%; c) NMFA, POCl_3 , CH_2Cl_2 , rt 2 d, 94%; d) KOH, N_2H_4 , $(\text{CH}_2\text{OH})_2$, reflux 8 h, 85%

Scheme 3: Alternative synthesis of 6 enabling ring-modified derivatives.

An alternative method for generating tetramethoxytoluene 6 in a cleaner and slightly longer route is shown above in Scheme 3. In order to circumvent the problems associated with the Ullmann reaction a new method for incorporating the four methoxy substituents was devised that utilizes the cleavage of trimethoxybenzaldehyde to the corresponding phenol and then O-alkylation to tetramethoxybenzene. At this stage formylation followed by Wolffe-Kishner reduction provides toluene 6 in higher yield than direct alkylation of benzene 18. Another notable aspect of this synthesis is that it leads to a 2-unsubstituted benzaldehyde (19) ready for incorporation of 2-position substituents that is not accessible in the literature synthesis.

Bayer-Villiger oxidation of trimethoxybenzaldehyde (16) followed by *in situ* hydrolysis of the formate provides quantitative formation of trimethoxyphenol (17). Phenol 17 can then be alkylated in 85% yield to generate 1,2,3,4-tetramethoxybenzene (18).^{17,18} The first transformation is sufficiently clean to avoid further purification of 17, and tetramethoxybenzene is readily recrystallized.¹⁷ Formylation of tetramethoxybenzene proceeds in quantitative yield, and a Wolffe-Kishner reduction is then performed on the resulting benzaldehyde 19 to generate tetramethoxytoluene in greater than 90% yield.¹⁹⁻²¹ This is another clean transformation not requiring further purification. The remaining transformations beginning with compound 6 are already described in the original E3330 synthesis and do not need further elaboration. (Scheme 1) This modified synthesis of 6 implements more facile steps to generate E3330 and takes the literature procedure of 7 steps with an overall yield of 15% to an 8 step synthesis with an overall yield of 24%.

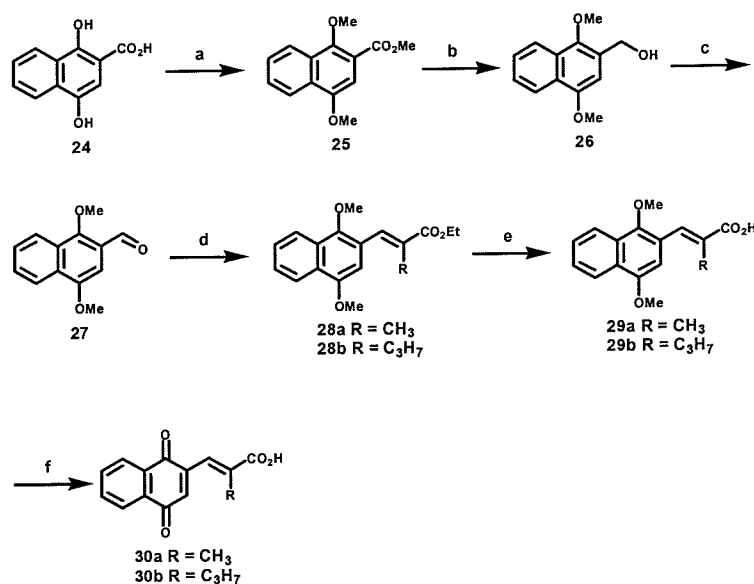
2-Chloro E3330

a) SO_2Cl_2 , CH_2Cl_2 , rt 15 min, 97%; b) NaH , $(\text{EtO})_2\text{P}(\text{O})\text{CHCH}_3\text{CO}_2\text{Et}$, toluene, reflux 8 h, 49%; c) KOH , EtOH , reflux 30 min, 95%; d) CAN , $\text{H}_2\text{O}:\text{CH}_3\text{CN}$ 1:1, rt 3 h, 22%

Scheme 4: Ring modified derivatives synthesized from precursor 19.

5

The modified synthesis of E3330 also enables ring substitution not possible with the literature method. A chlorine substituent at the 2-position of E3330 would affect the electronics of the ring while maintaining an isosteric substitution to the ring methyl. To generate the 2-chloro derivative of E3330 (23), aldehyde 19 was chlorinated using SO_2Cl_2 at room temperature, which proceeds in excellent yield. Unlike the 3-methyl derivatives, the 3-chloro derivative 20 suffered from reduced E selectivity during the Emmons reaction, where up to 15% of the Z product is observed at room temperature. E and Z isomers were easily distinguished by the chemical shift of the vinyl proton. The E isomer vinyl proton appears downfield of the Z isomer by as much as 0.5 ppm in some derivatives. Emmons condensation of 20 in refluxing toluene provides 100% E product, which can then be saponified in KOH/EtOH . (scheme 4) The final oxidation to 23 was initially attempted with nitric acid and no starting material or product was recovered. This suggested the nitric acid conditions were too harsh for either the tetramethoxybenzene or the quinone product. CAN was then evaluated and found to be a sufficiently mild oxidant to perform the transformation without destroying the product or starting material. Thus 23 was finally synthesized from 22 in 40% yield via oxidation with CAN.

3-Unsubstituted Naphthoquinones

a) K₂CO₃, MeI, acetone, reflux 12 h, 96%; b) LiAlH₄, THF, rt 8 h, 97%; c) PCC, CH₂Cl₂, rt 8 h, 85%; d) NaH, (EtO)₂P(O)CHRCO₂Et, toluene, reflux 8 h, 59 - 73%; e) KOH, EtOH, reflux 30 min, 83 - 99%; f) HNO₃, AcOH, EtOAc, rt 4 h, 37 - 58%

Scheme 5: Literature based synthesis of alcohol 26 and subsequent transformations to supply 3-unsubstituted naphthoquinones 30a,b.

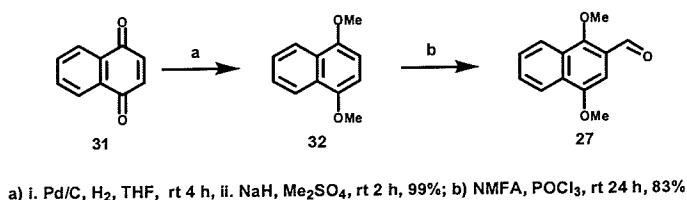
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Efforts were then directed toward synthesis of naphthoquinone derivatives. The simplest series included no substituent at the 3-position; without a sterically hindering substituent these compounds would help to expose the potential for Michael addition reactions on the quinone.

10

Initially, the synthesis of aldehyde 27 was performed using a route that had been previously used in the Borch group to generate alcohol 26.²² (Scheme 5) This route was also used to generate 3-methyl derivatives where alcohol 26 was alkylated using nBuLi/MeI; unfortunately, this alkylation resulted in 70 – 80 % yields where the starting material and product were difficult to separate. This led to the investigation of other means to generate 1,4-dimethoxy-2-naphthylaldehyde (27) and 1,4-dimethoxy-3-methyl-2-naphthylaldehyde (34). The reductive alkylation of 1,4-naphthoquinone leads to 1,4-dimethoxynaphthalene 32 in quantitative yield.²³ (Scheme 6) Formylation of 32 using TiCl₄/CHCl₂OCH₃ provides aldehyde 27.²⁴

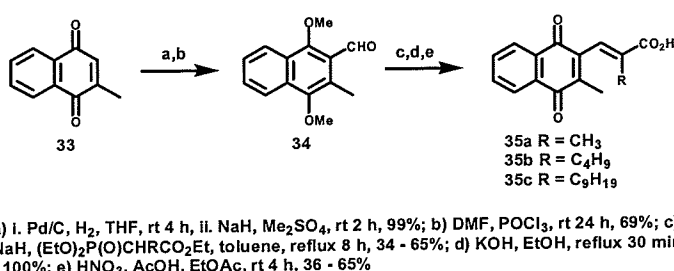
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Scheme 6: Synthesis of aldehyde 27.

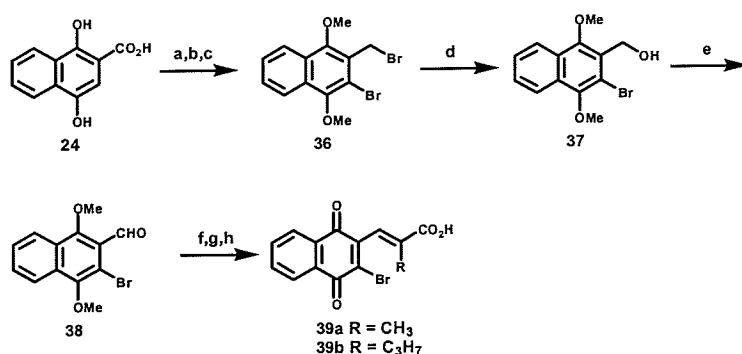
Aldehyde 27 was then utilized in the Emmons reaction with either ethyl 2-phosphonopropionate or ethyl 2-phosphonopentanoate to generate esters 28a and 28b, respectively. The Emmons condensation with aldehyde 27 preceded at room temperature to produce nearly 100% E product. Saponification and oxidation of the resulting derivatives proceeded without incident. (Scheme 5) The final oxidation of the 3-unsubstituted naphthalenes resulted in 70% yield.

3-Methyl Naphthoquinones



Scheme 7: Efficient synthesis of 3-Methyl naphthoquinone derivatives.

The 3-methyl derivatives were then prepared. Synthesis of the 3-methyl series began with the reductive alkylation of naphthoquinone 33 followed by formylation to generate aldehyde 34.^{23,24} (Scheme 7) The Emmons reaction with aldehyde 34 resulted in approximately 85% E product when carried out in THF at room temperature and essentially 100% E in refluxing toluene. Separation of E and Z isomers by chromatography was difficult; typically the Z isomer could not be isolated in pure form. Ester hydrolysis using KOH/EtOH proceeded rapidly at 80 °C, and the oxidation was performed with nitric acid in ethyl acetate.

3-Bromo Naphthoquinones

a) K₂CO₃, MeI, acetone, reflux 12 h, 96%; b) LiAlH₄, THF, rt 8 h, 97%; c) i. HBr, CH₂Cl₂; ii. Br₂, CH₂Cl₂, 56%; d) CaCO₃, H₂O:Glyme 1:1, reflux 12 h, 100%; e) PCC, CH₂Cl₂, rt 8 h, 88%; f) NaH, (EtO)₂P(O)CHRCO₂Et, toluene, reflux 8 h, 41 - 47%; g) KOH, EtOH, reflux 30 min, 47 - 100%; h) Ag(II)O, HNO₃, AcOH, EtOAc, rt 30 min, 46%

Scheme 8: Initial synthetic strategy for incorporating the 3-bromo substitution in naphthoquinone derivatives.

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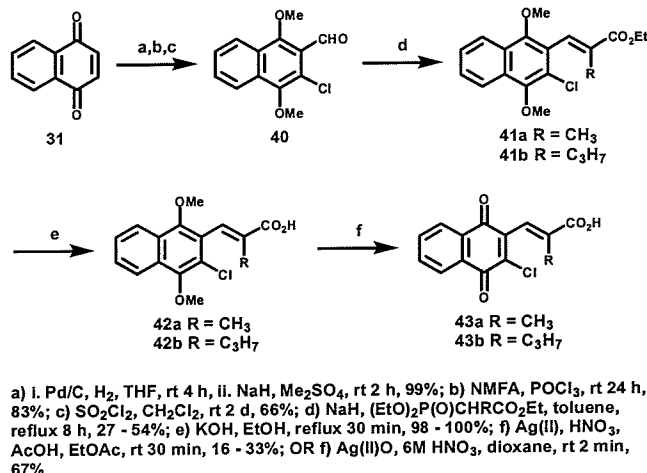
Substituents at the 3-position were prepared. Bromine and chlorine substitution were the first derivatives explored, and later fluorine with the greatest electronegativity was prepared.

The 3-bromo derivatives were initially prepared by a lengthy synthesis. (Scheme 8) Problems were encountered with the bromination of aldehyde 27 using bromine, where oxidation to the carboxylic acid was observed as a side reaction. In order to avoid this problem, bromination of alcohol 26 (Scheme 5) was attempted, and it was discovered that regardless of conditions, *in situ* generated HBr displaced the alcohol to generate dibromide 36. (Scheme 8) The 3-bromo alcohol 37 could be easily regenerated from 36 in quantitative yield using CaCO₃/glyme.²⁵ Oxidation of the alcohol provided aldehyde 38 in reasonable yield. Subsequently it was determined that the best route was to brominate 1,4-dimethoxy-2-naphthaldehyde (27), accepting the loss of product due to oxidation.

As an Emmons substrate the 3-bromo aldehyde 38 produced a significant amount of Z-olefin product; even in boiling toluene 15% Z isomer was observed. This led to low yields of purified E product due to typical difficulties separating the E and Z isomers. After hydrolysis, oxidation to the quinone was first attempted using HNO₃/EtOAc/AcOH, but only starting material was recovered. By adding Ag(II)O to the nitric acid conditions complete conversion to the quinone was

observed by TLC and NMR.^{16,22} (Scheme 8) The resulting quinones were obtained in 70% yield.

3-Chloro Naphthoquinones



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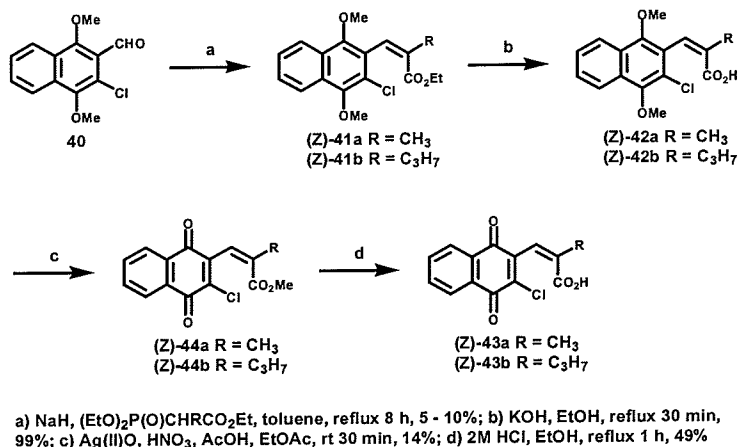
Scheme 9: Synthesis of 3-chloro naphthoquinones from common precursor 27.

Synthesis of the 3-chloronaphthoquinone series was undertaken starting with aldehyde 27. SO₂Cl₂ proved to be a much milder reagent than the brominating reagents, thus no problems were encountered converting 27 to chloroaldehyde 40. (Scheme 9) As an alternative approach, attempts were made to formylate 2-chloro- and 2-bromo-1,4-dimethoxynaphthalene. However, it seems the electron withdrawing nature of the halogens was too great to allow formylation of these substrates.

Aldehyde 40 was used as the substrate for the Emmons reaction, generating esters 41a,b in 75% yield. The Emmons reaction with aldehyde 40 resulted in low E-selectivity, approximately 15% Z isomer was produced in boiling toluene. (Scheme 9) Hydrolysis and final ring oxidation utilized the same conditions as the 3-bromo derivatives and proceeded well to give quinones 43a,b.

The possibility of separating E and Z isomers after final oxidation was to be explored, so a mixture of E and Z Emmons products (*E*-41a and *Z*-41a) was saponified and oxidized under typical conditions. ((Scheme 9, Scheme 10)

-17-



Scheme 10: Unexpected transformation of Z-isomer Emmons products upon oxidation of hydrolyzed Z-42b.

5 The resulting mixture of E and Z products was chromatographed, and two products were readily separated and analyzed by MS and NMR. The slow eluting band was identified as pure E isomer 43a. The less polar compound appeared to be the Z isomer although an additional 3-proton peak at 3.06 ppm was observed. NMR and MS analysis ultimately confirmed that the product was the methyl ester Z-44a.

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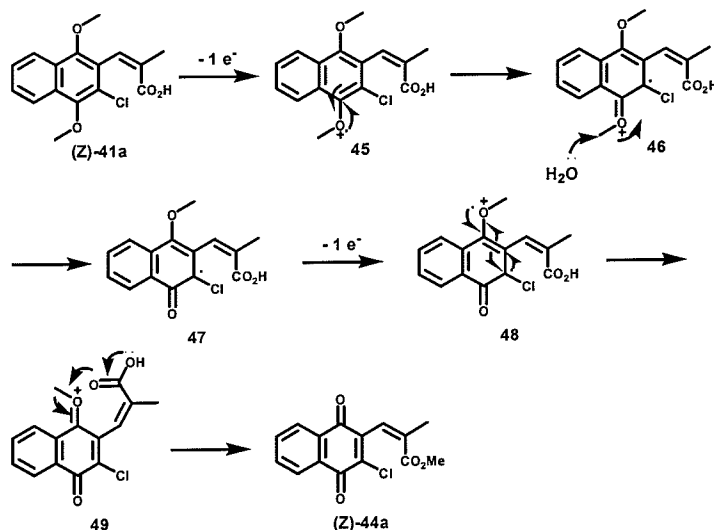


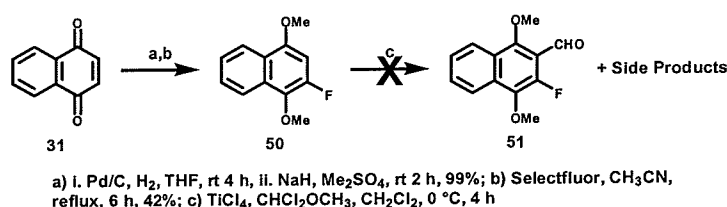
Figure 7: Proposed mechanism for intramolecular esterification during nitric acid oxidation of (Z)-44a.

15

After examining the potential rotamers of the Z isomer it became apparent that during oxidation, the carboxylic acid of the Z isomer would be able to

attack the methyl group of the oxonium intermediate 49, performing an intramolecular esterification. (Figure 7) This was further verified by hydrolysis of the ester (Z-44a) in HCl/EtOH; KOH/EtOH was attempted but destroyed the starting material. Therefore it was postulated that separation of E and Z ester isomers is not necessary after the Emmons reaction, because the Z methyl ester and E carboxylic acid are readily separable after final oxidation. The only series that did not appear to undergo this intramolecular esterification was the 3-unsubstituted derivatives, suggesting substitution at the 3 position favors the rotamer that can undergo cyclization.

10

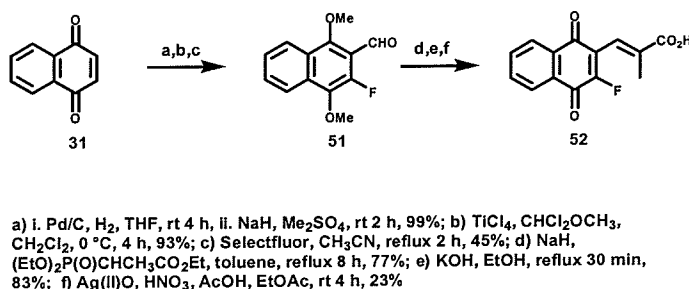
3-Fluoro Naphthoquinones

Scheme 11: Initial synthetic strategy for preparing 3-fluoro naphthylaldehyde 51.

15

Aromatic fluorinations can be difficult transformations to execute; fortunately, advances in fluoride cation chemistry have enabled the synthesis of compounds that were previously inaccessible. Based on reactivity, the approach outlined in Scheme 11 was considered to generate aldehyde 51, because the aromatic ring of 1,4-dimethoxynaphthalene (Compound 32, Scheme 6) would be more electron rich than that of aldehyde 27. Fluorination of both 1,4-dimethoxynaphthalene to prepare 50, and 1,4-dimethoxy-2-naphthaldehyde to produce 51 proceeded well in refluxing acetonitrile, although the reaction with aldehyde 27 produced side products that resulted in lower yields. Formylation of 50 was then attempted using TiCl₄ and CHCl₂OCH₃ in CH₂Cl₂, and surprisingly the starting material was completely consumed within 4 hours. It was expected that with the electron withdrawing fluorine adjacent to the formylation site this transformation would be difficult; however, TLC of the reaction mixture showed one component that had the same R_f as previously synthesized aldehyde 51. Upon examination of the reaction product by NMR it was determined that the formylated compound was not simply aldehyde 51, but a mixture of four regioisomers. ¹⁹F NMR gave the most compelling analysis of the reaction

mixture, for there were three sets of doublets corresponding to fluorine atoms adjacent to an aromatic proton, and one singlet corresponding to the 3-fluoro product 51 obtained through fluorination of unsubstituted aldehyde 27. The doublets possessed the same coupling constants observed in 1,4-dimethoxy-2-fluoronaphthalene, and it was obvious that the strategy outlined in Scheme 11 was not going to work.



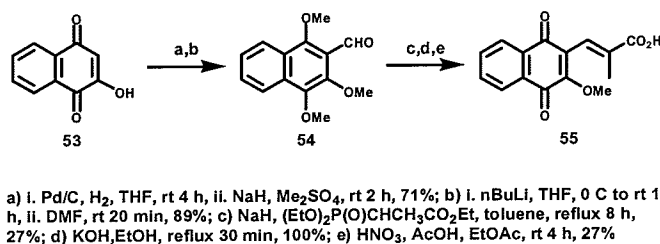
Scheme 12: Revised synthesis of 3-fluoro aldehyde 51 and subsequent transformation to generate 3-fluoro naphthoquinone 52.

10

Fortunately, aldehyde 51 had previously been synthesized via fluorination of aldehyde 27, so the Emmons reaction was then carried out using 51. (Scheme 12) Aldehyde 51 possessed similar E:Z selectivity to the other 3-halo aldehydes, where the crude reaction mixture was approximately 5:1 E:Z. Small amounts of pure Emmons isomers were collected for spectral analysis. The majority of the product was collected as a mixture of the two isomers, and the mixture was used in the subsequent saponification and oxidation. As expected the Z isomer was completely converted to the methyl ester during the final oxidation reaction, allowing rapid separation from the E acid final product. The Z methyl ester was then hydrolyzed with 2 M HCl in THF to generate the Z product.

20

3-Methoxy Naphthoquinones

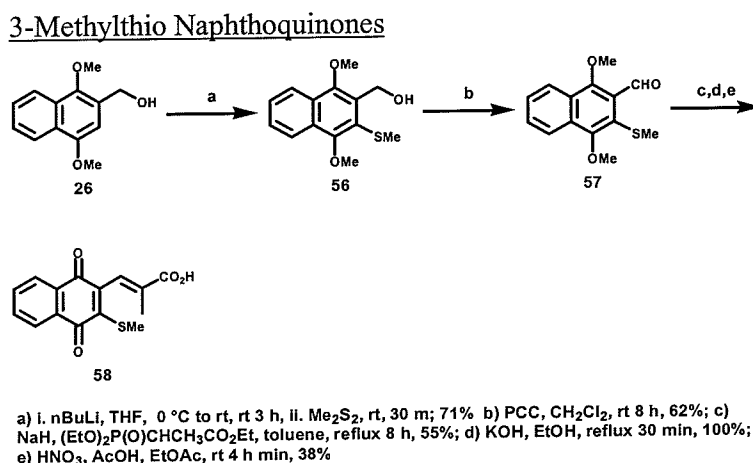


Scheme 13: Synthetic strategy for preparing 3-methoxynaphthoquinone 55.

25

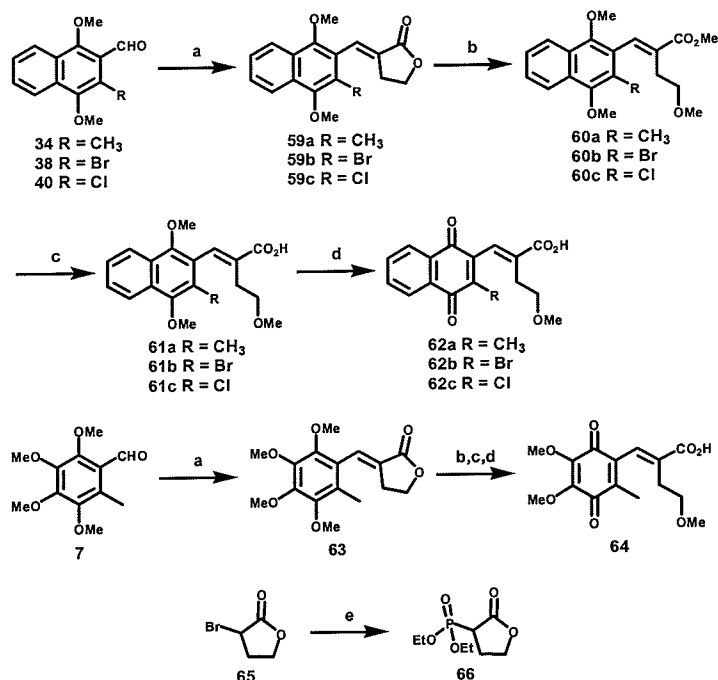
Electronegative atoms have already been substituted at the 3-position of the naphthoquinone derivatives; however, all of the substituents were halogens that are relatively isosteric to the methyl group. Methoxy and methylthio substituents were later explored that would retain an electronegative character but possess greater steric bulk

The synthesis of 3-methoxy substituted naphthoquinone derivative 55 is outlined in Scheme 3. The Emmons reaction with aldehyde 54 as a substrate resulted in the lowest E selectivity of any substrate encountered; nearly 50% Z is observed in boiling toluene. Separation of the resulting E and Z esters proved difficult and only small quantities of purified E isomer were collected. The final saponification and oxidation were carried out without problems.



Scheme 14: Literature based synthesis of methylthio alcohol 56 and subsequent transformations to produce methylthio naphthoquinone 58.

To generate the 3-methylthio naphthoquinone derivatives, alcohol 26 was deprotonated using nBuLi and allowed to react with methyldisulfide.²² (Scheme 14) A reproducible 80% yield was observed in the formation of 56. The Emmons reaction proceeded with low E selectivity; approximately 30% Z isomer was observed by NMR. Interestingly, of all the naphthoquinones synthesized, the 3-unsubstituted derivatives had the highest E selectivity when the Emmons reaction was run at room temperature. This is most likely due to the steric influence the unsaturated acid moiety experiences from the bulkier 3-position substituents. The purified E isomer was saponified and oxidized to generate 58 as a red solid.

Ether side chain quinones

a) NaH, 66, toluene, reflux 8 h, 42 - 100%; b) H₂SO₄, CH(OCH₃)₃, MeOH, reflux 12 h, 58 - 100% c) KOH, EtOH, reflux 30 min, 77 - 100%; d) Ag(II)O, HNO₃, AcOH, rt 4 h, 19 - 70%; e) POEt₃, reflux, 5 h, 72%

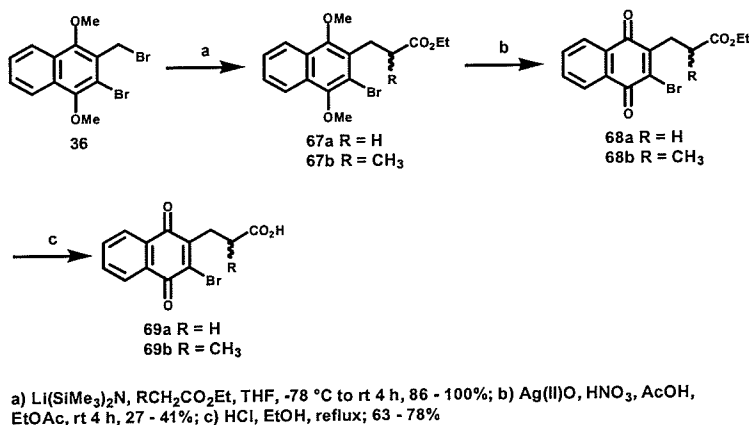
Scheme 15: Synthetic strategy for incorporating an ether sidechain into the benzoquinone and naphthoquinone series.

A degree of diversity in the sidechain was employed by installing a methoxyethyl sidechain in a number of derivatives. Synthesis of butyrolactone phosphonate 66 by Arbusov's method followed by an Emmons reaction resulted in lactones 59a-c and 63 in reasonable yield.²⁶ (Scheme 15) The benzaldehyde derivative 63 showed the highest E selectivity; the 3-methyl, 3-bromo, and 3-chloro naphthaldehyde derivatives resulted in 15 – 30% Z isomer. Isomer separation was as difficult with the lactone Emmons products as with the aliphatic derivatives. Following purification the lactones were converted to ether/esters 60a-c using trimethyl orthoformate in boiling methanol with catalytic H₂SO₄.²⁷ Saponification and oxidation gave the final products 62a-c and 64 in reasonable yield. The 3-chloro (62c) and 3-bromo (62b) derivatives required Ag(II)O during the nitric acid oxidation to the quinone, whereas the methyl derivatives (62a and 64) were converted with nitric acid.

3-Bromo Saturated naphthoquinones. The double bond of E3330 was conserved throughout all compounds prepared so far, where the E stereochemistry was anticipated to be important for binding. Derivatives synthesized to test the significance of the double bond include the Z isomer of potent inhibitor 43a, a completely saturated derivative of 39a, and an epoxidized derivative of 43a that would maintain a degree of 3-dimensional orientation while removing the double bond character.

All attempts to reduce the double bond of ester 41a using H_2/Pd , $NaBH_4/MeOH/CuCl$, and N_2H_4/H_2O_2 were unsuccessful. An alternative route is outlined in Scheme 16 that utilizes the enolate of ethyl propionate to attack the halomethyl-carbon of a 3-halo-2-halomethyl-1,4-dimethoxynaphthalene. This would generate two enantiomers at the alpha position, which could then be hydrolyzed and oxidized. Initially the two enantiomers would be tested as a racemic mixture; if they showed promise they could later be resolved.

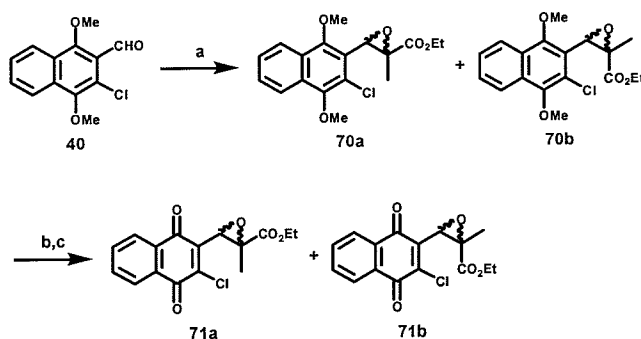
Reaction of 36 with the lithium enolate of ethyl propionate proceeded rapidly to completion. (Scheme 16) With the flexibility of the saturated side chain it was expected that both enantiomers would experience intramolecular esterification during the ring-oxidation reaction. To prevent this potential re-esterification the ethyl ester hydrolysis was performed following ring oxidation. Oxidation of the racemate proceeded smoothly with nitric acid and $Ag(II)O$ at room temperature. After purification the racemic mixture was hydrolyzed using 2 M HCl in refluxing THF to generate 69b as a mixture of two isomers. Using the same procedure, the lithium enolate of ethyl acetate was used to generate 69a, the derivative lacking substitution alpha to the carboxylic acid.



Scheme 16: Syntheses of saturated 3-bromo naphthoquinones 69a and

b.

- 5 3-Chloro Epoxide naphthoquinones. Initially, the most promising route to forming epoxides 70a,b appeared to be performing a Prelezhof reaction on ester 41a. Unfortunately, *t*-BuOOH, mCPBA, and H_2O_2 all failed to generate the epoxide. An alternative strategy was to condense the 3-chloroaldehyde 40 with the lithium enolate of ethyl 2-bromopropionate in a Darzens reaction to generate the
- 10 epoxide.²⁸ (Compounds 71a and b, Scheme 17) Although this was an established route of epoxide formation, the Darzens reaction had the potential for generating four diastereomers, where as the direct epoxidation of 41a would only produce two enantiomers.



- 15 a) $\text{Li}(\text{SiMe}_3)_2\text{N}$, $\text{CH}_3\text{CHBrCO}_2\text{Et}$, THF, -78°C to rt 4 h, 97%; b) KOH , EtOH , reflux, 1 h, 100%; c) $\text{Ag}(\text{II})\text{O}$, HNO_3 , AcOH , EtOAc , rt 3 h, 20%

Scheme 17: Darzens condensation to generate epoxide derivatives of

41a results in four diastereomers.

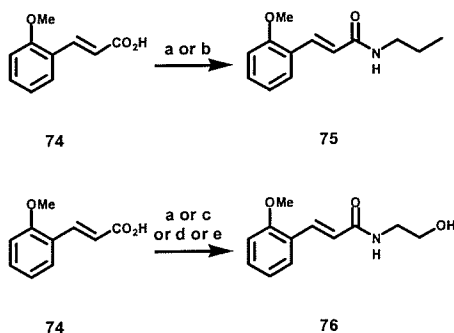
The Darzens reaction was carried out on 40, and the diastereomeric mixture was hydrolyzed and oxidized. Efforts would then be directed to separating the individual isomers.

5 Amide and Biotin Derivatives. Derivatives with high redox inhibitory activities were selected for derivatization of the carboxylate to generate the corresponding amides. Amides were desired to enable modification of the parent compounds without affecting the naphthalene core which is expected to be of great significance to binding. Derivatives with an amide functional group would provide a
10 site for increasing hydrophilicity or tethering to other organic molecules. Derivatives tethered to biotin through an amide linkage would act as molecular tools in various experiments including affinity chromatography and surface plasmon resonance (SPR). The former experiment would enable the isolation of proteins that interact with the derivative, while the latter would provide dissociation constant (K_D) data for specific
15 proteins. Simple hydroxyethylamides were first synthesized to determine the effects of modifying the carboxylate group.

Model Chemistry. Derivatives bearing an amide function needed to be tested for activity prior to developing complex biotin-conjugated species.
20 Hydroxyethylamide derivatives of 1 and 43a were to be synthesized to ensure that derivatization of the carboxylic acid did not negatively affect redox inhibition. (72 and 73, respectively; Figure 8) In addition to synthesizing model amides, model chemistry was also required to optimize the transformation of precious intermediates to biotinylated compounds.

25 The most direct approach to amides 72 and 73 begins with amidation of the corresponding dimethoxyarenes followed by oxidation to the quinone. The first step was optimized using trans o-methoxycinnamic acid and ethanolamine. Scheme 18) *N,N'*-Dicyclohexylcarbodiimide (DCC) was determined to give higher yields than 1-[3-(Dimethylamino)propyl]-3-ethylcarbodiimide (EDC/EDCI), where complete
30 conversion was observed with the former and roughly 50% conversion with the latter. Finally the stoichiometry of the reagents was examined; two equivalents of DCC with 1 equivalent of amine provided complete conversion to the corresponding amide.

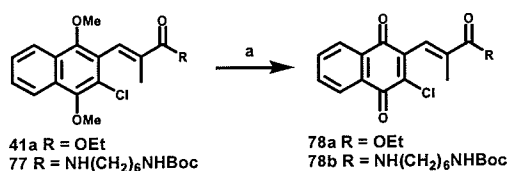
-25-



- a) Acid, HOBT 0.1 eq, EDCI 1 eq, DMF:CH₂Cl₂ 1:2, rt 40 min, then amine 1.5 eq rt, stir 18 h rt.
 b) Acid, HOBT 0.1 eq, DCC 1 eq, DMF:CH₂Cl₂ 1:2, rt 40 min, then amine 1.5 eq rt, stir 18 h rt.
 c) Acid, HOBT 0.1 eq, DCC 2 eq, DMF:CH₂Cl₂ 1:1, stir rt 80 min, then amine 1 eq, stir 18 h rt.
 d) Acid, HOBT 0.1 eq, DCC 1 eq, DMF:CH₂Cl₂ 1:1, stir rt 80 min, then amine 2 eq, stir 18 h rt.
 e) Acid, HOBT 0.1 eq, DCC 2 eq, DMF:CH₂Cl₂ 1:1, stir rt 80 min, then amine 2 eq, stir 18 h rt.

Scheme 18: Model chemistry for optimal Steglich conditions

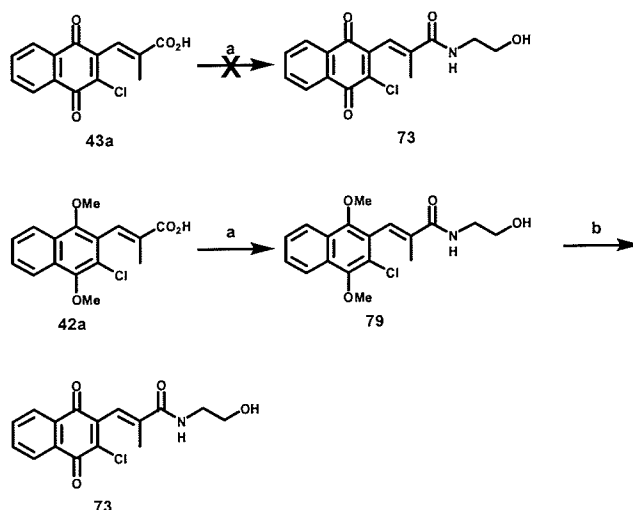
The second transformation modeled was the ring oxidation of
 5 dimethoxynaphthalenes 41a and 77 using ceric ammonium nitrate (CAN) in
 acetonitrile/water. (Scheme 19) CAN-mediated oxidations result in reaction mixtures
 requiring more extensive purification than when using nitric acid. Unfortunately, the
 sulfide moiety in biotin is not stable to nitric acid and would likely oxidize to the
 sulfoxide or sulfone. Only one reference has shown oxidation of a biotinylated
 10 substrate using CAN at 0 °C for 20 minutes without oxidation of biotin.²⁹ However,
 the reported HPLC data suggests oxidation to the sulfone and sulfoxides took place.
 Thus the oxidation reaction of dimethoxyarenes needed to be studied to determine the
 minimum equivalents of CAN and time required to perform the oxidation. Both
 substrates 41a and 77 were converted to the corresponding naphthoquinones using 6
 15 equivalents of CAN at 0 °C in less than 20 minutes.



a) CAN 6 eq, MeCN:H₂O 1:1, 0 °C, 20 min

Scheme 19: Model oxidation chemistry using CAN.

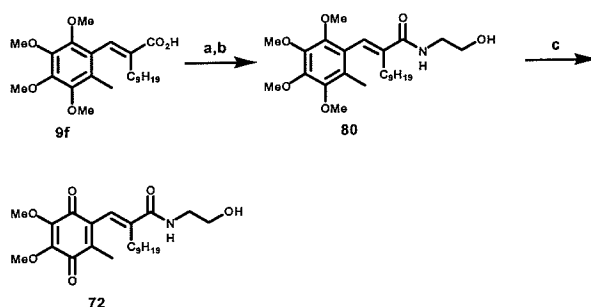
-26-



a) i. HOBT 0.1 eq, DCC 2.0 eq, DMF:CH₂Cl₂ 1:1, rt 1.5 h ii. Ethanolamine 1.5 eq., rt 12 h, 83% b) Ag(II)O, HNO₃, AcOH, EtOAc, rt 30 min, 60%

Scheme 20: Synthesis of amide 73.

With the model chemistry completed the synthesis of amides 72 and 73 could begin. Quinone 43a was initially used as a substrate for amidation to prepare quinone 73; however, no conditions were found to efficiently perform the transformation. (Scheme 20) The alternative strategy was to perform the oxidation after coupling dimethoxynaphthalene 42a to ethanolamine. Carboxylic acid 42a was completely consumed under optimized Steglich conditions, and the resulting product was oxidized with nitric acid. The simple amides lacked the biotin group that necessitated the use of a mild oxidant, enabling the use of nitric acid to readily perform the oxidations. Quinone 72 was synthesized in the same manner as 73. (Scheme 21)

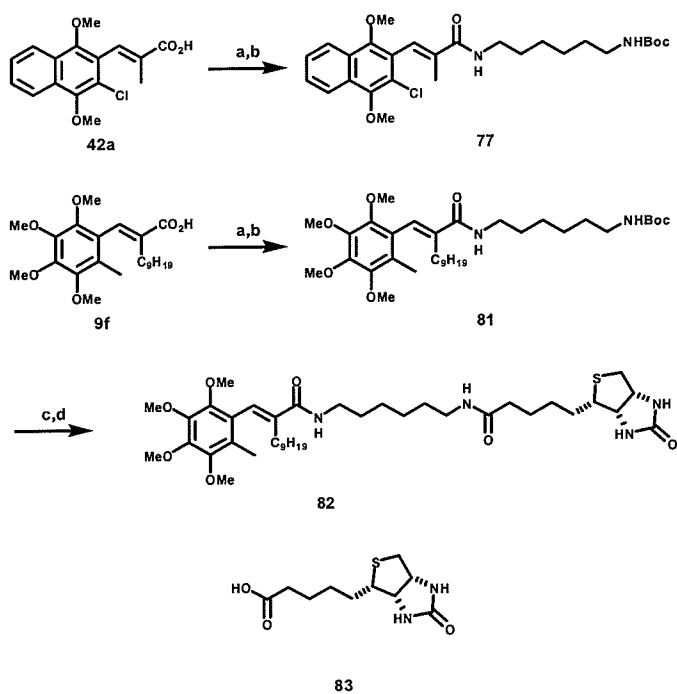


a) HOBT 0.1 eq, DCC 2.0 eq, DMF:CH₂Cl₂ 1:1, rt 1.5 h; b) Ethanolamine 1.5 eq., rt 12 h, 81%; c) Ag(II)O, HNO₃, AcOH, EtOAc, rt 30 min, 45%

Scheme 21: Synthesis of model amide 72.

Amido-quinones 72 and 73 were comparable in activity to the original carboxylic acids, and therefore the amide was determined to be a practical method for conjugating the molecules to biotin, or for imparting further modifications to improve the water solubility and target selectivity of the drugs.

Biotinylated derivative amidation reactions. Two strategies were available for conjugating dimethoxyarenes 42a and 9f to biotin through an aliphatic linker. The first strategy was to couple the dimethoxyarene acids to *N*-Boc-1,6-diaminohexane and then couple the deprotected linker to biotin. (Scheme 22) The second strategy was to generate biotinylating reagent 85 and couple this directly to the dimethoxyarene unsaturated carboxylic acids. (Scheme 23) The second strategy proved the shortest and biotinylating reagent 85 was readily synthesized.

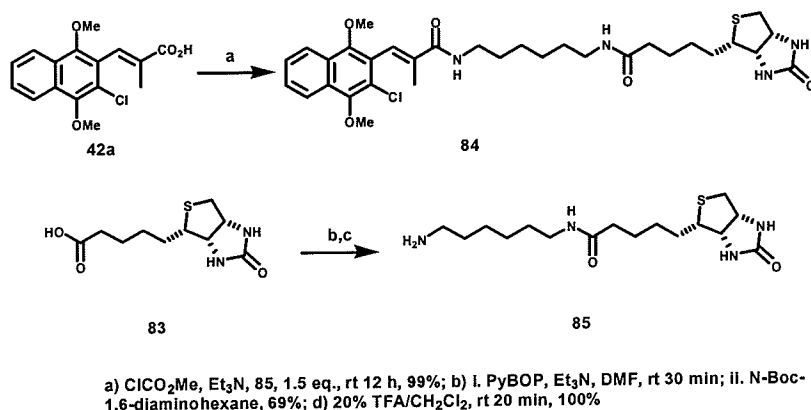


a) HOBt 0.1 eq, DCC 2.0 eq, DMF:CH₂Cl₂ 1:1, rt 1.5 h; b) *N*-Boc-1,6-diaminohexane 1.5 eq., rt 12 h, 78 - 100%; c) 20% TFA/CH₂Cl₂, rt 20 m, 100%; d) HOBt 0.1 eq, DCC 2.0 eq, DMF, rt 1 h; 82, Et₃N, rt 12 h, 90%

Scheme 22: Amidation route utilizing iterative coupling strategy.

Even though the second route was ultimately utilized in the synthesis of the biotinylated reagents, the first route provided insight into unexpected problems

with the DCC coupling reaction. Optimized Steglich conditions were applied to both dimethoxyarenes 9f and 42a with *N*-Boc-1,6-diaminohexane as the amine component. The reaction began with pure E 1,4-dimethoxyarene reagents; however, purification resulted in two components in a ratio of approximately 1:1. The two compounds were identified as E and Z isomers of the coupled products through HMQC and nOe NMR experiments. DCC conditions were resulting in isomerization of the E double bond and had to be replaced to retain isomeric purity. The substrate used for model chemistry lacked a substituent on the double bond alpha to the carbonyl; thus it is likely the cis and trans isomers were sufficiently different in energy to prevent isomerization. Acid 42a was later converted to the corresponding amide using either methyl chloroformate, oxalyl chloride, or PyBOP without double bond isomerization. (Scheme 23)

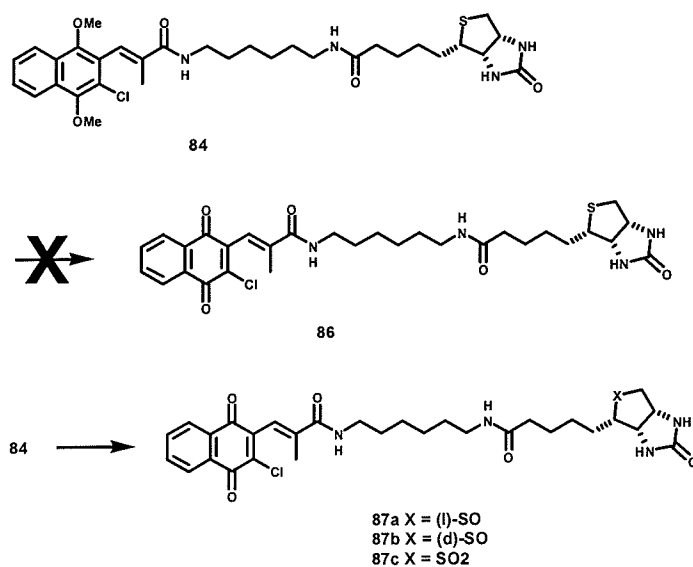


Scheme 23: Synthetic pathway to amides using biotinylating reagent 85.

Biotinylated dimethoxyarene oxidation. Avidin attached to the surface of SPR chips provides a pseudocovalent interaction with biotin enabling the chip to be coated with drug molecules. The sulfide of biotin is highly reactive toward oxidizing reagents, which can oxidize the sulfide to the corresponding sulfoxides (*R* and *S*) or further to the sulfone. Biotinylated 84 was initially oxidized using the minimum conditions previously determined for derivativeous amide 77; however, the reaction required an hour at room temperature to see complete disappearance of methoxy groups in the ^1H NMR spectrum. (Scheme 24) The methylene protons and methide carbon adjacent to the sulfur of biotin were expected to be the most diagnostic of

sulfide oxidation. Unfortunately, both regions were obscured by resonances from the aminohexane linker.

An alternative strategy was to monitor the CAN oxidation using HPLC. The ratio of UV absorbance at 300 and 245 nm was determined for compounds containing either a dimethoxynaphthalene or naphthoquinone moiety, where the ratio was approximately 0.16 for the former and 0.25 for the latter. A CAN-mediated oxidation of 84 was then monitored by HPLC, where the reaction was stirred at 0 °C and with 18 equivalents of CAN. The first HPLC trace was taken after 5 minutes reaction, and no starting material was present. Interestingly, NMR spectra taken after 30 minutes showed substantial methoxy peaks. This indicates that the sulfide oxidation is taking place rapidly at 0 °C, because a new dimethoxynaphthalene species began to appear in less than 5 min.



Conditions: CAN, MeCN:H₂O 1:1, 1 h

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Scheme 24: Oxidation of 92 using CAN.

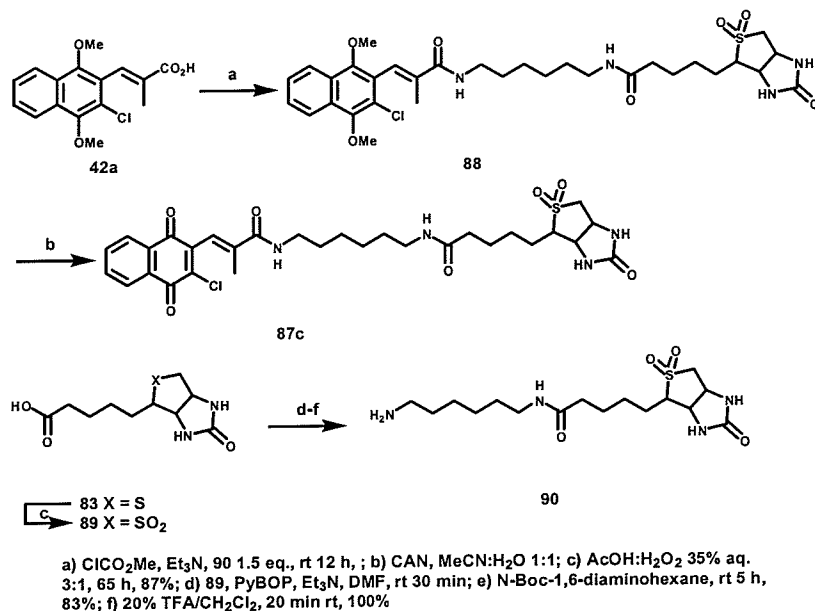
Fortunately, both sulfoxides (*R* and *S*) and the sulfone of biotin bind avidin with 30 – 40% of the affinity of the parent sulfide.³⁰ With this information, coupled to the discovery that the dimethoxynaphthalene moiety could not be oxidized without oxidation of the sulfide of biotin, it was determined that the reaction should be allowed to proceed until only quinone-sulfone 87c was observed by HPLC. (Scheme 24) It was hypothesized that if no dimethoxynaphthalene is present in the

20

sample, a mixture of the four biotinylated quinones (86 and 87a-c) should all bind in a pseudocovalent manner to the avidin-coated chip. CAN transformed 84 to 87c; however, separation of the quinone from CAN was difficult.

Column purification of 87c was only possible with MeOH/CH₂Cl₂ conditions, and these conditions also eluted CAN. More than 15 equivalents of CAN were required to complete the transformation to 87c, thus removing CAN through chromatography or precipitation was not efficient. Reverse-phase HPLC purification was an alternative, but would be slow for milligram scale preparation.

10 Biotin sulfone derivatives. An alternative strategy was then devised that would generate only the biotinsulfone quinones. (Scheme 25) The sulfonobiotinylating reagent 90 was synthesized via oxidation of biotin followed by coupling to *N*-Boc-1,6-diaminohexane and deprotection of the terminal amine. Biotinsulfone and the corresponding Boc protected 6-aminohexylamide are insoluble
15 in most organic solvents, making subsequent transformations very difficult. The solubility profiles did lend to purification, where the oxidation of biotin precipitates the sulfone from the acetic acid solution, and the coupling reaction precipitates the product from the DMF solution. Both products are collected and washed to give pure product in excellent yield. Unfortunately, the insolubility of the biotinylating reagent
20 makes coupling to the dimethoxynaphthalene difficult. Desthiobiotin is another molecular tool available for conjugation where the biotin sulfide is removed. The cyclic urea of desthiobiotin only sacrifices a 20-fold loss in activity from the femptomolar binding affinity of biotin (10⁻¹⁵ M).



Scheme 25: Synthesis of sulfonobiotinylating reagent 90 and target quinone 87c.

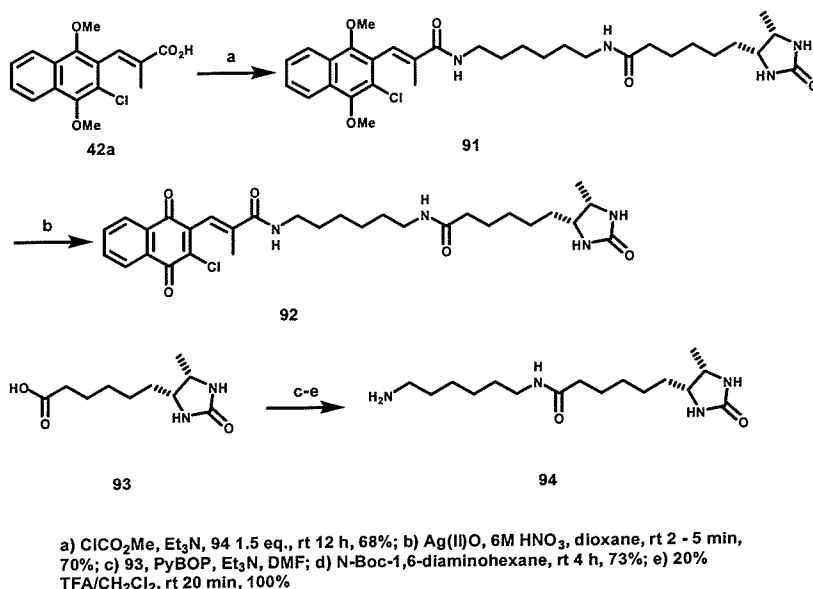
5 Desthiobiotin derivatives. Desthiobiotin (93) is an derivative of biotin that lacks the sulfide heterocycle. The biotin sulfoxides and sulfone bind avidin approximately 3-fold weaker than biotin; comparatively desthiobiotin binds avidin approximately 20-fold weaker than biotin.^{31,32} Biotin binds avidin with a dissociation constant in the femtomolar range (10^{-15} M); a loss of between one and two orders of magnitude by using desthiobiotin will still provide pseudocovalent adhesion of the

10 drug molecule to the SPR chip.

The synthesis of desthiobiotinylated 43a proceeded without problems following the previously devised chemistries. (Scheme 26) Desthiobiotin reagent 94 was synthesized using PyBOP coupling with *N*-Boc-1,6-diaminohexane in 65 - 70 %

15 yield following recrystallization. Dimethoxynaphthalene 42a was then coupled to 94 using PyBOP, and the product was then oxidized using 5 equivalents of CAN at room temperature. Desthiobiotin derivative 92 was synthesized in milligram quantities and purified by flash chromatography for characterization.

-32-



Scheme 26: Synthesis of desthiobiotinylated 43a.

Samples of purified 92 from oxidation reactions were used with HPLC to monitor the coupling of quinone 43a to generate 92 via a non-oxidative route. Both oxalyl chloride and PyBOP conditions resulted in the formation of the activated carboxyl; however, PyBOP conditions resulted in only traces of product and oxalyl chloride resulted in no product formation. Desthiobiotin 92 is inseparable from dimethoxynaphthalene precursor 91 by liquid chromatography, where only 1:19 to 1:9 MeOH: CH_2Cl_2 is capable of moving the compound on TLC. Furthermore, the CAN-mediated oxidation was not a clean reaction, and HPLC purification would be required. The HPLC trace of a crude CAN-mediated oxidation is shown in Figure 9A.

Authentic 92 had been synthesized and characterized through the CAN oxidation reaction, and all that remained was to optimize the synthesis to get the cleanest product directly from the final transformation. Nitric acid and $\text{Ag}(\text{II})\text{O}$ were applied to the oxidation of 91 following the method previously used to oxidize all 3-halo dimethoxynaphthalenes, and this transformation resulted in a substantially cleaner oxidation product than CAN. (Figure 9B) Although the silver (II) oxidation was cleaner than the CAN oxidation, the resulting reaction mixture still required HPLC purification. An alternative silver (II) oxidation procedure was then employed that used dilute nitric acid in 1,4-dioxane to generate a soluble silver nitrate salt.³³

This transformation was complete in less than 3 minutes at room temperature with 5 – 7 equivalents of Ag(II)O and resulted in an extremely clean product.

Figure 9: HPLC spectra of oxidation and coupling reactions to synthesize quinone 92. A. The crude reaction mixture of a 1 hour CAN-mediated oxidation using 6 equivalents of oxidant. B. Standard nitric acid/argentic oxide oxidation of dimethoxynaphthalene 91. C. New nitric acid/argentic oxide conditions utilizing soluble silver nitrate in dioxane for the oxidation of 91. D. UV spectra of product (92) faster eluting component from Ag(II)O oxidation in dioxane. E. Crude reaction mixture of PyBOP coupling quinone 43a to desthiobiotinylating reagent 94. F. Flash chromatography purification of PyBOP coupling reaction from Figure 9E. G. Sample from Figure 9F after storage in MeCN for 8 days at -20 °C. All samples were run at 40:60 acetonitrile:water on a C8 analytical column, spectra collected at 300 nm. The retention time for the product is 12.6 min and the peak is indicated by an arrow. Decomposition products are indicated by an asterisk.

All of the sideproducts observed in the CAN and original silver (II) oxidations were absent from the reaction in dioxane, although there were now two peaks with identical UV spectra and similar retention times. (Figure 9C) The only product observed in both ^1H and ^{13}C NMR of the crude reaction mixture corresponded to that of previously synthesized quinone 92. This led to the hypothesis that the new species observed at 11.6 minutes was likely a silver complex with either the olefin or the quinone bonds of 92. Washing the sample with dilute HCl and brine reduced the quantity of the 11.6 minute peak, consistent with the hypothesis that this is a complex between the product observed at 12.6 minutes and silver (I).

Concurrently, a coupling reaction between quinone 43a and amine 94 was being explored via HPLC. The methods were oxalyl chloride and PyBOP coupling, where the activation step of both reactions was confirmed by either gas evolution (oxalyl chloride) or ^{31}P NMR (PyBOP). HPLC analysis showed no product in the oxalyl chloride reaction and minimal product in the PyBOP coupling. (Figure 9D/E) The reacting quinone is easily separated from the desthiobiotinylated quinone, thus optimizing this reaction would lead to a product that could be purified by flash chromatography.

Allowing the reaction to activate with PyBOP and triethylamine for too long (2 h) resulted in the initial gold solution turning deep red, which has previously

been an indication that the quinone has decomposed in the presence of a nucleophile. When the resulting red solution was then treated with amine 94 only traces of coupled product were observed by HPLC. The activation step was then shortened to 10 minutes followed by a 30 minute treatment with amine 94 and a homogeneous yellow solution was maintained throughout the reaction with a yield of greater than 60%. As predicted, the coupling reaction to synthesize 92 provided a reaction mixture that was easily purified by flash chromatography. However, the reaction between a quinone and an amine has been very difficult to control, frequently resulting in a dark green or red solution following base addition during the activation step. Thus the coupling route to 92 is advantageous in that product can be easily separated from other quinone or desthiobiotin containing species, but unfavorable in the respect that the reaction can take a catastrophic turn for presently unapparent reasons.

Without structural data for Ape1, it was hypothesized that collecting sufficient biological data from a wide range of inhibitors would drive a qualitative structure activity relationship (QSAR) assessment. Thus, a crystal structure of the 3-chloro derivative 43a was sought to provide a solid foundation for QSAR studies.

Figure 12: A. Crystal of inhibitor 43a used for X-ray diffraction study. B. Structure generated from data collected from X-ray diffraction studies on 43a.

Crystals of inhibitor 43a (Figure 12A) were grown using vapor diffusion, and the data collected was used to generate the structure in Figure 12B. From this crystal structure a conformation of the inhibitor was derived. The unsaturated acid moiety of the crystal structure possesses an anticipated trans-diene configuration, and the quinone ring is slightly contorted into a boat conformation. The exocyclic double bond and the ring reside nearly 30° from parallel, which is most likely due to sterics of the 3-chloro substituent. (Figure 13) Structure derived from X-ray diffraction study shows both the relationship between quinone and unsaturated acid planes as well as trans-diene like unsaturated acid conformation.

When mixtures of E and Z isomers were produced, from either the Emmons reaction or later from isomerizations encountered in the Steglich reaction, definitive assignments of E and Z needed to be given to the compounds isolated. The ¹H NMR chemical shift of the vinyl proton is significantly different for E and Z isomers, where the E vinyl proton appears further downfield by as much as 0.7 ppm.

However, a more convincing analysis was sought to further prove the identity of the isomers. A concrete foundation was given to this developing evidence by the X-ray crystal structure determined for 43a. The observable E double bond geometry in the crystal structure is unquestionable, and the preceding E and Z isomers could be
5 identified in the unsaturated acid series of the naphthalene compounds by tracing the lineage of *E*-43a backwards. As expected the E isomers had the downfield vinyl protons, and the upfield shifts corresponded to the Z isomers.

For the naphthalene unsaturated acids comparing the vinyl proton shifts was sufficient for later compound identification. However, when isomers were
10 encountered with the Steglich conditions, the vinyl protons in the amide products were appearing further upfield than expected. The relative shifts of the vinyl protons, as well as the expected geometrical effects on shifts of other protons including the amide and alpha protons, all correlated to the expected assignment of E and Z isomers. To ensure our assignments were correct with these new unsaturated amides,
15 2D and nOe NMR were taken to identify the beta carbon in the former and observe enhancements of the vinyl proton in the latter.

Previously identified E and Z isomers *E*-42a and *Z*-42a were again used in both type of advanced NMR experiments. First, HMQC spectra of *E*-42a and *Z*-42a were collected to identify the beta carbon, and it was determined that the E isomer had a
20 downfield shift of 3.5 ppm (134.6 and 131.1 ppm respectively). (Figure 14A and 14B) Second, the same samples were run in nOe experiments where the allylic methyl protons were irradiated (1.90 ppm for E and 2.20 ppm for Z). For the E isomer no enhancements were observed to the vinyl proton; the Z isomer did experience enhancement of the vinyl proton upon irradiation of the allylic protons.
25 (Figure 15A and Figure 15B) A third known entity was incorporated into the "training" data set, and this was 9f (Scheme 1), the unsaturated acid precursor to E3330. In this instance the beta carbon was again identified via the HMQC spectra (136.4 ppm, Figure 14C); however the nOe irradiation was performed on the vinyl proton rather than the allylic protons because the alpha substituent has now changed
30 from a simple methyl to a nonyl group. Irradiation did not show enhancement of the methylene protons of the nonyl group, but did show enhancement of the ring methyl, as expected. (Figure 15C) Finally, the first simple amide generated (79) was examined to compare the effects of converting an unsaturated acid to the unsaturated

amide. (Figure 14D and Figure 15D) The nOe enhancement followed the experimental data of the other E isomers where no enhancement of the vinyl proton was observed upon irradiation of the allylic protons. Without having the Z isomer, comparisons could not be made regarding the chemical shifts of the beta carbons from the HMQC data; however, assignment of the beta carbon (128.12 ppm) was still possible. Later the E isomer of 79 was synthesized from pure E acid using methyl chloroformate, confirming the geometry of the previous NMR sample.

Figure 14: HMQC spectra of A. *E*-42a; B. *Z*-42a; C. 9f; and D. 79.

Peaks corresponding to the vinyl proton/beta carbon have been circled in black.

Figure 15: nOe spectra of A. *E*-42a; B. *Z*-42a; C. 9f; and D. 79. Site of proton irradiated in experiment is denoted on structure by an asterix. Diagnostic regions positive for enhancement are represented by a closed circle, a broken circle denotes diagnostic areas negative for enhancement. A. No enhancement of the vinyl proton is observed by the irradiation of the allylic protons of *E*-42a at 1.95 ppm. These are expected results for a confirmed E olefin. B. Enhancement of the vinyl proton at 6.98 ppm is observed after irradiation of the allylic protons of *Z*-42a at 2.28 ppm. Enhancement was expected for the confirmed Z olefin. C. Irradiation of the vinyl proton at 7.62 ppm does not show enhancement of the methylene protons of 9f; however, enhancement is observed in the ring methyl peak at 2.12 ppm. This is keeping with the lack of enhancement observed in the E olefins. D. Irradiation of the allylic protons of 79 does not show enhancement of the vinyl protons, suggesting an E olefin.

Figure 16: Analysis of Z and E isomers (*Z*)-77 and (*E*)-77, respectively, by direct comparison of ¹H NMR spectra (A/B), HMQC spectra (C/D), nOe enhancement from irradiation of allylic protons (E/F), and nOe enhancement from irradiation of vinyl protons (G/H). A/B. The vinyl proton of the Z isomer (6.64 ppm, Figure 16A) is significantly further upfield than that of the corresponding E isomer (7.36 ppm, Figure 16B). C/D. The HMQC data for the Z and E isomers correlate to the same pattern observed in authentic E and Z isomers, where the Z beta carbon is further upfield (122.4 ppm, Figure 16C) than the E beta carbon (127.3 ppm, Figure 16D). nOe spectra of the Z isomer shows irradiation at the allylic position (Figure 16E) has little effect on the remainder of the molecule, but irradiation at the vinyl proton (Figure 16G) shows enhancement to a ring methoxy group. Irradiation

of both the allylic (Figure 16F) and vinyl (Figure 16H) protons of the E isomer has no transference to other parts of the molecule.

Figure 17: Direct comparison of Z and E isomers (*Z*)-81 and (*E*)-81, respectively, by their corresponding ¹H NMR spectra (A/B), HMQC spectra (C/D), and nOe enhancement from irradiation of vinyl protons (E/F). Comparison to the ¹H spectrum (G) and nOe enhancement by irradiation of the vinyl proton (H) of another compound ((*E*)-80) helps identify conserved phenomena. A/B. As before the *Z* isomer displays an upfield shift of the vinyl protons. C/D. The chemical shift for the beta carbon in the *Z* isomer is further upfield (123.6 ppm vs. 126.7 ppm), consistent with the training set of known compounds. E. Interestingly, the irradiation of the vinyl proton from the *Z* isomer does not generate a nOe effect to the methylene protons. F. Further strange phenomena are observed upon irradiation of the vinyl protons of the *E* isomer. Transference is observed to a methoxy peak (3.69 ppm) and a peak at 2.02 ppm. Closer examination indicates the enhanced peak at 2.02 ppm is the ring methyl and not the allylic methylene protons, thus the *E* assignment for the spectra on the right stands. G. The proton spectrum is provided for (*E*)-80, which shows similar peak patterns to the *E* isomers. Furthermore the beta carbon is shifted to 127.8 ppm, corresponding to the *E* isomers. H. Irradiation of the vinyl proton of (*E*)-80 results in a nOe enhancement of a peak at 2.03 ppm, corresponding to the ring methyl and not the allylic methylene protons.

Derivatives of E3330 have been synthesized where five aspects of the inhibitor were systematically examined, including: 1) benzoquinone core; 2) ring methyl; 3) alpha n-nonyl substituent; 4) exocyclic double bond; and 5) carboxylic acid moiety. Without structural insight into the binding pocket of Ape1, derivatives were designed in a SAR approach to develop a lead inhibitor that could later be further elaborated with structural information.

Data collected from the limited benzoquinone series showed the nonyl sidechain of E3330 to be similar in activity to the methyl and butyl derivatives; furthermore, the data showed that a sidechain of at least a methyl group was desirable to retain an activity level near that of E3330. Knowledge of the alpha substituent on the double bond was then transferred to the more easily modified naphthoquinone series where further explorations into the 3-substituent on the ring could commence. Naphthoquinone derivatives were first developed with

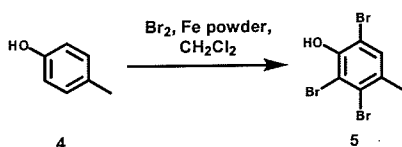
modifications to the 3-position including unsubstituted, methyl, fluoro, chloro, bromo, methoxy, and methylthio derivatives. All derivatives with an electronegative atom attached to the 3-position showed 3 to 30 times greater activity than the methyl substituted derivative.

5 The final derivatives in the naphthoquinone series defined the significance of the unsaturated acid moiety. Methyl ester and hydroxyethylamide derivatives both showed complete retention of activity compared to the parent carboxylic acids. Furthermore, diversification of the double bond through epoxidation and saturation provided compounds with similar activities to the
10 unsaturated derivatives. The most interesting discovery came from the Z isomer of the potent naphthoquinone 43a; activity was retained while reversing the orientation of the acid and alpha substituent on the double bond. This data was the most compelling suggesting the lack of significance of the exocyclic unsaturated acid in binding.

15 The data collected from the derivatives prepared begin to show preferences for the redox active site of Ape1. Biotin-conjugated inhibitors have been synthesized to provide samples for SPR studies to determine dissociation constants for 43a. This molecular tool may also be used in affinity chromatography to determine selectivity among proteins from a cell lysate.

20 Reagents were used as received from commercial sources, as were anhydrous solvents including ethyl acetate, toluene, benzene, methanol, DMF, diethyl ether, and 1,2-dimethoxyethane. THF, CH₂Cl₂, and acetonitrile were distilled prior to use, and acetone was dried over activated MS for 2 hours under argon. Flash chromatographic separations were performed using 32-63 μm silica gel; thin layer
25 chromatography was performed with Analtech 250 μm GHLF plates with 254 nm fluorescent indicator. All ¹H NMR were run on a Bruker 300 MHz NMR equipped with a multinuclear (¹H, ¹³C, ¹⁹F, and ³¹P) 5mm probe. ¹H spectra were calibrated either CHCl₃ at 7.24 ppm, (CH₃)₂SO at 2.49, or (CH₃)CO at 2.04 ppm. ¹³C NMR were calibrated to CHCl₃ at 77.0 ppm. 2D NMR and nOe experiments were
30 performed on a Bruker 500 MHz NMR equipped with a multinuclear (¹H, ¹³C, ¹⁹F, and ³¹P) 5mm probe. Melting points were measured using a Mel-Temp II and 300 °C mercury thermometer. All MP are reported unadjusted. Elemental analyses were performed at the Purdue University Microanalysis Lab. Small molecule

crystallography was performed at the Purdue University Chemistry Crystallography Center. Mass Spectrum data were collected at the Purdue University Mass Spectrum lab. Ape1 redox inhibition assays were performed at Indiana University School of Medicine. Data were then analyzed by EMSA in the same lab. Cell killing data were collected on compounds of interest. Initial toxicology was performed in the toxicology lab at IUSoM.



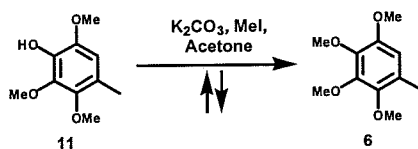
4-Methyl-2,3,6-tribromophenol (5):

According to the modified procedures of Shinkawa et al. and Keinan et al.,^{14,16} p-cresol (4, 5.2 mL, 50 mmol) was dissolved in CH₂Cl₂ (300 mL) at room temperature in a 2-neck 500 mL round bottom flask attached to an addition funnel and a KOH trap. Fe (0.050 g, 0.90 mmol) was added at room temperature, and then bromine (7.8 mL, 150 mmol) in CH₂Cl₂ (50.0 mL) was added dropwise to the reaction. Following the addition the reaction was stirred for an additional 8 hrs at room temperature. The reaction was then added to a separation funnel and shaken with water until the red color disappeared. The organic layer was then separated, dried over MgSO₄, filtered, and condensed to provide a white solid. The crude product was separated from 2,6-dibromo p-cresol via recrystallization from hexanes. 5 (15.39 g, 44.74 mmol, 89%) was obtained as fine white needles.

R_f = 0.20 (1:9 EtOAc:hexanes)

mp = 90 – 91 °C (Literature 95 - 106 °C){#930}{#920}

¹H NMR (CDCl₃): δ 2.38 (s, 3H); 5.85 (s, 1H, OH); 7.36 (s, 1H)

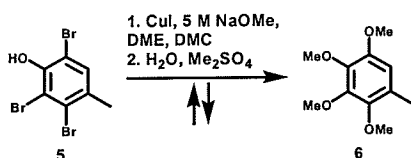


2,3,4,5-tetramethoxytoluene (6):

According to a modification of the procedure by Brimble et al.,³⁶ 11 (0.660 g, 3.33 mmol) and K₂CO₃ (4.08 g, 29.5 mmol) were added to a flame-dried 250 mL round bottom flask followed by dry acetone (120.0 mL) and MeI (2.0 mL, 32 mmol) at room temperature. A water-jacketed reflux condenser was attached and the reaction was heated under reflux for 12 hours. The reaction was then cooled, filtered, and the solvent was removed under reduced pressure. The brown residue was then resuspended in CH₂Cl₂, dried over MgSO₄, filtered, and condensed. The resulting colorless oil was then purified by flash chromatography (1:9 EtOAc:hexanes) to provide 6 (0.690 g, 3.25 mmol, 99%) as a colorless oil.

R_f = 0.57 (7:13 EtOAc:hexanes)

¹H NMR (CDCl₃): δ 2.20 (s, 3H); 3.76 (s, 3H); 3.79 (s, 3H); 3.84 (s, 3H); 3.91 (s, 3H); 6.42 (s, 1H)



15

2,3,4,5-tetramethoxytoluene (6):

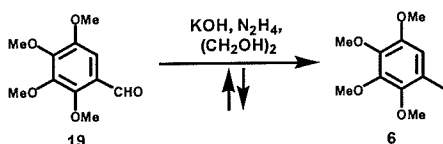
Following a modified procedure by Keinan et al.,¹⁴ NaOMe (25%, 4.37 M, 60.0 mL, 262 mmol) was added to a 3 neck flame-dried 250 mL round bottom flask attached to a dean stark trap. DME (60.0 mL) and DMC (5.0 mL) were added and the reaction was distilled until 38.0 mL of MeOH was removed (54%, 11.9 M NaOMe). Alternatively Na (6.03 g, 262 mmol) can be dissolved in MeOH (70.0 mL), DME (60.0 mL) and DMC (5.0 mL) are then added, and MeOH (44.0 mL) was distilled to provide 54% NaOMe. The reaction was cooled to room temperature and CuI (6.32 g, 33.2 mmol) was added, and the thick white reaction becomes a thick dark purple solution. The reaction was heated to boiling and the dean stark trap was replaced with a water-jacketed reflux condenser. 5 (7.97 g, 23.2 mmol) was dissolved in DME (10.0 mL) and then added at reflux slow enough to prevent bumping. Eventually the solution becomes too thick to stir and boils violently. The solution was allowed to boil under reflux for 24 hrs and progress was monitored by NMR.

Upon reaching completion the reaction was cooled to ~ 50 °C and water (155.0 mL) was added. Then Me₂SO₄ (20.0 mL, 211 mmol) was added slowly

and the reaction was allowed to cool to room temperature while stirring. The reaction stirs for a further 2 hrs and was then acidified and filtered through celite. The reaction was then extracted with ethyl acetate and washed with brine. After drying over MgSO_4 the reaction was filtered and condensed. The crude oil was purified by flash column chromatography (1:49 EtOAc:hexanes or 1:49 EtOAc/ CH_2Cl_2) to provide 6 (3.21 g, 15.1 mmol, 65%) as a colorless oil that was modestly contaminated with 2,4,5-trimethoxytoluene and 3,4,5-trimethoxytoluene.

$R_f = 0.57$ (7:13 EtOAc:hexanes)

$^1\text{H NMR}$ (CDCl_3): δ 2.20 (s, 3H); 3.76 (s, 3H); 3.79 (s, 3H); 3.84 (s, 3H); 3.91 (s, 3H); 6.42 (s, 1H)

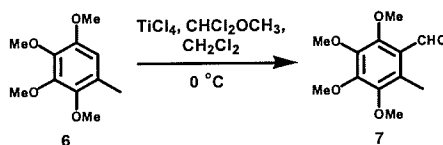


2,3,4,5-tetramethoxytoluene (6):

According to a generalized procedure by Matsubara et al.,²¹ 19 (2.99 g, 13.2 mmol) was added to a flame-dried 100 mL round bottom flask, and then ethylene glycol (28.0 mL), KOH (2.36 g, 42.1 mmol), and hydrazine (6.0 mL, 190 mmol) was added at room temperature. The reaction was heated under reflux for 8 hours and then cooled. The solution was poured into brine and extracted with CH_2Cl_2 . The organic layer was washed with dilute NaOH, brine, and then dried over MgSO_4 . The crude product could be used without further purification, or purified using flash chromatography (7:13 EtOAc:hexanes) to provide 6 (2.37 g, 11.2 mmol, 85%) as a colorless oil.

$R_f = 0.57$ (7:13 EtOAc:hexanes)

$^1\text{H NMR}$ (CDCl_3): δ 2.43 (s, 3H); 3.74 (s, 3H); 3.89 (s, 3H); 3.92 (s, 3H); 4.00 (s, 3H); 10.41 (s, 1H)

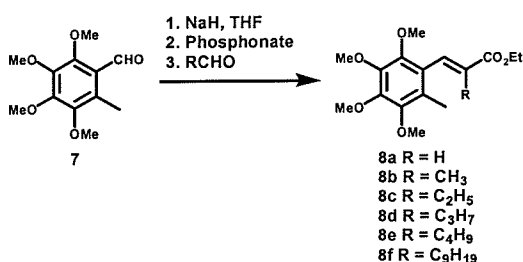


6-methyl-2,3,4,5-tetramethoxybenzaldehyde (7):

According to the procedure by Ohkawa et al.,¹⁵ 6 (0.690 g, 3.25 mmol) was dissolved in CH₂Cl₂ (2.0 mL) in a flame-dried 25 mL round bottom flask and cooled to 0 °C. α,α-dichloromethyl methyl ether (0.85 mL, 9.6 mmol) was then added at 0 °C, followed by TiCl₄ (1 M in CH₂Cl₂, 9.0 mL, 9.0 mmol) at 0 °C. The reaction was warmed slowly to room temperature and stirred for 6 hours under argon. The reaction was then poured into chilled water and stirred for 10 minutes. The reaction was diluted with EtOAc, washed with brine, dried over MgSO₄, filtered, and condensed. The crude oil was then purified by flash chromatography (1:49 EtOAc:hexanes if made via p-cresol; 3:17 EtOAc:hexanes if made via Wolffe-Kishner reduction) to provide 7 (0.696 g, 2.90 mmol, 89%) as a yellow oil.

R_f = 0.26 (3:17 EtOAc:hexanes)

¹H NMR (CDCl₃): δ 2.44 (s, 3H); 3.74 (s, 3H); 3.89 (s, 3H); 3.92 (s, 3H); 4.00 (s, 3H); 10.24 (s, 1H)



Ethyl (E)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-propenoate (8a):

According to the modified procedure of Murphy et al.,²⁶ NaH (0.131 g, 3.27 mmol) was added to a flame-dried 50 mL 3-neck round bottom flask connected to a water-jacketed reflux condenser. The flask was purged with Argon and a drying tube was attached to the top. THF (15.0 mL) was added to the flask followed by phosphonate (triethylphosphonoacetate, 0.36 mL, 1.8 mmol) at room temperature. The reaction was stirred at room temperature for 30 minutes, and then the aldehyde (0.323 g, 1.34 mmol) was dissolved in THF (10.0 mL) and added quickly at room temperature. The reaction was stirred for another 12 h at room temperature, then diluted with ethyl acetate and washed with brine. The organic layer was dried, filtered, and condensed. The resulting oil was purified via flash column chromatography (CH₂Cl₂ to 1:19 EtOAc:CH₂Cl₂) to provide 8a (0.343 g, 1.11 mmol, 83%) as a pale yellow oil.

$R_f = 0.17$ (CH_2Cl_2)

E:Z = 1:0 in THF at room temperature.

$^1\text{H NMR}$ (CDCl_3): δ 1.32 (t, 3H, $J = 7.2$ Hz); 2.26 (s, 3H); 3.76 (s, 3H);
3.78 (s, 3H); 3.88 (s, 3H); 3.94 (s, 3H); 4.24 (q, 2H, $J = 7.2$ Hz); 6.52 (d, 1H, $J = 16.2$
5 Hz); 7.77 (d, 1H; $J = 16.2$ Hz)

Ethyl (*E*)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-methylpropenoate (8b):

Compound 8b was prepared from 7 (0.569g, 2.37 mmol) as described
above for 8a to give 0.674 g (2.08 mmol, 88%) of the product as a yellow oil
10 following flash chromatography (1:3 EtOAc:hexanes).

$R_f = 0.48$ (1:3 EtOAc:hexanes)

$^1\text{H NMR}$ (CDCl_3): δ 1.31 (t, 3H, $J = 7.2$ Hz); 1.71 (d, 3H, $J = 1.2$ Hz);
2.01 (s, 3H); 3.67 (s, 3H); 3.77 (s, 3H); 3.87 (s, 3H); 3.91 (s, 3H); 4.24 (q, 2H, $J = 7.2$
15 Hz); 7.47 (d, 1H, $J = 0.6$ Hz)

Ethyl (*E*)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-ethylpropenoate (8c):

Compound 8c was prepared from 7 (0.437 g, 1.82 mmol) as described
above for 8a to give 0.258 g (0.762 mmol, 42%) of the product as a colorless oil
following flash chromatography (1:3 EtOAc:hexanes).

20 $R_f = 0.50$ (1:3 EtOAc:hexanes)

$^1\text{H NMR}$ (CDCl_3): δ 0.94 (t, 3H, $J = 7.5$ Hz); 1.33 (t, 3H, $J = 7.2$ Hz);
2.02 (s, 3H); 2.15 (q, 2H, $J = 7.5$ Hz); 3.69 (s, 3H); 3.78 (s, 3H); 3.89 (s, 3H); 3.92 (s,
3H); 4.26 (q, 2H, $J = 7.2$ Hz); 7.36 (s, 1H)

25 Ethyl (*E*)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-propylpropenoate (8d):

Compound 8d was prepared from 7 (0.437 g, 1.82 mmol) as described
above for 8a to give 0.275 g (0.780 mmol, 43%) of the product as a colorless oil
following flash chromatography (1:3 EtOAc:hexanes).

$R_f = 0.52$ (1:3 EtOAc:hexanes)

30 $^1\text{H NMR}$ (CDCl_3): δ 0.75 (t, 3H, $J = 7.2$ Hz); 1.33 (t, 3H, $J = 7.2$ Hz);
1.35 (m, 2H); 2.03 (s, 3H); 2.11 (m, 2H); 3.69 (s, 3H); 3.78 (s, 3H); 3.88 (s, 3H); 3.93
(s, 3H); 4.25 (q, 2H, $J = 7.2$ Hz); 7.38 (s, 1H)

Ethyl (*E*)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-butylpropenoate (8e):

Compound 8e was prepared from 7 (0.650 g, 2.71 mmol) as described above for 8a to give 0.484 g (1.32 mmol, 49%) of the product as a yellow oil following flash chromatography (1:9 EtOAc:hexanes).

5 $R_f = 0.54$ (1:3 EtOAc:hexanes)

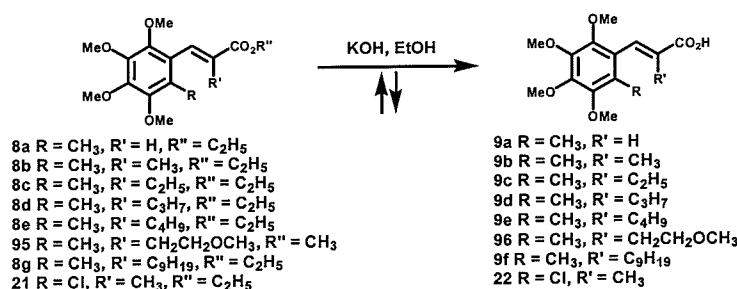
$^1\text{H NMR}$ (CDCl_3): δ 0.73 (t, 3H, $J = 7.2$ Hz); 1.12 (m, 2H); 1.29 (m, 2H); 1.32 (t, 3H, $J = 7.2$ Hz); 2.03 (s, 3H); 2.13 (m, 2H); 3.69 (s, 3H); 3.78 (s, 3H); 3.88 (s, 3H); 3.92 (s, 3H); 4.25 (q, 2H, $J = 7.2$ Hz); 7.37 (s, 1H)

10 Ethyl (*E*)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-nonylpropenoate (8f):

Compound 8f was prepared from 7 (0.581 g, 2.42 mmol) as described above for 8a to give 0.621 g (1.42 mmol, 59%) of the product as a colorless oil following flash chromatography (3:17 EtOAc:hexanes).

$R_f = 0.40$ (3:17 EtOAc:hexanes)

15 $^1\text{H NMR}$ (CDCl_3): δ 0.84 (t, 3H, $J = 7.2$ Hz); 1.08 – 1.22 (m, 11H); 1.24 – 1.35 (m, 3H); 1.33 (t, 3H, $J = 7.2$ Hz); 2.03 (s, 3H); 2.12 (m, 2H); 3.69 (s, 3H); 3.78 (s, 3H); 3.88 (s, 3H); 3.93 (s, 3H); 4.25 (q, 2H, $J = 7.2$ Hz); 7.37 (s, 1H)

20 (*E*)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-propenoic acid (9a):

Method A: Emmons ester 8a (0.066 g, 0.21 mmol) was dissolved in EtOH (10.0 mL) and then KOH (0.095 g, 1.69 mmol) was added to the reaction. The reaction was heated to boiling and stirred at this temperature for 30 minutes. The reaction was then cooled, acidified, and extracted with ethyl acetate. The organic layer was washed with brine, dried over MgSO₄, filtered, and condensed. The resulting acid was then used as crude, or can be purified via flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH) or recrystallization from Et₂O/hexanes to provide 9a (0.046 g, 0.16 mmol, 78%) as a light tan solid.

Method B: Emmons ester 8a was dissolved in DME (10.0 mL) to which NaOH (2 M, 2.0 mL, 2.0 mmol) was then added at room temperature. The reaction was heated to reflux for 3 hours or until TLC (1:4 EtOAc:hexanes) indicated that all starting material had been consumed. The reaction was then acidified, diluted
5 with EtOAc, washed 3 times with brine, dried over MgSO₄, filtered, and condensed.

$R_f = 0.16$ (2:3 Et₂O:hexanes 0.5% AcOH)

mp = 96 – 97 °C

¹H NMR (CDCl₃): δ 3.77 (s, 3H); 3.81 (s, 3H); 3.89 (s, 3H); 3.95 (s, 3H); 6.59 (d, 1H, J = 16.2 Hz); 7.90 (d, 1H, J = 16.2 Hz)

10

(E)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-methylpropenoic acid (9b):

Compound 9b was prepared from 8b (0.156 g, 0.481 mmol) as described above for 9a using Method B to give 0.121 g (0.408 mmol, 85%) of the product as a light yellow solid following flash chromatography (2:3 Et₂O:hexanes
15 0.5% AcOH) and recrystallization from Et₂O/hexanes.

$R_f = 0.16$ (2:3 Et₂O:hexanes 0.5% AcOH)

mp = 98 – 102 °C

¹H NMR (CDCl₃): δ 1.76 (d, 3H, J = 1.2 Hz); 2.05 (s, 3H); 3.69 (s, 3H); 3.79 (s, 3H); 3.90 (s, 3H); 3.93 (s, 3H); 7.64 (d, 1H, J = 1.2 Hz)

20

(E)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-ethylpropenoic acid (9c):

Compound 9c was prepared from 8c (0.041 g, 0.12 mmol) as described above for 9a to give 0.010 g (0.033 mmol, 27%) of the product as a gold oil following flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH).

25

$R_f = 0.16$ (2:3 Et₂O:hexanes 0.5% AcOH)

¹H NMR (CDCl₃): δ 0.98 (t, 3H, J = 7.2 Hz); 2.04 (s, 3H); 2.18 (q, 2H, J = 7.2 Hz); 3.70 (s, 3H); 3.79 (s, 3H); 3.90 (s, 3H); 3.93 (s, 3H); 7.53 (s, 1H)

(E)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-propylpropenoic acid (9d):

Compound 9d was prepared from 8d (0.034 g, 0.098 mmol) as described above for 9a to give 0.029 g (0.090 mmol, 92%) of the product as a gold oil following flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH).

30

$R_f = 0.18$ (2:3 Et₂O:hexanes 0.5% AcOH)

¹H NMR (CDCl₃): δ 0.77 (t, 3H, J = 7.2 Hz); 1.41 (m, 2H); 2.04 (s, 3H); 2.13 (m, 2H); 3.70 (s, 3H); 3.79 (s, 3H); 3.89 (s, 3H); 3.93 (s, 3H); 7.55 (s, 1H)

(E)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-butylpropenoic acid (9e):

5 Compound 9e was prepared from 8e (0.166 g, 0.453 mmol) as described above for 9a using Method B to give 0.144 g (0.426 mmol, 94%) of the product as a yellow amorphous solid following flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

R_f = 0.26 (2:3 Et₂O:hexanes 0.5% AcOH)

10 mp = 70 – 85 °C

¹H NMR (CDCl₃): δ 0.74 (t, 3H, J = 7.2 Hz); 1.19 (m, 4H); 2.04 (s, 3H); 2.15 (m, 2H); 3.70 (s, 3H); 3.79 (s, 3H); 3.89 (s, 3H); 3.93 (s, 3H); 7.53 (s, 1H)

(E)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-nonylpropenoic acid (9f):

15 Compound 9f was prepared from 8f (0.121 g, 0.277 mmol) as described above for 9a using Method B to give 0.107 g (0.262 mmol, 93%) of the product as a colorless oil following flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH).

R_f = 0.36 (2:3 Et₂O:hexanes 0.5% AcOH)

20 ¹H NMR (CDCl₃): δ 0.84 (t, 3H, J = 6.9 Hz); 1.13 (m, 12H); 1.36 (m, 2H); 2.04 (s, 3H); 2.14 (m, 2H); 3.70 (s, 3H); 3.79 (s, 3H); 3.89 (s, 3H); 3.93 (s, 3H); 7.537 (s, 1H)

¹³C NMR (CDCl₃): δ 12.9, 14.1, 22.7, 28.0, 28.3, 29.3, 29.5, 33.8, 31.9, 53.4, 60.7, 60.9, 61.1, 61.3, 124.7, 135.6, 136.6, 144.7, 146.5, 146.7, 147.8,
25 172.5

(E)-3-(2-chloro-3,4,5,6-tetramethoxyphenyl)-2-methylpropenoic acid (22):

30 Compound 22 was prepared from 21 (0.255 g, 0.740 mmol) as described above for 9a using Method A to give 0.222 g (0.701 mmol, 95%) of the product as a red amorphous solid following flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

R_f = 0.20 (2:3 Et₂O:hexanes 0.5% AcOH)

¹H NMR (CDCl₃): δ 1.81 (s, 3H); 3.71 (s, 3H); 3.86 (s, 3H); 3.91 (s, 3H); 7.57 (d, 1H, J = 1.2 Hz)

(E)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-methoxyethylpropenoic acid

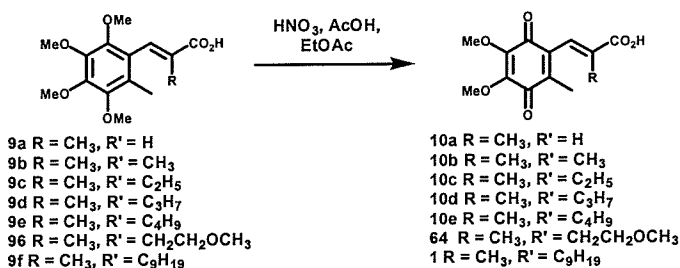
5 (96):

Compound 96 was prepared from 95 (0.074 g, 0.21 mmol) as described above for 9a using Method A to give 0.070 g (0.21 mmol, 100%) of the product as a tan solid following flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

10 R_f = 0.16 (2:3 Et₂O:hexanes 0.5% AcOH)

mp = 97 – 99 °C

¹H NMR (CDCl₃): δ 2.07 (s, 3H); 2.45 (t, 2H, J = 6.9 Hz); 3.20 (s, 3H); 3.68 (s, 3H); 3.69 (q, 2H, J = 6.9 Hz); 3.76 (s, 3H); 3.87 (s, 3H); 3.90 (s, 3H); 7.59 (s, 1H)



15

(E)-3-(4,5-dimethoxy-2-methyl-3,6-dioxocyclohexa-1,4-dienyl)-propenoic acid (10a):

Method A: Following modifications to the procedures by Shinkawa et al. and Flader et al.,^{16,22} acid 9a (0.089 g, 0.31 mmol) was dissolved in ethyl acetate (10.0 mL) at room temperature, then HNO₃ (1.0 mL) and AcOH (6 drops) are added at room temperature and the reaction was stirred for 4 hours. The reaction was then diluted with EtOAc (20.0 mL) washed with brine, dried over MgSO₄, filtered, and condensed. The red oil was then purified by either flash column chromatography (1:1 Et₂O:hexanes 0.5% AcOH) or recrystallization from Et₂O/hexanes to afford 10a.

25

Method B: Following the procedure of Flader et al.,²² 9a (0.046, 0.16 mmol) was dissolved in acetonitrile (5.0 mL) at room temperature, then ceric ammonium nitrate (0.294 g, 0.536 mmol) dissolved in water (5.0 ml) was added at room temperature. The reaction was stirred for 30 minutes and then extracted with

CH₂Cl₂. The organic layer was washed with brine, dried over MgSO₄, filtered, and condensed. The resulting red solid was the recrystallized (Et₂O/hexanes) to provide 10a (0.024 g, 0.093 mmol, 57%) as a red solid.

R_f = 0.06 (2:3 Et₂O:hexanes 0.5% AcOH)

5 mp = 116 – 125 °C

¹H NMR (CDCl₃): δ 2.19 (s, 3H); 4.00 (s, 6H); 6.76 (d, 1H, J = 16.2 Hz); 7.60 (d, 1H, J = 16.2 Hz)

10 (E)-3-(4,5-dimethoxy-2-methyl-3,6-dioxocyclohexa-1,4-dienyl)-2-methylpropenoic acid (10b):

Compound 10b was prepared from 9b (0.057 g, 0.19 mmol) as described above for 10a using Method B to give 0.016 g (0.060 mmol, 31%) of the product as a red solid following flash chromatography (1:1 Et₂O:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

15 R_f = 0.06 (2:3 Et₂O:hexanes 0.5% AcOH)

mp = 134 – 136 °C

¹H NMR (CDCl₃): δ 1.77 (d, 3H, J = 1.2 Hz); 1.95 (d, 3H, J = 1.2 Hz); 4.01 (s, 3H); 4.03 (s, 3H); 7.39 (s, 1H)

20 (E)-3-(4,5-dimethoxy-2-methyl-3,6-dioxocyclohexa-1,4-dienyl)-2-ethylpropenoic acid (10c):

Compound 10c was prepared from 9c (0.010 g, 0.033 mmol) as described above for 10a to give 0.003 g (0.010 mmol, 32%) of the product as a red solid following flash chromatography (1:1 Et₂O:hexanes 0.5% AcOH) and

25 recrystallization from Et₂O/hexanes.

R_f = 0.10 (2:3 Et₂O:hexanes 0.5% AcOH)

mp = 124 – 131 °C

¹H NMR (CDCl₃): δ 1.01 (t, 3H, J = 7.2 Hz); 1.94 (d, 3H, J = 1.2 Hz); 2.12 (q, 2H, J = 7.2 Hz); 3.99 (s, 3H); 4.01 (s, 3H); 7.23 (d, 1H, J = 1.2 Hz)

30

(E)-3-(4,5-dimethoxy-2-methyl-3,6-dioxocyclohexa-1,4-dienyl)-2-propylpropenoic acid (10d):

Compound 10d was prepared from 9d (0.029 g, 0.090 mmol) as described above for 10a to give 0.016 g (0.053 mmol, 59%) of the product as a red solid following flash chromatography (1:1 Et₂O:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

5 R_f = 0.12 (2:3 Et₂O:hexanes 0.5% AcOH)
 mp = 95 – 99 °C
 ¹H NMR (CDCl₃): δ
 0.76 (t, 3H, J = 7.2 Hz); 1.41 (m, 2H); 1.91 (d, 3H, J = 1.5 Hz); 2.04
 (m, 2H); 3.95 (s, 3H); 3.98 (s, 3H); 7.24 (s, 1H)

10

(E)-3-(4,5-dimethoxy-2-methyl-3,6-dioxocyclohexa-1,4-dienyl)-2-butylpropenoic acid (10e):

Compound 10e was prepared from 9e (0.015 g, 0.044 mmol) as described above for 10a to give 0.005 g (0.018 mmol, 40%) of the product as a red solid following flash chromatography (1:1 Et₂O:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

15 R_f = 0.12 (2:3 Et₂O:hexanes 0.5% AcOH)
 mp = 54 – 55 °C
 ¹H NMR (CDCl₃): δ 0.82 (t, 3H, J = 7.2 Hz); 1.22 (m, 2H); 1.39 (m,
20 2H); 1.95 (d, 3H, J = 1.2 Hz); 2.10 (m, 2H); 3.99 (s, 3H); 4.02 (s, 3H); 7.24 (s, 1H)

(E)-3-(4,5-dimethoxy-2-methyl-3,6-dioxocyclohexa-1,4-dienyl)-2-nonylpropenoic acid (1):

Compound 1 was prepared from 9f (1.13 g, 2.77 mmol) as described above for 10a using Method A to give 0.443 g (1.17 mmol, 42%) of the product as a red solid following flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

25 R_f = 0.16 (2:3 Et₂O:hexanes 0.5% AcOH)
 mp = 56 – 57 °C (Lit. 68 °C) {#280}
30 elemental analysis: calculated C(66.65%), H(7.99%); found
 C(66.32%), H(7.89%)

¹H NMR (CDCl₃): δ 0.84 (t, 3H, J = 6.6 Hz), 1.18 (bs, 14H); 1.39 (bs, 2H); 1.94 (d, 3H, J = 1.5 Hz); 2.09 (t, 3H, J = 7.2 Hz); 3.99 (s, 3H); 4.02 (s, 3H); 7.26 (d, 1H, J = 1.5 Hz)

5 (E)-3-(4,5-dimethoxy-2-methyl-3,6-dioxocyclohexa-1,4-dienyl)-2-methoxyethylpropenoic acid (64):

Compound 64 was prepared from 96 (0.070 g, 0.21 mmol) as described above for 10a using Method A to give 0.012 g (0.039 mmol, 19%) of the product as a red solid following flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH) and

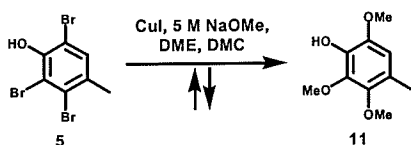
10 recrystallization from Et₂O/hexanes.

R_f = 0.06 (2:3 Et₂O:hexanes 0.5% AcOH)

mp = 104 – 106 °C

¹H NMR (CDCl₃): δ 1.95 (d, 3H, J = 1.5 Hz); 2.40 (t, 2H, J = 6.6 Hz); 3.24 (s, 3H); 3.44 (t, 2H, 6.6 Hz); 3.99 (s, 3H); 4.01 (s, 3H); 7.35 (d, 1H, J = 1.5 Hz)

15



4-Methyl-2,3,6-trimethoxyphenol (11):

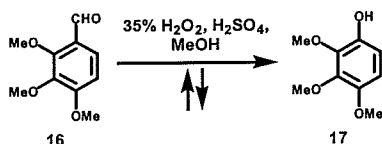
Following a modified procedure by Shinkawa et al. and Keinan et al.,^{14,16} NaOMe (25%, 4.37 M, 50.0 mL, 219 mmol) was added to a 3 neck flame-dried 100 mL round bottom flask attached to a dean stark trap. It was imperative to use a sufficiently large stirbar to allow stirring of the very concentrated solution. DME (24.0 mL) and DMC (8.5 mL) were added and the reaction was distilled until 31.5 mL of MeOH was removed (11.8 M NaOMe). Alternatively, Na (5.04 g, 219 mmol) can be dissolved in MeOH (70.0 mL), DME (60.0 mL) and DMC (5.0 mL) are then added, and MeOH (45.0 mL) was distilled. The white, opaque reaction was cooled to room temperature and CuI (5.173 g, 27.1 mmol) was added, at which point the reaction becomes a thick dark purple solution. The reaction was heated to boiling and the dean stark trap was replaced with a water-jacketed reflux condenser. 5 (5.89 g, 17.1 mmol) was dissolved in DME (10.0 mL) and then added at reflux slow enough to prevent bumping. Eventually the solution becomes too thick to stir and boils

violently. The solution was allowed to boil under reflux for 24 hrs and progress was monitored by NMR.

Upon reaching completion the reaction was cooled to ~ 50 °C and water was added (50.0 mL). The reaction was acidified slowly and then filtered through celite. The reaction was then extracted with ethyl acetate and washed with brine. After drying over MgSO₄ the reaction was filtered and condensed. The crude oil was purified by flash column chromatography (1:49 Et₂O:CH₂Cl₂) to provide 11 (1.67 g, 8.43 mmol, 49%) as a colorless oil.

R_f = 0.26 (1:4 EtOAc:hexanes)

¹H NMR (CDCl₃): δ 2.18 (s, 3H); 3.76, (s, 3H); 3.82 (s, 3H); 3.92 (s, 3H); 5.42 (bs, 1H, OH); 6.41 (s, 1H)

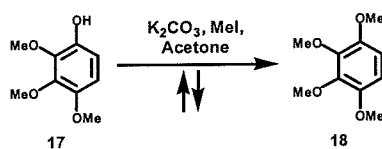


2,3,4-trimethoxyphenol (17):

Following a modified procedure by Tremblay et al.,¹⁷ 2,3,4-trimethoxybenzaldehyde (16, 6.075 g, 31.0 mmol) was dissolved in MeOH (60.0 mL), and then H₂SO₄ (0.6 mL) and 35% aq. H₂O₂ (4.0 mL, ~ 40 mmol) was added at room temperature. The reaction was then heated to reflux for 2 hrs and monitored by TLC (1:4 EtOAc:hexanes) for completion. When the reaction was complete the solution was cooled and extracted with ethyl acetate. The layers are separated and the organic layer was washed with brine, dried over MgSO₄, and filtered. Flash chromatography (1:4 EtOAc:hexanes) provides 17 (5.564 g, 30.2 mmol, 98%) as a light red oil.

R_f = 0.29 (1:4 EtOAc:hexanes)

¹H NMR (CDCl₃): δ 3.79 (s, 3H); 3.87 (s, 3H); 3.94 (s, 3H); 5.34 (broad s, 1H, OH); 6.57 (q, 2H, J = 9.0, 22.8 Hz)



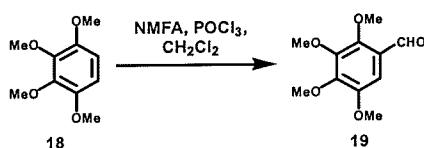
1,2,3,4-tetramethoxybenzene (18):

Following the procedure by Tremblay et al.,¹⁷ 17 (3.851 g, 20.9 mmol) was dissolved in dry acetone (90.0 mL), and K₂CO₃ (9.36 g, 67.7 mmol) was added followed by MeI (9.0 mL, 144 mmol). The reaction was heated under reflux for 26 h and monitored by TLC (1:9 EtOAc:hexanes) for completion. When complete the reaction was cooled to room temperature and filtered. The acetone was removed under reduced pressure and the residue was taken up in CH₂Cl₂ (50 mL). The suspension was filtered, dried over MgSO₄, filtered again, and condensed. The crude product can be purified by flash chromatography (1:4 EtOAc:hexanes), however, recrystallization from Et₂O/hexanes was sufficient to provide pure 18 (3.405 g, 17.2 mmol, 82%) as white needles.

R_f = 0.35 (1:4 EtOAc:hexanes)

mp = 86 – 87 °C (Lit. 87 – 87.5 °C)³⁷

¹H NMR (CDCl₃): δ 3.80 (s, 6H); 3.88 (s, 6 H); 6.56 (s, 2H)

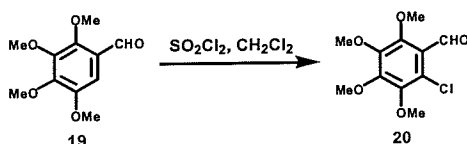
2,3,4,5-tetramethoxybenzaldehyde (19):

Following the procedure by Syper et al.,¹⁹ N-methylformanilide (1.0 mL, 8.1 mmol) was added to a flame dried 10 mL round bottom flask under argon and a drying tube. POCl₃ (1.0 mL, 11 mmol) was added at room temperature and the Argon line was removed. After 5 minutes 18 (1.067 g, 5.38 mmol) was dissolved in CH₂Cl₂ (2.0 mL) and added at room temperature. The reaction was stirred at room temperature under a drying tube for 48 hrs and monitored by ¹H NMR. When complete the reaction was diluted with EtOAc, washed with saturated brine, dried over MgSO₄, filtered, and condensed. The resulting product was separated from remaining N-methylformanilide using flash chromatography (1:4 Et₂O:hexanes) to provide 19 (1.141 g, 5.04 mmol, 94%) as a colorless oil.

R_f = 0.17 (1:4 Et₂O:hexanes)

Mp = oil (Lit. 38 °C d)³⁸

¹H NMR (CDCl₃): δ 3.85 (s, 3H); 3.92 (s, 3H); 3.95 (s, 3H); 3.97 (s, 3H); 7.09 (s, 1H); 10.27 (s, 1H)



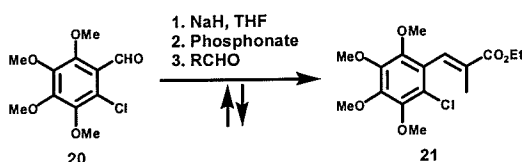
5

2-Chloro-3,4,5,6-tetramethoxybenzaldehyde (20):

According to a general aryl chlorination procedure by Lopez-Alvarado,³⁹ 19 (0.767 g, 3.39 mmol) was dissolved in CH₂Cl₂ (10.0 mL) at room temperature and then SO₂Cl₂ (neat, 0.31 mL, 3.7 mmol) was added at room temperature. The reaction was stirred for 1 hour and monitored by ¹H NMR for completion. The reaction was then diluted with CH₂Cl₂, washed with brine, dried over MgSO₄, filtered, and condensed. The resulting oil was then purified by flash column chromatography (1:4 Et₂O:hexanes) to provide 20 (0.861 g, 3.30 mmol, 97%) as a colorless oil.

15 R_f = 0.27 (1:4 Et₂O:hexanes)

¹H NMR (CDCl₃): δ 3.84 (s, 3H); 3.89 (s, 3H); 3.90 (s, 3H); 4.02 (s, 3H); 10.34 (s, 1H)



20

Ethyl (E)-3-(2-chloro-3,4,5,6-tetramethoxyphenyl)-2-methylpropenoate (21):

According to the modified procedure of Murphy et al.,²⁶ NaH (0.455 g, 11.3 mmol) was added to a flame-dried 50 mL 3-neck round bottom flask connected to a water-jacketed reflux condenser. The flask was purged with Argon and a drying tube was attached to the top. Toluene (20.0 mL) was added to the flask followed by phosphonate (1.3 mL, 6.0 mmol) at room temperature. The reaction was heated under reflux for 30 minutes, and the aldehyde (20, 0.861g, 3.30 mmol) was dissolved in toluene (14.0 mL) and added slowly at reflux. The reaction was heated for another 8 h under reflux. The reaction was then cooled to room temperature, diluted with ethyl

25

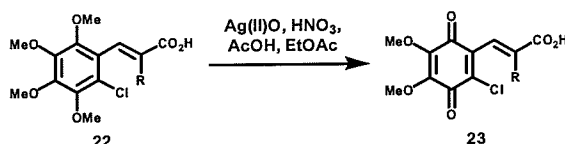
acetate, and washed with brine. The organic layer was dried, filtered, and condensed. The resulting oil was purified via flash column chromatography (1:9 i-Pr₂O:hexanes) to provide 21 (0.559 g, 1.62 mmol, 49%) as a colorless oil.

R_f = 0.29 (1:4 Et₂O:hexanes)

5 E:Z = 1:0 in refluxing toluene

¹H NMR (CDCl₃): δ 1.34 (t, 3H, J = 7.2 Hz); 1.78 (d, 3H, J = 1.5 Hz); 3.69 (s, 3H); 3.86 (s, 3H); 3.90 (s, 3H); 3.94 (s, 3H); 4.26 (q, 2H, J = 7.2 Hz); 7.42 (q, 1H, J = 1.5 Hz)

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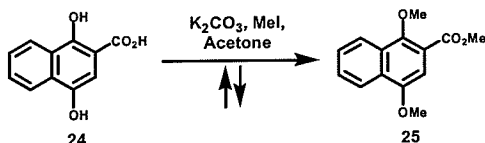
(E)-3-(2-chloro-4,5-dimethoxy-3,6-dioxocyclohexa-1,4-dienyl)-2-methylpropenoic acid (23):

Following a modified procedure of Flader et al.,²² 22 (0.124 g, 0.391 mmol) was dissolved in acetonitrile (10.0 mL) at room temperature, then ceric ammonium nitrate (0.970 g, 1.77 mmol) dissolved in water (8.0 ml) was added at room temperature. The reaction was stirred for 30 minutes and then extracted with CH₂Cl₂. The organic layer was washed with brine, dried over MgSO₄, filtered, and condensed. The red oil was then purified by either flash column chromatography (1:1 Et₂O:hexanes 0.5% AcOH) or recrystallization from Et₂O/hexanes to afford 23 (0.026 g, 0.091 mmol, 22%) as a red solid.

R_f = 0.32 (1:1 Et₂O:hexanes 0.5% AcOH)

mp = 183 – 185 °C

¹H NMR (CDCl₃): δ 1.83 (d, 3H, J = 1.2 Hz); 4.03 (s, 3H); 4.05 (s, 3H); 7.28 (d, 1H, J = 1.2Hz)



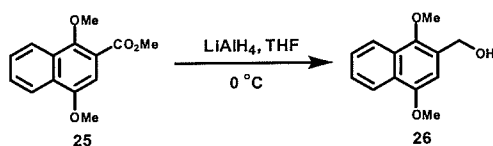
Methyl 1,4-dimethoxy-2-naphthoate (25):

According to a modification of the procedure by Brimble et al.,³⁶ 1,4-dihydroxy-2-naphthoic acid (24, 2.77 g, 13.6 mmol) and K₂CO₃ (14.01 g, 101.4 mmol) were added to a flame-dried 250 mL round bottom flask followed by dry acetone (120.0 mL) and MeI (13.0 mL, 209 mmol) at room temperature. A water-jacketed reflux condenser was attached and the reaction was heated under reflux for 12 hours. The reaction was then cooled, filtered, and the solvent was removed under reduced pressure. The brown residue was then resuspended in CH₂Cl₂, dried over MgSO₄, filtered, and condensed. The resulting brown oil/solid was then purified by either flash chromatography (7:13 EtOAc:hexanes) or recrystallized from Et₂O/hexanes to afford 25 (3.19 g, 13.0 mmol, 96%) as brown granular crystals.

R_f = 0.44 (3:17 EtOAc:hexanes)

mp = 50 – 52 °C (Lit. 48 – 50 °C)²²

¹H NMR (CDCl₃): δ 3.98 (s, 3H); 3.99 (s, 3H); 4.00 (s, 3H); 7.14 (s, 1H); 7.57 (m, 2H); 8.22 (m, 2H)



1,4-dimethoxy-2-hydroxymethylnaphthalene (26):

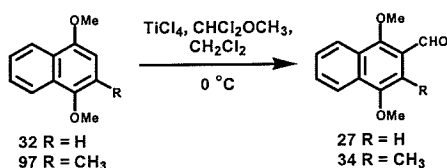
According to the procedure by Flader et al.,²² lithium aluminum hydride (0.855 g, 21.4 mmol) was added to a flame-dried 250 mL round bottom flask under argon to which dry THF (150.0 mL) was added at room temperature. Ester 25 (5.05 g, 20.5 mmol) was then dissolved in THF (50.0 mL) and added slowly at room temperature under argon, and the reaction was stirred at room temperature for 8 hours. The reaction was then quenched by adding H₂O (1.0 mL) dropwise at 0 °C, followed by 2 M NaOH (2.0 mL), and then H₂O (3.0 mL). The resulting suspension was then filtered and the filtrate was acidified with dilute HCl, washed with saturated brine, dried over MgSO₄, and filtered. The condensed filtrate resulted in a crude solid that could be purified by flash column chromatography (7:13 EtOAc:hexanes) or recrystallization from Et₂O/hexanes to afford 26 (4.34 g, 19.9 mmol, 97%) as long white needles.

R_f = 0.30 (7:13 EtOAc:hexanes)

mp = 66 – 68 °C (Lit. 69 - 70 °C)²²

¹H NMR (CDCl₃): δ 2.29 (broad s, 1H); 3.89 (s, 3H); 3.96 (s, 3H); 4.86 (s, 2H); 6.79 (s, 1H); 7.49 (m, 2H); 8.01 (dd, 1H, J = 1.2, 7.5 Hz); 8.21 (dd, 1H, J = 1.2, 7.5 Hz)

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1,4-dimethoxy-2-naphthaldehyde (27):

Method A:

10 Following a modified procedure of Ito et al.,²⁴ to a flame-dried 50 mL round bottom flask was added 32 (1.34 g, 7.12 mmol) dissolved in CH_2Cl_2 (10.0 mL) and then cooled to 0°C under Argon. Then TiCl_4 (1 M in CH_2Cl_2 , 8.0 mL, 8.0 mmol) was added slowly at 0°C followed by α,α -dichloromethyl methyl ether (0.71 mL, 8.0 mmol) at 0°C . The reaction was stirred at 0°C for 3 hours and the poured into water and stirred for 10 minutes at room temperature. The reaction was then extracted with EtOAc, washed with saturated brine, dried over MgSO_4 , filtered, and condensed. The resulting oil was purified using flash chromatography (CH_2Cl_2) to provide 27 (1.43 g, 6.62 mmol, 93%) as a white solid that was recrystallized from Et_2O :hexanes to provide white needles.

20 Alternatively, α,α -dichloromethyl methyl ether was added to CH_2Cl_2 in a flame-dried round bottom flask 0°C . TiCl_4 was added at 0°C and stirred for 5 minutes. Then 32 was added at 0°C dissolved in CH_2Cl_2 and the reaction was stirred at 0°C for 4 hrs. The reaction was then poured into water and stirred for 10 minutes at room temperature. The reaction was extracted with EtOAc, washed with saturated brine, dried over MgSO_4 , filtered, and condensed.

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Method B:

To a flame dried 50 mL round bottom flask was added phosphorousoxychloride (5.0 mL, 55 mmol) and then *N*-methylformanilide (4.9 mL, 54 mmol) at room temperature. The colorless clear solution became a pale yellow

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solution over 10 minutes at room temperature, and then solid 32 (4.99 g, 40.5 mmol) was added to the reaction at room temperature, and the residual 32 was added dissolved in CH_2Cl_2 (2.0 mL). The reaction quickly became orange and too thick to stir. After 12 h at room temperature CH_2Cl_2 was added (5 x 5.0 mL) in portions over a 4 hour period to resume stirring while keeping the reaction concentrated. After 30 hours a sample was removed, treated with water, dried, and analyzed by TLC (1:3 EtOAc:hexanes) and ^1H NMR to determine no remaining starting material. The orange suspension was then diluted with CH_2Cl_2 to a final volume of 150 mL, and the red solution was treated with ice and stirred for 2 hours. The organic layer was then separated, washed with brine, dried over MgSO_4 , filtered, and condensed. The resulting tan solid was then suspended in acetone (75.0 mL) and brought to a boil at which point the solution was clear/brown. Boiling hexane was added to a total volume of 125 mL and the solution was cooled to room temperature and then to 20°C . Tan needles were collected and 27 (4.77 g, 22.1 mmol, 83%) was determined pure by NMR.

$$R_f = 0.62 (\text{CH}_2\text{Cl}_2)$$

$$\text{mp} = 108 - 109^\circ\text{C} (\text{Lit. } 120 - 121^\circ\text{C})^{23}$$

^1H NMR (CDCl_3): δ 4.01 (s, 3H); 4.08 (s, 3H); 7.11 (s, 1H); 7.62 (m, 2H); 8.23 (m, 2H); 10.56 (s, 1H)

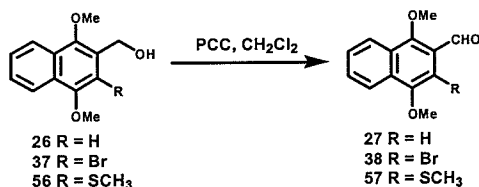
1,4-dimethoxy-3-methyl-2-naphthaldehyde (34):

Compound 34 was prepared from 97 (1.90 g, 9.39 mmol) as described above for 27 following method A to give 1.490 g (6.47 mmol, 69%) of the product as a white solid that was recrystallized from Et_2O /hexanes to provide white needles.

$$R_f = 0.57 (3:7 \text{ EtOAc:hexanes})$$

$$\text{mp} = 78 - 80^\circ\text{C} (\text{Lit. } 83.5 - 93.7^\circ\text{C})^{24}$$

^1H NMR (CDCl_3): δ 2.63 (s, 3H); 3.85 (s, 3H); 4.05 (s, 3H); 7.59 (dt, 2H, $J = 7.2, 33.3$ Hz); 8.14 (dd, 2H, $J = 8.4, 26.1$ Hz)



1,4-dimethoxy-2-naphthaldehyde (27):

Pyridinium chlorochromate (PCC, 1.04 g, 4.8 mmol) was added to a flame-dried 100 mL round bottom flask followed by dry CH₂Cl₂ (25.0 mL) at room temperature under Argon. Alcohol 26 (0.607 g, 2.78 mmol) was dissolved in CH₂Cl₂ (5.0 mL) and added slowly at room temperature. The reaction was stirred for a further 12 h at room temperature before being poured into a slurry of fluoricil, MgSO₄, and CH₂Cl₂. After stirring the suspension was filtered through celite and condensed. The resulting solid was purified by flash column chromatography (CH₂Cl₂) to provide 27 (0.510 g, 2.36 mmol, 85%) as white needles. The product was also purified by recrystallization in Et₂O:hexanes if no starting material was present.

R_f = 0.62 (CH₂Cl₂)

mp = 108 – 109 °C (Lit. 120 - 121 °C)²³

¹H NMR (CDCl₃): δ 4.01 (s, 3H); 4.08 (s, 3H); 7.11 (s, 1H); 7.62 (m, 2H); 8.23 (m, 2H); 10.56 (s, 1H)

3-bromo-1,4-dimethoxy-2-naphthaldehyde (38):

Compound 38 was prepared from 37 (1.85 g, 6.24 mmol) as described above for 27 to give 1.61 g (5.47 mmol, 88%) of the product as a white needles following flash chromatography (3:17 EtOAc:hexanes). The product was also purified by recrystallization in Et₂O/hexanes if no starting material was present.

R_f = 0.29 (1:9 EtOAc:hexanes)

mp = 99 – 100 °C (Lit. 110 °C)³⁸

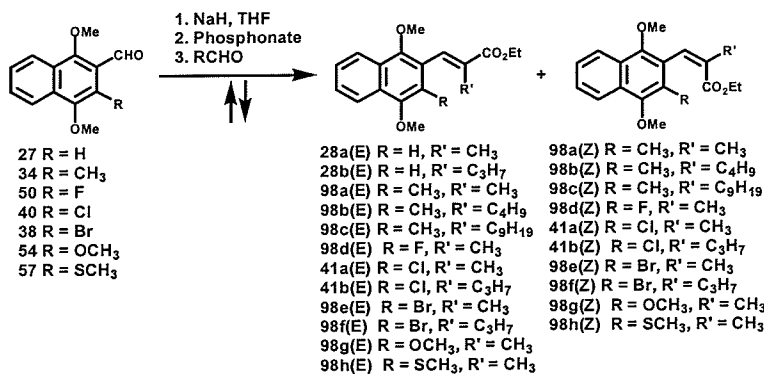
¹H NMR (CDCl₃): δ 3.98 (s, 3H); 4.05 (s, 3H); 7.65 (m, 2H); 8.18 (dd, 2H, J = 8.1, 33 Hz); 10.53 (s, 1H)

1,4-Dimethoxy-3-methylsulfonyl-2-naphthaldehyde (57):

Compound 57 was prepared from 56 (0.514 g, 1.94 mmol) as described above for 27 to give 0.308 g (1.17 mmol, 62%) of the product as a yellow oil/solid following flash chromatography (1:9 EtOAc:hexanes).

R_f = 0.26 (1:9 EtOAc:hexanes)

¹H NMR (CDCl₃): δ 2.47 (s, 3H); 4.01 (s, 3H); 4.04 (s, 3H); 7.62 (m, 2H); 8.13 (d, 1H, J = 8.1 Hz); 8.21 (d, 1H, J = 8.1 Hz); 10.70 (s, 1H)



Ethyl (*E*)-3-(1,4-dimethoxynaphthalen-2-yl)-2-methylpropenoate (28a):

According to the modified procedure of Murphy et al.,²⁶ NaH (0.303 g, 7.59 mmol) was added to a flame-dried 50 mL round bottom flask connected to a water-jacketed reflux condenser. The flask was purged with Argon and a drying tube was attached to the top. Toluene (20.0 mL) was added to the flask followed by phosphonate (1.0 mL, 4.6 mmol) at room temperature. The reaction was heated under reflux for 30 minutes, and aldehyde 27 (0.542 g, 2.51 mmol) was dissolved in toluene (5.0 mL) and added slowly at reflux. The reaction was heated for another 8 h under reflux. The reaction was then cooled to room temperature, diluted with ethyl acetate, and washed with brine. The organic layer was dried, filtered, and condensed. The resulting oil was purified via flash column chromatography (<1:19 iPr₂O:hexanes) and recrystallized from Et₂O/hexanes to provide pure 28a (0.554 g, 1.84 mmol, 73%) as a colorless oil.

R_f = 0.30 (1:19 iPr₂O:hexanes, 4 developments)

E:Z = 20:1 in refluxing toluene

¹H NMR (CDCl₃): δ 1.36 (t, 3H, J = 7.2 Hz); 2.10 (d, 3H, J = 1.2 Hz); 3.91 (s, 3H); 3.96 (s, 3H); 4.29 (q, 2H, J = 7.2 Hz); 6.70 (s, 1H); 7.51 (m, 2H); 7.96 (d, 1H, J = 1.2 Hz); 8.152 (m, 2H)

Ethyl (*E*)-3-(1,4-dimethoxynaphthalen-2-yl)-2-propylpropenoate (28b):

Compound 28b was prepared from 27 (0.495 g, 2.29 mmol) as described above for 28a to give 0.443 g (1.35 mmol, 59%) of the product as a white solid following flash chromatography (1:19 Et₂O:hexanes) and recrystallization from Et₂O/hexanes.

R_f = 0.35 (1:19 i-Pr₂O:hexanes, 4 developments)

E:Z = 20:1 at -78 °C

mp = 36 – 38 °C

¹H NMR (CDCl₃): δ 0.94 (t, 3H, J = 7.2 Hz); 1.36 (t, 3H, J = 7.2 Hz);
1.60 (m, 2H); 2.53 (m, 2H); 3.84 (s, 3H); 3.96 (s, 3H); 4.29 (q, 2H, J = 7.2 Hz); 6.71
5 (s, 1H); 7.51 (m, 2H); 7.96 (s, 1H); 8.09 (dd, 1H, J = 1.2, 7.5 Hz); 8.21 (dd, 1H, J =
1.8, 7.5 Hz)

Ethyl (E)-3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-methylpropenoate

(41a):

10 Compound 41a was prepared from 40 (2.93 g, 11.7 mmol) as described
above for 28a to give 2.56 g (7.65 mmol, 65%) of the product as a yellow solid
following flash chromatography (1:19 Et₂O:hexanes) and recrystallization from
Et₂O/hexanes. (1.50 g E, yellow solid; 0.960 g E/Z, gold oil; 0.101 g Z, gold solid)
R_f = E = 0.32; Z = 0.24 (1:19 iPr₂O:hexanes, 4 developments)

15 E:Z = 15:5 in refluxing toluene

mp = 108 – 109 °C

¹H NMR (CDCl₃): □ 1.37 (t, 3H, J = 7.2 Hz); 1.83 (s, 3H); 3.75 (s,
3H); 3.98 (s, 3H); 4.30 (q, 2H, J = 7.2); 7.55 (m, 2H); 7.68 (s, 1H); 8.11 (m, 2H)

20 Ethyl (E)-3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-propylpropenoate

(41b):

Compound 41b was prepared from 40 (0.261 g, 1.04 mmol) as
described above for 28a to give 0.115 g (0.32 mmol, 32%) of the product as a yellow
solid following flash chromatography (1:19 Et₂O:hexanes) and recrystallization from
25 Et₂O/hexanes. (0.057 g E; 0.098 g E/Z)

R_f = E = 0.31; Z = 0.23 (1:19 i-Pr₂O:hexanes, 4 developments)

E:Z = 15:5 in refluxing toluene

¹H NMR (CDCl₃): δ 0.72 (t, 3H, J = 7.5); 1.36 (t, 3H, J = 7.2); 1.41 (m,
2H); 2.22 (m, 2H); 3.77 (s, 3H); 3.98 (s, 3H); 4.30 (q, 2H, J = 7.2); 7.55 (m, 2H); 7.57
30 (s, 1H); 8.11 (m, 2H)

Ethyl (E)-3-(1,4-dimethoxy-3-methylnaphthalen-2-yl)-2-methylpropenoate

(98a):

Compound 98a was prepared from 34 (0.506 g, 2.20 mmol) as described above for 28a to give 0.541 g (1.42 mmol, 65%) of the product as a colorless oil following flash chromatography (1:19 *i*-Pr₂O:hexanes).

$R_f = E = 0.22$; $Z = 0.15$ (1:19 *i*-Pr₂O:hexanes, 4 developments)

5 $E:Z = 20:1$ in refluxing toluene.

¹H NMR (CDCl₃): δ 1.36 (t, 3H, $J = 7.2$ Hz); 1.79 (s, 3H); 2.28 (s, 3H); 3.73 (s, 3H); 3.87 (s, 3H); 4.30 (q, 2H, $J = 7.2$ Hz); 7.49 (m, 2H); 7.70 (s, 1H); 8.07 (m, 2H)

10 Ethyl (*E*)-3-(1,4-dimethoxy-3-methylnaphthalen-2-yl)-2-butylpropenoate (98b):

Compound 98b was prepared from 34 (0.383 g, 1.67 mmol) as described above for 28a to give 0.209 g (0.58 mmol, 34%) of the product as a colorless oil following flash chromatography (1:9 EtOAc:hexanes) and

15 recrystallization from Et₂O/hexanes.

$R_f = E = 0.37$; $Z = 0.27$ (1:19 *i*-Pr₂O:hexanes, 4 developments)

$E:Z = 20:1$ in refluxing toluene

¹H NMR (CDCl₃): δ 0.70 (t, 3H, $J = 7.2$ Hz); 1.11 (m, 2H); 1.31 (m, 2H); 1.36 (t, 3H, $J = 7.2$ Hz); 2.21 (m, 2H); 2.28 (s, 3H); 3.75 (s, 3H); 3.86 (s, 3H);
20 4.29 (q, 2H, $J = 7.2$ Hz); 7.49 (m, 2H); 7.59 (s, 1H); 8.08 (m, 2H)

Ethyl (*E*)-3-(1,4-dimethoxy-3-methylnaphthalen-2-yl)-2-nonylpropenoate (98c):

Compound 98c was prepared from 34 (0.479 g, 2.08 mmol) as described above for 28a to give 0.373 g (0.874 mmol, 41%) of the product as a yellow oil following flash chromatography (1:9 EtOAc:hexanes).

$R_f = 0.29$ (1:19 *i*-Pr₂O:hexanes, 4 developments)

$E:Z = 20:1$ in refluxing toluene

¹H NMR (CDCl₃): δ 0.81 (t, 3H, $J = 6.9$ Hz); 1.07 (m, 10H); 1.29 (m, 4H); 1.36 (t, 3H, $J = 7.2$ Hz); 2.20 (t, 2 hexanes, $J = 7.2$ Hz); 2.28 (s, 3H); 3.75 (s, 3H); 3.87 (s, 3H); 4.30 (q, 2H, $J = 7.2$ Hz); 7.48 (m, 2H); 7.59 (s, 1H); 8.08 (m, 2H)
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Ethyl (*E*)-3-(1,4-dimethoxy-3-fluoronaphthalen-2-yl)-2-methylpropeonoate

(98d):

Compound 98d was prepared from 50 (0.216 g, 0.922 mmol) as described above for 28a to give 0.226 g (0.710 mmol, 77%) of the product as a yellow oil following flash chromatography (1:19 Et₂O:hexanes). (0.093 g pure *E*; 0.128 g *E/Z*; 0.005 g *Z*)

R_f = *E* = 0.25; *Z* = 0.17 (1:19 Et₂O:hexanes, 3 developments)

E:Z = 5:1 in refluxing toluene

¹H NMR (CDCl₃): δ 1.36 (t, 3H, *J* = 7.2 Hz); 1.91 (t, 3H, *J* = 1.8 Hz); 3.80 (s, 3H); 4.05 (d, 3H, *J* = 1.2 Hz); 4.30 (q, 2H, *J* = 7.2 Hz); 7.51 (m, 2H); 7.67 (s, 1H); 8.09 (dd, 1H, *J* = 1.2, 7.5 Hz); 8.14 (dd, 1H, *J* = 1.2, 7.5 Hz)

¹⁹F NMR (CDCl₃): δ -137.41 (s, 1F)

Ethyl (*E*)-3-(3-bromo-1,4-dimethoxynaphthalen-2-yl)-2-methylpropenoate

(98e):

Compound 98e was prepared from 38 (0.515 g, 1.75 mmol) as described above for 28a to give 0.373 g (0.984 mmol, 56%) of the product as a white solid following flash chromatography (1:19 i-Pr₂O:hexanes) and recrystallization from Et₂O/hexanes. (0.314 g *E*; 0.059 g *Z*)

R_f = *E* = 0.26; *Z* = 0.19 (1:19 i-Pr₂O:hexanes, 4 developments)

E:Z = 17:3 in refluxing toluene

mp = 102 – 103 °C

¹H NMR (CDCl₃): δ 1.37 (t, 3H, 7.2 Hz); 1.81 (d, 3H, *J* = 1.2 Hz); 3.74 (s, 3H); 3.97 (s, 3H); 4.31 (q, 2H, *J* = 7.2 Hz); 7.56 (m, 2H); 7.65 (d, 1H, *J* = 1.2 Hz); 8.11 (m, 2H)

Ethyl (*E*)-3-(3-bromo-1,4-dimethoxynaphthalen-2-yl)-2-propylpropenoate

(98f):

Compound 98f was prepared from 38 (0.514 g, 1.75 mmol) as described above for 28a to give 0.346 g (0.849 mmol, 49%) of the product as a yellow solid following flash chromatography (1:19 Et₂O:hexanes) and recrystallization from Et₂O/hexanes. (0.291 g *E*; 0.055 g *Z*)

R_f = *E* = 0.33; *Z* = 0.23 (1:19 i-Pr₂O:hexanes, 4 developments)

E:Z = 17:3 in refluxing toluene

mp = 89 – 90 °C

¹H NMR (CDCl₃): δ 0.72 (t, 3H, J = 7.2 Hz); 1.36 (t, 3H, J = 6.9 Hz);
1.40 (m, 2H); 2.21 (m, 2H); 3.76 (s, 3H); 3.97 (s, 3H); 4.30 (q, 2H, J = 7.2 Hz); 7.54
5 (s, 1H); 7.56 (m, 2H); 8.11 (m, 2H)

Ethyl (E)-3-(1,3,4-trimethoxynaphthalen-2-yl)-2-methylpropenoate (98g):

Compound 98g was prepared from 54 (0.330 g, 1.33 mmol) as
described above for 28a to give 0.119 g (0.360 mmol, 27%) of the product as a yellow
10 oil following flash chromatography (1:9 Et₂O:hexanes) and recrystallization from
Et₂O/hexanes. (E/Z fractions discarded)

R_f = E = 0.17; Z = 0.11 (1:19 i-Pr₂O:hexanes, 4 developments)

E:Z = 11:9 in refluxing toluene

¹H NMR (CDCl₃): δ 1.36 (t, 3H, J = 7.2 Hz); 1.87 (d, 3H, J = 1.5 Hz);
15 3.75 (s, 3H); 3.87 (s, 3H); 3.98 (s, 3H); 4.29 (q, 2H, J = 7.2 Hz); 7.47 (m, 2H); 7.73
(d, 1H, J = 1.5 Hz); 8.09 (m, 2H)

Ethyl (E)-3-(1,4-dimethoxy-3-methylsulfanylnaphthalen-2-yl)-2-methylpropenoate (98h):

20 Compound 98h was prepared from 57 (0.308 g, 1.17 mmol) as
described above for 28a to give 0.231 g (0.667 mmol, 55%) of the product as an
amorphous yellow solid following flash chromatography (1:9 EtOAc:hexanes) and
recrystallization from Et₂O/hexanes. (0.165 g E; 0.065 g E/Z)

R_f = 0.26 (1:9 EtOAc:hexanes)

25 E:Z = 7:3 in refluxing toluene

¹H NMR (CDCl₃): □ 1.37 (t, 3H, J = 7.2 Hz); 1.82 (s, 3H); 2.37 (s,
3H); 3.72 (s, 3H); 4.00 (s, 3H); 4.30 (q, 2H, J = 7.2 Hz); 7.54 (m, 2H); 7.86 (s, 1H);
8.10 (m, 2H)

Z Isomers:

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Ethyl (3Z)-3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-methylpropenoate ((Z)-41a):

Compound (Z)-41a was prepared from 40 (2.93 g, 11.7 mmol) as described above for 28a to give 2.56 g (7.65 mmol, 65%) of the product as a yellow solid following flash chromatography (1:19 Et₂O:hexanes) and recrystallization from Et₂O/hexanes. (1.50 g E, yellow solid; 0.959 g E/Z, gold oil; 0.101 g Z, gold solid)

5 $R_f = 0.24$ (1:19 i-Pr₂O:hexanes, 4 developments)

E:Z = 15:5 in refluxing toluene

mp = 122 – 128 °C

¹H NMR (CDCl₃): δ 0.81 (t, 3H, J = 7.2 Hz); 2.20 (d, 3H, J = 1.8 Hz);
3.77 (s, 3H); 3.96 (q, 2H, J = 7.2 Hz); 3.96 (s, 3H); 6.83 (d, 1H, J = 1.5 Hz); 7.50 (m,
10 2H); 8.06 (m, 2H)

Ethyl (3Z)-3-(1,4-dimethoxy-3-fluoronaphthalen-2-yl)-2-methylpropenoate ((Z)-98d):

Compound (Z)-98d was prepared from 50 (0.216 g, 0.922 mmol) as described above for 28a to give 0.226 g (0.710 mmol, 77%) of the product as a yellow solid following flash chromatography (1:19 Et₂O:hexanes). (0.093 g pure E; 0.128 g E/Z; 0.0047 g Z)

$R_f = 0.17$ (1:19 iPr₂O:hexanes)

mp = 37 – 39 °C

20 E:Z = 17:3 in refluxing toluene

¹H NMR (CDCl₃): δ 0.97 (t, 3H, J = 7.2 Hz); 2.20 (d, 3H, J = 1.5 Hz);
3.83 (s, 3H); 4.01 (d, 3H, J = 1.2 Hz); 4.05 (, 2H, J = 7.2 Hz); 6.79 (d, 1H, J = 1.5
Hz); 7.47 (m, 2H); 8.08 (m, 2H)

¹⁹F NMR (CDCl₃): δ -138.93 (s, 1F)

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Ethyl (3Z)-3-(1,4-dimethoxy-3-methylsulfanylnaphthalen-2-yl)-2-methylpropenoate ((Z)-98h, NO REFERENCE):

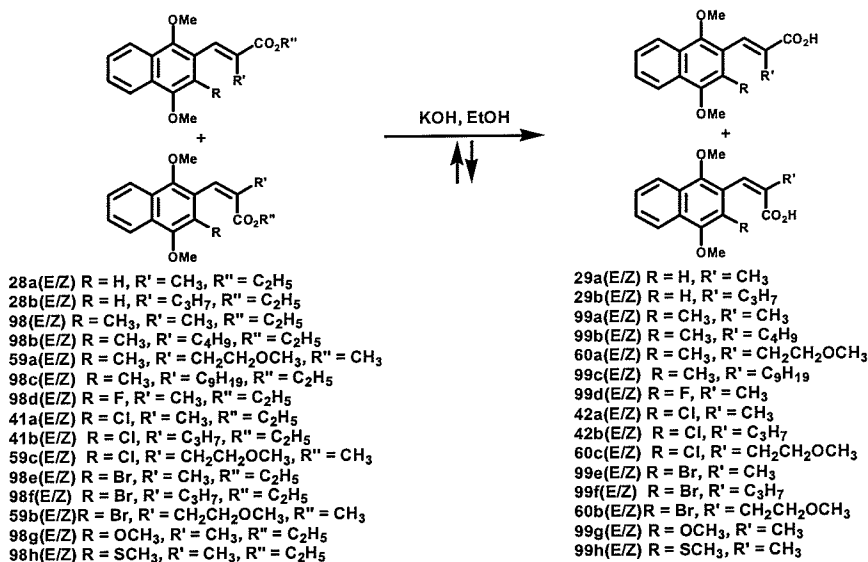
Compound (Z)-98h was prepared from 57 (0.308 g, 1.17 mmol) as described above for 28a to give 0.2306 g (0.667 mmol, 55%) of the product as an amorphous yellow solid following flash chromatography (1:9 EtOAc:hexanes). (0.165 g E; 0.065 g E/Z)

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$R_f = 0.26$ (1:9 EtOAc:hexanes)

E:Z = 7:3 in refluxing toluene

$^1\text{H NMR}$ (CDCl_3): δ 0.78 (t, 3H, $J = 7.2$ Hz); 2.20 (d, 3H, $J = 1.8$ Hz); 2.38 (s, 3H); 3.72 (s, 3H); 3.93 (q, 2H, $J = 7.2$ Hz); 3.99 (s, 3H); 6.99 (d, 1H, $J = 1.5$ Hz); 7.48 (m, 2H); 8.05 (m, 2H)



5

(E)-3-(1,4-dimethoxynaphthalen-2-yl)-2-methylpropenoic acid (29a):

Emmons ester 28a (0.231 g, 0.769 mmol) was dissolved in EtOH (10.0 mL) and then KOH (0.400 g, 7.13 mmol) was added to the reaction. The reaction was then heated to boiling and stirred at this temperature for 30 minutes. The reaction was then cooled, acidified, and extracted with ethyl acetate. The organic layer was washed with brine, dried over MgSO₄, filtered, and condensed. The resulting acid was then used as crude, or can be purified via flash chromatography (1:3 EtOAc:hexanes 0.5% AcOH) or recrystallization from Et₂O/hexanes to provide 29a (0.175 g, 0.643 mmol, 83%) as a white solid.

15

$R_f = 0.24$ (1:3 EtOAc:hexanes 0.5% AcOH)

mp = 149 – 155 °C

$^1\text{H NMR}$ (CDCl_3): δ 2.16 (d, 3H, $J = 1.2$); 3.86 (s, 3H); 3.99 (s, 3H); 6.75 (s, 1H); 7.53 (m, 2H); 8.15 (d, 1H, $J = 1.2$ Hz); 8.17 (m, 2H)

20

(E)-3-(1,4-dimethoxynaphthalen-2-yl)-2-propylpropenoic acid (29b):

Compound 29b was prepared from 28b (0.215 g, 0.656 mmol) as described above for 29a to give 0.193 g (0.642 mmol, 99%) of the product as a white

solid following flash chromatography (1:3 EtOAc:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

$R_f = 0.24$ (1:3 EtOAc:hexanes 0.5% AcOH)

mp = 139 – 141.5 °C

5 ¹H NMR (CDCl₃): δ 0.98 (t, 3H, J = 7.2 Hz); 1.67 (m, 2H); 2.58 (m, 2H); 3.87 (s, 3H); 3.99 (s, 3H); 6.76 (s, 1H); 7.53 (m, 2H); 8.11 (m, 1H); 8.16 (s, 1H); 8.22 (m, 2H)

(E)-3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-methylpropenoic acid (42a):

10 Compound 42a was prepared from 41a (0.959 g, 2.90 mmol) as described above for 29a to give 0.872 g (2.84 mmol, 98%) of the product as a tan solid following flash chromatography (3:17 acetone:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

$R_f = 0.08$ (3:17 acetone:hexanes 0.5% AcOH)

15 mp = 155 – 157 °C

¹H NMR (CDCl₃): δ 1.88 (s, 3H); 3.77 (s, 3H); 3.99 (s, 3H); 7.58 (m, 2H); 7.85 (s, 1H); 8.123 (m, 2H)

¹³C NMR (CDCl₃): δ 14.7, 61.4, 62.0, 122.2, 123.0, 124.2, 126.8, 127.5, 127.7, 129.0, 132.1, 135.0, 148.7, 150.7, 172.3

20

(E)-3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-propylpropenoic acid (42b):

25 Compound 42b was prepared from 41b (0.028 g, 0.077 mmol) as described above for 29a to give 0.026 g (0.077 mmol, 100%) of the product as a red solid following flash chromatography (1:3 EtOAc:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

$R_f = 0.19$ (1:3 EtOAc:hexanes 0.5% AcOH)

mp = 188 – 190 °C

¹H NMR (CDCl₃): δ 0.74 (t, 3H, J = 7.2 Hz); 1.44 (m, 2H); 2.26 (m, 3H); 3.79 (s, 3H); 3.989 (s, 3H); 7.56 (m, 2H); 7.75 (s, 1H); 8.13 (m, 2H)

30

(E)-3-(1,4-dimethoxy-3-methylnaphthalen-2-yl)-2-methoxyethylpropenoic acid (60a):

Compound 60a was prepared from 59a (0.104 g, 0.302 mmol) as described above for 29a to give 0.076 g (0.23 mmol, 77%) of the product as a tan solid following flash chromatography (1:3 EtOAc:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

5 R_f = 0.10 (1:3 EtOAc:hexanes 0.5% AcOH)
 mp = 145 – 148 °C
 ¹H NMR (CDCl₃): δ 2.30 (s, 3H); 2.57 (t, 2H, J = 6.6 Hz); 3.17 (s, 3H);
3.44 (t, 2H, J = 6.6 Hz); 3.77 (s, 3H); 3.88 (s, 3H); 7.50 (m, 2H); 7.86 (s, 1H); 8.08
(dt, 2H, J = 8.4, 1.2 Hz)

10

(E)-3-(3-bromo-1,4-dimethoxynaphthalen-2-yl)-2-methoxyethylpropenoic acid (60b):

Compound 60b was prepared from 59b (0.179 g, 0.437 mmol) as described above for 29a to give 0.060 g (0.15 mmol, 35%) of the product as a tan solid following flash chromatography (1:3 EtOAc:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

15

 R_f = 0.12 (1:3 EtOAc:hexanes 0.5% AcOH)
 mp = 158 – 160 °C
 ¹H NMR (CDCl₃): δ 2.57 (t, 3H, J = 6.3 Hz); 3.27 (s, 3H); 3.45 (t, 3H,
20 J = 6.3 Hz); 3.79 (s, 3H); 3.98 (s, 3H); 7.57 (m, 2H); 7.72 (s, 1H); 8.12 (m, 2H)

(E)-3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-methoxyethylpropenoic acid (60c):

Compound 60c was prepared from 59c (0.064 g, 0.17 mmol) as described above for 29a to give 0.067 g (0.19 mmol, 112%) of the product as a tan solid following flash chromatography (1:3 EtOAc:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

25

 R_f = 0.12 (1:3 EtOAc:hexanes 0.5% AcOH)
 mp = 145 – 146 °C
30 ¹H NMR (CDCl₃): δ 2.60 (t, 2H, J = 6.6 Hz); 3.21 (s, 3H); 3.45 (t, 2H,
J = 6.6 Hz); 3.80 (s, 3H); 3.98 (s, 3H); 7.56 (m, 2H); 7.80 (s, 1H); 8.11 (m, 2H)

(E)-3-(1,4-dimethoxy-3-methylnaphthalen-2-yl)-2-methylpropenoic acid

(99a):

Compound 99a was prepared from 98a (0.176 g, 0.560 mmol) as described above for 29a to give 0.134 g (0.468 mmol, 83%) of the product as a light
5 yellow solid following flash chromatography (3:17 acetone:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

R_f = 0.20 (1:3 EtOAc:hexanes 0.5% AcOH)

mp = 153 – 155 °C

¹H NMR (CDCl₃): δ 1.80 (s, 3H); 3.75 (s, 3H); 3.89 (s, 3H); 7.51 (m,
10 2H); 7.72 (s, 1H); 8.09 (m, 2H)

(E)-3-(1,4-dimethoxy-3-methylnaphthalen-2-yl)-2-butylpropenoic acid (99b):

Compound 99b was prepared from 98b (0.148 g, 0.415 mmol) as described above for 29a to give 0.154 g (0.469 mmol, 113%) of the product as a white
15 solid following flash chromatography (1:3 EtOAc:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

R_f = 0.24 (1:3 EtOAc:hexanes 0.5% AcOH)

mp = 133 – 134 °C

¹H NMR (CDCl₃): δ 0.70 (t, 3H, J = 7.2 Hz); 1.13 (m, 2H); 1.38 (m,
20 2H); 2.26 (m, 2H); 2.31 (s, 3H); 3.77 (s, 3H); 3.88 (s, 3H); 7.51 (m, 2H); 7.78 (s, 1H);
8.10 (m, 2H)

(E)-3-(1,4-dimethoxy-3-methylnaphthalen-2-yl)-2-nonylpropenoic acid (99c):

Compound 99c was prepared from 98c (0.164 g, 0.384 mmol) as described above for 29a to give 0.152 g (0.381 mmol, 96%) of the product as a
25 colorless oil following flash chromatography (1:3 EtOAc:hexanes 0.5% AcOH).

R_f = 0.33 (1:3 EtOAc:hexanes 0.5% AcOH)

¹H NMR (CDCl₃): δ 0.81 (t, 3H, J = 7.2 Hz); 1.07 (m, 10H); 1.18 (m,
2H); 1.37 (m, 2H); 2.24 (m, 2H); 2.30 (s, 3H); 3.77 (s, 3H); 3.88 (s, 3H); 7.50 (m,
30 2H); 7.77 (s, 1H); 8.09 (m, 2H)

(E)-3-(1,4-dimethoxy-3-fluoronaphthalen-2-yl)-2-methylpropenoic acid (99d):

Compound 99d was prepared from 98d (0.128 g, 0.402 mmol) as described above for 29a to give 0.097 g (0.33 mmol, 83%) of the product as a white solid following flash chromatography (1:4 acetone:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

- 5 $R_f = 0.13$ (1:4 acetone:hexanes 0.5% AcOH)
 mp = 157 – 158.5 °C
 ¹H NMR (CDCl₃): δ 1.93 (d, 3H, J = 1.5 Hz); 3.82 (s, 3H); 4.06 (d, 3H, J = 1.5 Hz); 7.52 (m, 2H); 7.83 (d, 1H, J = 1.2 Hz); 8.10 (d, 1H, J = 8.4 Hz); 8.15 (d, 1H, J = 8.4 Hz)
10 ¹⁹F NMR (CDCl₃): δ -137.38 (s, 1F)

(E)-3-(3-bromo-1,4-dimethoxynaphthalen-2-yl)-2-methylpropenoic acid (99e):

- Compound 99e was prepared from 98e (0.314 g, 0.828 mmol) as described above for 29a to give 0.291 g (0.829 mmol, 100%) of the product as a white solid following recrystallization from Et₂O/hexanes.

- 15 $R_f = 0.32$ (1:1 Et₂O:hexanes 0.5% AcOH)
 mp = 143 – 145 °C
 ¹H NMR (CDCl₃): δ 1.86 (d, 3H, J = 1.2 Hz); 3.77 (s, 3H); 3.99 (s, 3H); 7.57 (m, 2H); 7.82 (d, 1H, J = 1.2 Hz); 8.13 (m, 2H)

20

(E)-3-(3-bromo-1,4-dimethoxynaphthalen-2-yl)-2-propylpropenoic acid (99f):

- Compound 99f was prepared from 98f (0.177 g, 0.435 mmol) as described above for 29a to give 0.078 g (0.21 mmol, 47%) of the product as a white solid following flash chromatography (1:3 EtOAc:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

- 25 $R_f = 0.19$ (1:3 EtOAc:hexanes 0.5% AcOH)
 mp = 187 – 194 °C
 ¹H NMR (CDCl₃): δ 0.74 (t, 3H, J = 7.2 Hz); 1.45 (m, 2H); 2.25 (m, 2H); 3.79 (s, 3H); 3.98 (s, 3H); 7.57 (m, 2H); 7.71 (s, 1H); 8.13 (m, 2H)

30

(E)-3-(1,3,4-trimethoxynaphthalen-2-yl)-2-methylpropenoic acid (99g):

Compound 99g was prepared from 98g (0.073 g, 0.22 mmol) as described above for 29a to give 0.068 g (0.22 mmol, 100%) of the product as a tan

solid following flash chromatography (1:3 EtOAc:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

R_f = 0.13 (1:3 EtOAc:hexanes 0.5% AcOH)

mp = 119 – 123 °C

5 ¹H NMR (CDCl₃): δ 1.91 (s, 3H); 3.77 (s, 3H); 3.89 (s, 3H); 3.99 (s, 3H); 7.49 (m, 2H); 7.91 (s, 1H); 8.10 (t, 2H, J = 6.6 Hz)

(E)-3-(1,4-dimethoxy-3-methylsulfonylnaphthalen-2-yl)-2-methylpropenoic acid (99h):

10 Compound 99h was prepared from 98h (0.165 g, 0.476 mmol) as described above for 29a to give 0.181 g (0.568 mmol, 118%) of the product as a orange solid following flash chromatography (1:3 EtOAc:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

R_f = 0.18 (1:3 EtOAc:hexanes 0.5% AcOH)

15 mp = XX – XX °C

¹H NMR (CDCl₃): δ 1.82 (d, 3H, J = 1.2 Hz); 2.37 (s, 3H); 3.72 (s, 3H); 4.00 (s, 3H); 7.51 (m, 2H); 7.99 (d, 1H, J = 1.2 Hz); 8.07 (m, 2H)

Z Isomers:

20 (3Z)-3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-methylpropenoic acid ((Z)-42a):

25 Compound (Z)-42a was prepared from (Z)-41a (0.959 g, 2.90 mmol) as described above for 29a to give 0.872 g (2.84 mmol, 99%) of the product as a yellow solid following flash chromatography (3:17 acetone:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

R_f = 0.08 (3:17 acetone:hexanes 0.5% AcOH)

mp = 145 – 155 °C

¹H NMR (CDCl₃): δ 2.20 (d, 3H, J = 1.5 Hz); 3.77 (s, 3H); 3.90 (s, 3H); 6.89 (q, 1H, J = 1.5 Hz); 7.50 (m, 2H); 8.04 (m, 2H)

30 ¹³C NMR (CDCl₃): δ 20.8, 61.3, 61.7, 122.2, 122.8, 125.9, 126.5, 127.1, 127.3, 128.6, 131.1, 132.6, 148.6, 149.9, 171.0

(3Z)-3-(1,4-dimethoxy-3-fluoronaphthalen-2-yl)-2-methylpropenoic acid ((Z)99d):

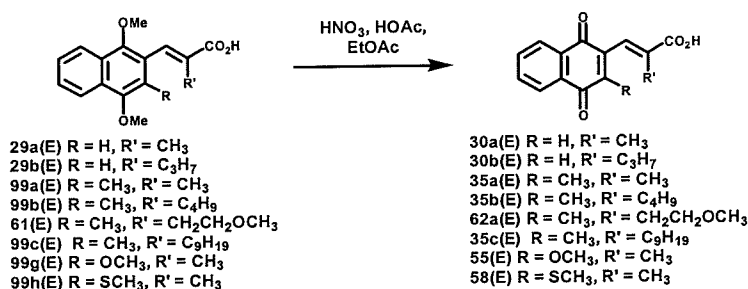
Compound (Z)-99d was prepared from (Z)-98e (0.128 g, 0.402 mmol) as described above for 29a to give 0.097 g (0.33 mmol, 83%) of the product as a white solid following flash chromatography (1:4 acetone:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

R_f = 0.13 (1:4 acetone:hexanes 0.5% AcOH)

mp = XX – XX °C

¹H NMR (CDCl₃): 2.23 (d, 3H, J = 1.5 Hz); 3.86 (s, 3H); 4.00 (d, 3H, J = 1.2 Hz); 6.92 (d, 1H, J = 1.5 Hz); 7.49 (m, 2H); 8.11 (two d, 2 H, buried under E isomer)

¹⁹F NMR (CDCl₃): δ -138.26 (s, 1F)

(E)-3-(1,4-naphthoquinon-2-yl)-2-methylpropenoic acid (30a):

Following modified procedures of Shinkawa et al. and Flader et al.,^{16,22} the acid 29a (0.114 g, 0.419 mmol) was dissolved in ethyl acetate (10 mL) at room temperature, then HNO₃ (1.0 mL) and AcOH (3 drops) were added at room temperature. The reaction was stirred at room temperature for 4 hours before being diluted with ethyl acetate and washed with brine. The organic layer was dried over MgSO₄, filtered, and condensed. The yellow oil was then purified by either flash column chromatography (2:3 Et₂O:hexanes 0.5% AcOH) or recrystallization from Et₂O/hexanes to afford 30a (0.059 g, 0.24 mmol, 58%) as a yellow solid.

Alternatively the reaction can be run as a mixture of E and Z isomers under the same conditions. Following workup the mixture will be the E acid and the Z methyl ester from an intramolecular esterification event taking place with the oxonium intermediate. Separation via flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH) was necessary to separate the ester and acid components.

$R_f = 0.43$ (2:3 Et₂O:hexanes 0.5% AcOH)

mp = 205 °C d

¹H NMR (CDCl₃): δ 2.13 (d, 3H, J = 1.2 Hz); 6.99 (s, 1H); 7.79 (m, 3H); 8.11 (m, 2H)

5 ¹H NMR (acetone-D₆): δ 2.15 (d, 3H, J = 1.5 Hz); 7.06 (s, 1H); 7.72 (m, 1H); 7.89 (m, 2H); 8.09 (m, 2H)

¹H NMR (DMSO-D₆): δ 2.04 (s, 3H); 7.06 (s, 1H); 7.52 (d, 1H, J = 1.5 Hz); 7.90 (m, 2H); 8.04 (m, 2H)

10 (E)-3-(1,4-naphthoquinon-2-yl)-2-propylpropenoic acid (30b):

Compound 30b was prepared from 29b (0.193 g, 0.643 mmol) as described above for 30a to give 0.064 g (0.24 mmol, 37%) of the product as a yellow solid following flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes. (0.064 g E; 0.006 g Z methyl ester)

15 $R_f = 0.60$ (2:3 Et₂O:hexanes 0.5% AcOH)

mp = 156 – 160 °C

¹H NMR (CDCl₃): δ 0.97 (t, 3H, J = 7.5 Hz); 1.58 (m, 2H); 2.46 (m, 2H); 6.94 (d, 1H, J = 1.2Hz); 7.77 (m, 3H); 8.12 (m, 2H)

20 (E)-3-(3-methyl-1,4-naphthoquinon-2-yl)-2-methylpropenoic acid (35a):

Compound 35a was prepared from 99a (0.083 g, 0.29 mmol) as described above for 30a to give 0.048 g (0.19 mmol, 65%) of the product as a yellow solid following flash chromatography (3:17 acetone:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

25 $R_f = 0.30$ (2:3 Et₂O:hexanes)

mp = 195 – 196 °C

elemental analysis: calculated C(70.31%), H(4.72%); found C(69.93%), H(4.79%)

30 ¹H NMR (CDCl₃): δ 1.81 (bs, 3H, J = 1.2 Hz); 2.11 (bs, 3H, J = 1.2 Hz); 7.58 (m, 1H, J = 1.2, 1.2 Hz); 7.73 (m, 2H); 8.09 (m, 2H)

(E)-3-(3-methyl-1,4-naphthoquinon-2-yl)-2-butylpropenoic acid (35b):

Compound 35b was prepared from 99b (0.148 g, 0.45 mmol) as described above for 30a to give 0.050 g (0.17 mmol, 37%) of the product as a yellow solid following flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

5 $R_f = 0.47$ (2:3 Et₂O:hexanes 0.5% AcOH)

mp = 119 – 121 °C

¹H NMR (CDCl₃): δ 0.78 (t, 3H, J = 7.2 Hz); 1.20 (m, 2H); 1.41 (m, 2H); 2.12 (d, 3H, J = 1.5 Hz); 2.16 (m, 2H); 7.46 (d, 1H, J = 1.5 Hz); 7.73 (m, 2H); 8.10 (m, 2H)

10

(E)-3-(3-methyl-1,4-naphthoquinon-2-yl)-2-nonylpropenoic acid (35c):

Compound 35c was prepared from 99c (0.152 g, 0.381 mmol) as described above for 30a to give 0.050 g (0.14 mmol, 36%) of the product as a yellow solid following flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

15

$R_f = 0.60$ (2:3 Et₂O:hexanes 0.5% AcOH)

mp = 64 – 66 °C

¹H NMR (CDCl₃): δ 0.81 (t, 3H, J = 6.9 Hz); 1.18 (m, 15H); 1.42 (m, 2H); 2.12 (d, 3H, J = 1.5 Hz); 2.14 (m, 2H); 7.46 (d, 1H, J = 1.5 Hz); 7.73 (m, 2H); 8.10 (m, 2H)

20

(E)-3-(3-methoxy-1,4-naphthoquinon-2-yl)-2-methylpropenoic acid (55):

Compound 58 was prepared from 99g (0.060 g, 0.20 mmol) as described above for 30a to give 0.015 g (0.05 mmol, 27%) of the product as a yellow solid following flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

25

$R_f = 0.43$ (2:3 Et₂O:hexanes 0.5% AcOH)

mp = 205 °C d

¹H NMR (CDCl₃): δ 1.83 (d, 3H, J = 1.5 Hz); 4.15 (s, 3H); 7.53 (d, 1H, J = 1.5 Hz); 7.73 (m (5), 2H); 8.08 (m, 2H)

30

(E)-3-(3-methylsulfanyl-1,4-naphthoquinon-2-yl)-2-methylpropenoic acid

(58):

Compound 55 was prepared from 99h (0.180 g, 0.565 mmol) as described above for 30a to give 0.063 g (0.22 mmol, 38%) of the product as a red fluffy solid following flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

5 $R_f = 0.45$ (2:3 Et₂O:hexanes 0.5% AcOH)

mp = 195 – 196 °C

¹H NMR (CDCl₃): δ 1.81 (d, 3H, J = 1.2 Hz); 2.58 (s, 3H); 7.56 (d, 1H, J = 1.2 Hz); 7.72 (m, 2H); 8.09 (m, 2H)

10 (E)-3-(3-methyl-1,4-naphthoquinon-2-yl)-2-methoxyethylpropenoic acid (62a):

Compound 62a was prepared from 61a (0.076 g, 0.23 mmol) as described above for 30a to give 0.049 g (0.16 mmol, 70%) of the product as a yellow solid following flash chromatography (2:3 Et₂O:hexanes 0.5% AcOH) and

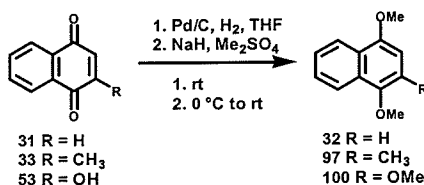
15 recrystallization from Et₂O/hexanes.

$R_f = 0.45$ (2:3 Et₂O:hexanes 0.5% AcOH)

mp = 147 – 148 °C

elemental analysis: calculated C(67.99%), H(5.37%); found C(68.10%), H(5.51%)

20 ¹H NMR (CDCl₃): δ 2.12 (d, 3H, J = 1.2 Hz); 2.45 (t, 2H, J = 6.6 Hz); 3.20 (s, 3H); 3.44 (t, 2H, J = 6.6 Hz); 7.53 (d, 1H, J = 1.2 Hz); 7.73 (m, 2H); 8.09 (m, 2H)



25

1,4-dimethoxynaphthalene (32):

Following the procedure of Evans et al.,²³ 1,4-naphthoquinone (31, 10.00 g, 63.20 mmol) and Pd/C (10 wt%, 0.994 g) were added to a flame-dried 500 mL round bottom flask at room temperature under Argon. THF (250.0 mL) was then added at room temperature, the reaction vessel was covered in foil, and then purged

30

with H₂ for 10 minutes. A balloon filled with H₂ was attached and the reaction stirred for 4 hrs at room temperature. The reaction was then purged with Argon before adding NaH (5.66 g, 142 mmol) slowly at 0 °C. After 10 minutes Me₂SO₄ (13.0 mL, 137 mmol) was added slowly at 0 °C. The reaction became too thick to stir after
5 adding Me₂SO₄, and 50 mL of THF were added to facilitate stirring. The dark green mixture was allowed to stir at room temperature for 4 hrs. The reaction was then filtered through celite, washed with brine, dried over MgSO₄, and condensed. The resulting solid was then purified by flash chromatography (EtOAc:hexanes) or recrystallized from Et₂O:hexanes to provide 32 (11.74 g, 62.42 mmol, 99%) as pink
10 needles.

R_f = 0.76 (CH₂Cl₂)

mp = 74 – 78 °C (Lit. 84 – 86 °C)²³

¹H NMR (CDCl₃): δ 3.95 (s, 6H); 6.69 (s, 2H), 7.50 (m, 2H); 8.20 (m, 2H)

15

1,4-dimethoxy-2-methylnaphthalene (97):

Compound 97 was prepared from 33 (3.54 g, 20.6 mmol) as described above for 32 to give 4.02 g (19.9 mmol, 97%) of the product as a low melting white solid following flash chromatography (1:19 EtOAc:hexanes).

20

R_f = 0.60 (3:7 EtOAc:hexanes)

mp = 29 – 31 °C (Literature 35.9 – 36.3)²⁴

¹H NMR (CDCl₃): δ 2.43 (s, 3H); 3.85 (s, 3H); 3.95 (s, 3H); 7.45 (dt, 2H, J = 7.2, 27.3 Hz); 8.09 (dd, 2H, J = 8.4, 50.1 Hz)

25

1,2,4-trimethoxynaphthalene (100):

Compound 100 was prepared from 53 (5.23 g, 33.3 mmol) as described above for 32 to give 5.19 g (23.8 mmol, 71%) of the product as a red oil that solidified in the freezer.

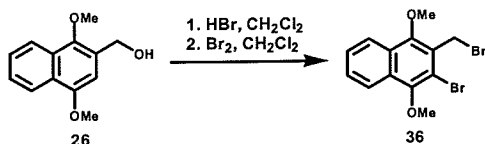
R_f = 0.17 (1:9 EtOAc:hexanes); 0.50 (CH₂Cl₂)

30

Mp = oil (Lit. 38 – 40 °C)³⁸

¹H NMR (CDCl₃): δ 3.91 (s, 3H); 3.98 (s, 3H); 3.99 (s, 3H); 6.63 (s, 1H); 7.40 (m, 2 H); 8.09 (dd, 2 H, J = 8.4, 30.9 Hz)

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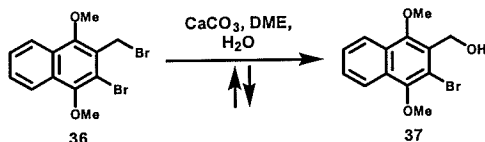
2-bromo-3-bromomethyl-1,4-dimethoxynaphthalene (36):

Alcohol 26 (9.80 g, 45.0 mmol) was dissolved in CH₂Cl₂ (150.0 mL) in a flame-dried 500 mL round bottom flask. Concentrated HBr (22.0 mL) was added to displace the alcohol, the solution was stirred for 2 h at room temperature. The reaction was then diluted with CH₂Cl₂ (300.0 mL) and Br₂ (2.40 mL, 47.7 mmol) was added dropwise dissolved in CH₂Cl₂ (50.0 mL) at room temperature. The reaction was stirred for 6 hours further before being washed with brine, dried over MgSO₄, and filtered. The resulting solid was purified using flash column chromatography (1:19 EtOAc:hexanes) to provide 36 (9.02 g, 25.1 mmol, 56%) as a yellow powder.

R_f = 0.46 (3:17 EtOAc:hexanes)

mp = 81 – 83 °C (Lit. 85 °C)⁴⁰

¹H NMR (CDCl₃): δ 3.98 (s, 3H); 4.08 (s, 3H); 4.92 (s, 2H); 7.56 (m, 2H); 8.08 (m, 2H)



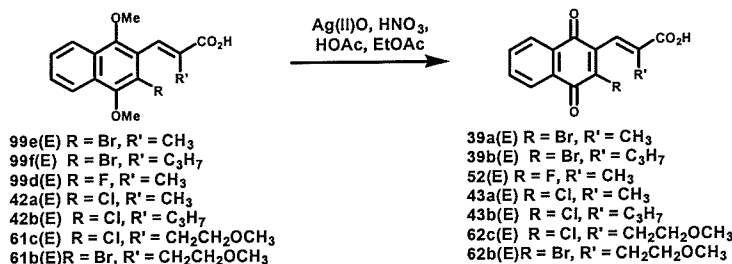
2-bromo-1,4-dimethoxy-3-hydroxymethylnaphthalene (37):

Following a modified procedure of Smith et al.,²⁵ dibromide 36 (1.73 g, 4.80 mmol) was dissolved in 1,2-dimethoxyethane (50.0 mL), and then added to CaCO₃ (2.50 g, 25.0 mmol) in H₂O (50.0 mL) at room temperature. The reaction was heated under reflux for TIME and then cooled to room temperature. The reaction was extracted with EtOAc (75.0 mL), and the organic layers are washed with brine. The organic layer was dried over MgSO₄ and filtered. The resulting pink solid was then purified by flash column chromatography (1:3 EtOAc:hexanes) to provide 37 (1.49 g, 5.01 mmol, 105%) as a pink solid.

R_f = 0.26 (1:3 EtOAc:hexanes)

mp = 93 – 96 °C (Lit. 116 – 117 °C)²²

$^1\text{H NMR}$ (CDCl_3): δ 3.97 (s, 3H); 4.00 (s, 3H); 5.01 (s, 2H); 7.55 (m, 2H); 8.09 (m, 2H)



5

(E)-3-(3-bromo-1,4-naphthoquinon-2-yl)-2-methylpropenoic acid (39a):

Following a modified procedure of Shinkawa et al. and Flader et al.,^{16,22} the acid 99e (0.291 g, 0.829 mmol) was dissolved in ethyl acetate (10.0 mL) at room temperature, then HNO₃ (1.0 mL) and AcOH (6 drops) are added at room temperature. Silver (II) oxide (0.379 g, 3.05 mmol) was then added and the reaction was stirred vigorously at room temperature for 1 hour before being filtered through a pasture pipette and cotton plug, washing the solid with ethyl acetate, and then washing the organic layer with brine. The organic layer was dried over MgSO₄, filtered, and condensed. The yellow oil was then purified by either flash column chromatography (1:1 Et₂O:hexanes 0.5% AcOH) or recrystallization from Et₂O/hexanes to afford 39a (0.122 g 0.380 mmol, 46%) as a yellow solid.

Alternatively the reaction can be run as a mixture of E and Z isomers under the same conditions. Following workup the mixture will be the E acid and the Z methyl ester from an intramolecular esterification event taking place with the oxonium intermediate. Separation via flash chromatography (1:1 Et₂O:hexanes 0.5% AcOH) was necessary to separate the ester and acid components.

R_f = 0.32 (1:1 Et₂O:hexanes 0.5% AcOH)

mp = 186 – 189 °C

elemental analysis: calculated C(52.36%), H(2.28%); found

25 C(52.50%), H(4.01%)

$^1\text{H NMR}$ (CDCl_3): δ 1.85 (d, 3H, J = 1.2 Hz); 7.33 (m, 1H); 7.91 (m, 2H); 8.14 (m, 2H)

(E)-3-(3-bromo-1,4-naphthoquinon-2-yl)-2-propylpropenoic acid (39b):

Compound 39b was prepared from 99f (0.078 g, 0.21 mmol) as described above for 39a to give 0.033 g (0.10 mmol, 46%) of the product as a yellow solid following flash chromatography (3:7 acetone:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

5 R_f = 0.22 (3:7 acetone:hexanes 0.5% AcOH)
 mp = 145 °C d
 ¹H NMR (CDCl₃): δ 0.81 (t, 3H, J = 7.2 Hz); 1.48 (m, 2H); 2.18 (dd, 1H, J = 7.5, 9.3 Hz); 7.29 (s, 1H); 7.79 (m, 2H); 8.13 (m, 1H); 8.20 (m, 1H)

10 (E)-3-(3-chloro-1,4-naphthoquinon-2-yl)-2-methylpropenoic acid (43a):

Compound 43a was prepared from 42a (0.872 g, 2.84 mmol) as described above for 39a to give 0.121 g (0.437 mmol, 16%) of the product as a yellow solid following flash chromatography (2:3 acetone:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes. (0.121 g E; 0.115 g Z methyl ester)

15 R_f = 0.44 (2:3 acetone:hexanes 0.5% AcOH)
 mp = 229 – 230 °C
 elemental analysis: calculated C(60.78%), H(3.28%); found C(60.48%), H(3.40%)
 ¹H NMR (CDCl₃): δ 1.87 (d, 3H, J = 1.5 Hz); 7.45 (d, 1H, J = 1.5 Hz);
20 7.79 (m, 2H); 8.13 (m, 1H); 8.19 (m, 1H)

(E)-3-(3-chloro-1,4-naphthoquinon-2-yl)-2-propylpropenoic acid (43b):

Compound 43b was prepared from 42b (0.053 g, 0.16 mmol) as described above for 39a to give 0.016 g (0.05 mmol, 33%) of the product as a yellow
25 solid following flash chromatography (2:3 acetone:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

 R_f = 0.47 (2:3 acetone:hexanes 0.5% AcOH)
 mp = 164 °C d
 ¹H NMR (CDCl₃): δ 0.81 (t, 3H, J = 7.5 Hz); 1.50 (m, 2H); 2.19 (t, 2H,
30 J = 7.5 Hz); 7.36 (s, 1H); 7.79 (m, 2H); 8.14 (m, 1H); 8.20 (m, 1H)

(E)-3-(3-fluoro-1,4-naphthoquinon-2-yl)-2-methylpropenoic acid (52):

Compound 52 was prepared from 99d (0.097 g, 0.33 mmol) as described above for 39a to give 0.020 g (0.08 mmol, 23%) of the product as a yellow solid following flash chromatography (3:17 acetone:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes. (0.020 g E; 0.015 g E starting material; 0.023 g Z methyl ester)

R_f = 0.08 (1:4 EtOAc:hexanes 0.5 % AcOH)

mp = 185 - 190 °C d

¹H NMR (CDCl₃): δ 1.94 (d, 3H, J = 3.9 Hz); 7.45 (s, 1H); 7.80 (m, 2H); 8.15 (m, 2H)

¹H NMR (DMSO): δ 1.83 (d, 3H, J = 3.9 Hz); 7.15 (s, 1H); 7.91 (m, 2H); 8.06 (m, 2H)

¹⁹F NMR (CDCl₃): δ -109.67 (s, 1F)

(E)-3-(3-bromo-1,4-naphthoquinon-2-yl)-2-methoxyethylpropenoic acid

15 (62b):

Compound 62b was prepared from 61b (0.060 g, 0.15 mmol) as described above for 39a to give 0.029 g (0.08 mmol, 53%) of the product as a yellow solid following flash chromatography (2:3 acetone:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

20 R_f = 0.45 (2:3 acetone:hexanes 0.5% AcOH)

mp = 168 - 172 °C

elemental analysis: calculated C(52.62%), H(3.59%); found C(53.57%), H(3.59%)

¹H NMR (CDCl₃): δ 2.52 (t, 2H, J = 6.6 Hz); 3.18 (s, 3H); 3.46 (t, 2H, J = 6.6 Hz); 7.41 (s, 1H); 7.78 (m, 2H); 8.12 (m, 1H); 8.19 (m, 1H)

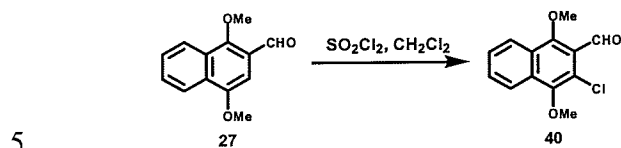
(E)-3-(3-chloro-1,4-naphthoquinon-2-yl)-2-methoxyethylpropenoic acid (62c):

Compound 62c was prepared from 61c (0.067 g, 0.19 mmol) as described above for 39a to give 0.032 g (0.10 mmol, 53%) of the product as a yellow solid following flash chromatography (2:3 acetone:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes.

R_f = 0.48 (2:3 acetone:hexanes 0.5% AcOH)

mp = 160 °C d

$^1\text{H NMR}$ (CDCl_3): δ 2.52 (t, 2H, $J = 6.3$ Hz); 3.17 (s, 3H); 3.45 (t, 2H, $J = 6.3$ Hz); 7.47 (s, 1H); 7.78 (m, 2H); 8.12 (m, 1H); 8.18 (m, 1H)



3-Chloro-1,4-dimethoxy-2-naphthaldehyde (40):

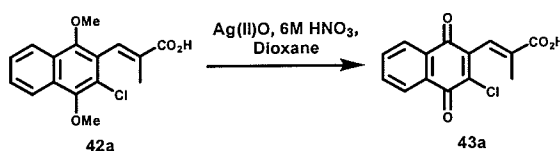
Following a general aromatic chlorination procedure by Lopez-Alvarado³⁹, aldehyde 27 (2.12 g, 9.81 mmol) was dissolved in CH_2Cl_2 (15.0 mL) at room temperature in a flame-dried 50 mL round bottom flask under argon and a drying tube. Neat SO_2Cl_2 (0.92 mL, 11 mmol) was added at room temperature and the Argon line was removed. After 20 h the reaction was complete by NMR, and the reaction was diluted with CH_2Cl_2 (50.0 mL), washed with brine, dried over MgSO_4 , and filtered. The resulting solid was purified by flash chromatography (1:1 CH_2Cl_2 :hexanes) to provide 40 (1.63 g, 6.52 mmol, 66%) as white needles.

15 $R_f = 0.21$ (1:1 CH_2Cl_2 :hexanes)

mp = 94 – 96 °C

$^1\text{H NMR}$ (CDCl_3): δ 3.99 (s, 3H); 4.05 (s, 3H); 7.64 (m, 2H); 8.17 (dd, 2H, $J = 8.4, 33$ Hz); 10.61 (s, 1H)

20



(E)-3-(3-chloro-1,4-naphthoquinon-2-yl)-2-methylpropenoic acid (43a):

Following a modified procedure by Snyder et al.,³³ dimethoxynaphthalene 42a (0.146 g, 0.476 mmol) and Ag(II)O (0.434 g, 3.51 mmol) were combined in a 5 mL round bottom flask and suspended in dioxane (1.5 mL). To the black suspension was added 6 M HNO_3 (1.0 mL, 6.0 mmol) at room temperature. The black Ag(II)O quickly dissolved with gas evolution resulting in a yellow solute with yellow precipitate. The reaction was stirred for 10 minutes at room temperature and TLC showed no starting material present. The suspension was first filtered and

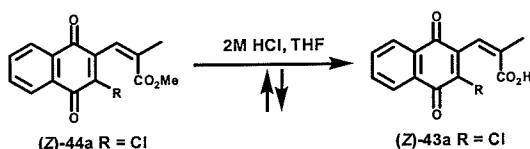
the filter cake was suspended in CH_2Cl_2 , treated with water, separated, washed with brine, dried, filtered, and condensed. The yellow reaction filtrate was likewise diluted with CH_2Cl_2 , treated with water, separated, washed with brine, dried over MgSO_4 , filtered, and condensed. The filter cake provided pure 43a that was then purified by

5 recrystallization from acetone/hexane (0.0601 g, 0.22 mmol, 47%). The filtrate provided a less pure 43a that was first purified by flash chromatography (1:4 EtOAc:hexanes 0.5 % AcOH) and then recrystallized from acetone/hexane (0.027 g, 0.099 mmol, 21%).

$R_f = 0.44$ (2:3 acetone:hexanes 0.5% AcOH)

10 $mp = 229 - 230^\circ\text{C}$

$^1\text{H NMR}$ (CDCl_3): δ 1.87 (d, 3H, $J = 1.5$ Hz); 7.45 (d, 1H, $J = 1.5$ Hz); 7.79 (m, 2H); 8.13 (m, 1H); 8.19 (m, 1H)



15 (2Z)-3-(3-chloro-1,4-naphthoquinon-2-yl)-2-methylpropenoic acid ((Z)-43a):

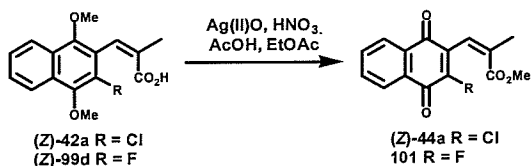
Methyl ester 44a (0.100 g, 0.344 mmol) was suspended in EtOH (3.0 mL), then 2 M HCl (10.0 mL) was added and the reaction was heated under reflux for 24 h. After TLC suggested all starting material was consumed the reaction was cooled to room temperature, diluted with brine, and extracted twice with CH_2Cl_2 . The

20 organic fractions were washed with brine, dried over MgSO_4 , filtered and condensed. The resulting acid was then separated from remaining starting material via flash column chromatography (1:9 EtOAc:hexanes 0 to 0.5% AcOH) to provide (Z)-43a (0.046 g, 0.16 mmol, 49%) as a fluffy yellow solid that was recrystallized from acetone:hexanes.

25 $R_f = 0.20$ (1:3 EtOAc:hexanes 0.5% AcOH)

$mp = 166 - 169^\circ\text{C}$

$^1\text{H NMR}$ (CDCl_3): δ 2.19 (d, 3H, $J = 1.5$ Hz); 6.58 (d, 1H, $J = 1.5$ Hz); 7.73 (m, 2H); 8.06 (m, 1H); 8.14 (m, 1H)



Methyl (2Z)-3-(3-chloro-1,4-naphthoquinon-2-yl)-2-methylpropenoate ((Z)-44a):

Following a modified procedure of Shinkawa et al. and Flader et al.,^{16,22} the acid (Z)-42a (0.872 g, 2.84 mmol) was dissolved in ethyl acetate (10 mL) at room temperature, then HNO₃ (1.0 mL) and AcOH (6 drops) are added at room temperature. Silver (II) oxide (2.63 g, 21.2 mmol) was then added in portions and the reaction was stirred vigorously at room temperature for 1 hour before being filtered through a pipette plugged with cotton, diluted with ethyl acetate, and washed with brine. The organic layer was dried over MgSO₄, filtered, and condensed. The yellow oil was then purified by either flash column chromatography (3:17 acetone:hexanes 0.5% AcOH) or recrystallization from Et₂O/hexanes to afford (Z)-44a (0.115 g, 0.396 mmol, 14%) as a dark gold solid. (0.115 g Z methyl ester; 0.121 g E acid)

Alternatively the reaction can be run as a mixture of E and Z isomers under the same conditions. Following workup the mixture will be the E acid and the Z methyl ester from an intramolecular esterification event taking place with the oxonium intermediate. Separation via flash chromatography (3:17 acetone:hexanes 0.5% AcOH) was necessary to separate the ester and acid components.

R_f = 0.24 (3:17 acetone:hexanes 0.5% AcOH)

mp = 227 °C d

¹H NMR (CDCl₃): δ 2.21 (d, 3H, J = 1.5 Hz); 3.06 (s, 3H); 7.43 (d, 1H, J = 1.5 Hz); 7.58 (dt, 1H, J = 7.5, 0.6 Hz); 7.77 (dt, 1H, J = 7.5, 1.5 Hz); 7.95 (d, 1H, J = 7.8 Hz); 8.15 (d, 1H, J = 7.5 Hz)

Methyl (2Z)-3-(3-fluoro-1,4-naphthoquinon-2-yl)-2-methylpropenoate (101):

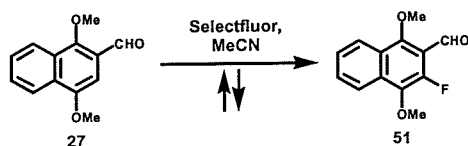
Compound 101 was prepared from (Z)-99d (0.097 g, 0.33 mmol) as described above for (Z)-43a using silver (II) oxide (0.309 g, 2.49 mmol) to give 0.023 g (0.082 mmol, 25%) of the product as a dark gold solid following flash chromatography (3:17 acetone:hexanes 0.5% AcOH) and recrystallization from Et₂O/hexanes. (0.0225 g Z; 0.0201 g E acid; 0.0151 g E starting material)

R_f = 0.32 (1:4 EtOAc:hexanes 0.5% AcOH)

mp = 118 – 120 °C

¹H NMR (CDCl₃): δ 2.18 (s, 3H); 3.07 (s, 3H); 7.32 (s, 1H); 7.60 (dt, 1H, J = 7.8, 1.5 Hz); 7.73 (dt, 1H, J = 7.8, 1.5 Hz); 7.94 (dd, 1H, J = 7.8, 1.5 Hz); 8.14 (dd, 1H, J = 7.8, 1.5 Hz)

5



1,4-Dimethoxy-3-fluoro-2-naphthaldehyde (51):

Aldehyde 27 (0.517 g, 2.39 mmol) was added to a flame-dried 50 mL round bottom flask under Argon, followed by Selectfluor (1.25 g, 3.37 mmol) and MeCN (20.0 mL). The reaction was then heated to reflux for 8 hours before being cooled and extracted with EtOAc. The organic layer was washed 3 times with brine, dried over MgSO₄, filtered, and condensed to provide the crude aldehyde as a yellow solid. Following flash chromatography (3:1 CH₂Cl₂:hexanes) aldehyde 51 (0.254 g, 1.08 mmol, 45%) was obtained as a yellow solid.

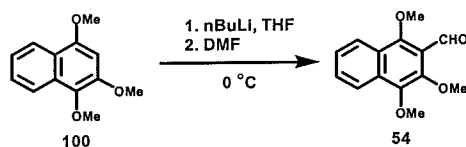
R_f = 0.36 (3:1 CH₂Cl₂:hexanes)

mp = 69 – 71 °C

¹H NMR (CDCl₃): δ 4.07 (s, 3H); 4.09 (d, 3H, J = 1.5 Hz); 7.54 (t, 1H, J = 7.8 Hz); 7.66 (t, 1H, J = 7.8 Hz); 8.18 (m, 2H); 10.54 (s, 1H)

¹⁹F NMR (CDCl₃): δ -146.26 (s, 1F)

20



1,3,4-trimethoxy-2-naphthaldehyde (54):

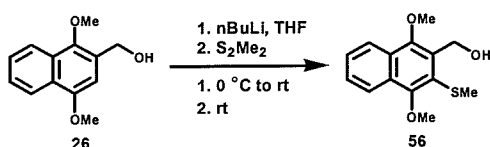
According to the procedure by Syper et al.,³⁸ 100 (1.07 g, 4.90 mmol) was dissolved in THF (20.0 mL) at 0 °C under Argon, and then nBuLi (1.6 M in hexanes, 4.0 mL, 10.0 mmol) was added at 0 °C. The reaction was stirred at 0 °C for 5 hours before DMF (0.850 mL, 11.0 mmol) was added at 0 °C. The reaction was stirred for another 30 minutes at room temperature before quenching with water. The reaction was diluted with ethyl ether and washed with saturated brine. The organic layer was dried over MgSO₄, filtered, and condensed. Crude product was used as a

5:1 mixture of product:starting material, affording 54 (1.07 g, 4.35 mmol, 89%) as a yellow oil. Following purification via column chromatography (CH_2Cl_2 to 1:9 EtOAc: CH_2Cl_2) pure aldehyde 54 was obtained as a yellow solid.

$$R_f = 0.25 \text{ (1:9 EtOAc:hexanes); } 0.20 \text{ (CH}_2\text{Cl}_2\text{)}$$

5 mp = 43 – 45 °C (Lit. 53 °C d)³⁸

¹H NMR (CDCl₃): δ 3.99 (s, 3H); 4.00 (s, 3H); 4.03 (s, 3H); 7.55 (m, 2H); 8.15 (dd, 2H, J = 8.4, 21 Hz); 10.57 (s, 1H)



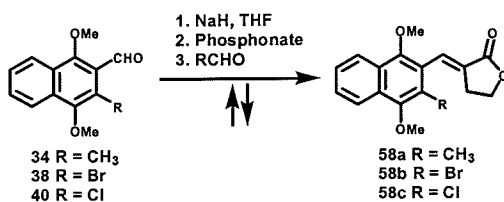
10 1,4-dimethoxy-2-hydroxymethyl-3-methylsulfanylnaphthalene (56):

Following the procedure of Flader et al.,²² alcohol 26 (0.521 g, 2.39 mmol) was dissolved in THF (9.0 ml) in a flame-dried 25 mL round bottom flask under Argon, and then cooled to 0 °C. At 0 °C nBuLi (2.5 M in hexanes, 2.4 ml, 6.0 mmol) was added slowly, then the ice bath was removed and the reaction was stirred at room temperature for 1 hour. Dimethyldisulfide (0.50 mL, 5.6 mmol) was added slowly at room temperature and the reaction was stirred for another 30 minutes at room temperature before being poured into water, acidified with 2 M HCl, and extracted with ethyl acetate. The organic fractions were combined and washed with brine, dried over MgSO₄, and filtered. The resulting solid was purified via flash column chromatography (1:4 EtOAc:hexanes) to afford 56 (0.446 g, 1.69 mmol, 71%) as a green solid.

$R_f = 0.48$ (7:13 EtOAc:hexanes)

mp = 60 – 62 °C (Lit. Oil)²²

¹H NMR (CDCl₃): δ 2.51 (s, 3H); 3.97 (s, 3H); 4.01 (s, 3H); 5.05 (s, 2H); 7.53 (m, 2H); 8.09 (m, 2H)



(E)-4'-(1,4-dimethoxy-2-methylnaphthalen-2-yl)-3-ethylidenetetrahydrofuran-2-one (58a):

According to the modified procedure of Murphy et al.,²⁶ NaH (0.269 g, 6.72 mmol) was added to a flame-dried 100 mL 3-neck round bottom flask connected to a water-jacketed reflux condenser. The flask was purged with Argon and a drying tube was attached to the top. Toluene (10.0 mL) was added to the flask followed by phosphonate (1.54 g, 6.95 mmol) dissolved in toluene (10.0 mL) at room temperature. The reaction was heated under reflux for 30 minutes, and the aldehyde (34, 0.486 g, 2.11 mmol) was dissolved in toluene (10.0 mL) and added slowly at reflux. The reaction was heated for another 8 h under reflux before being cooled to room temperature, diluted with ethyl acetate, and washed with brine. The organic layer was dried, filtered, and condensed. The resulting oil was purified via flash column chromatography (1:4 EtOAc:hexanes) and recrystallized from Et₂O/hexanes to provide 58a (0.674 g, 2.26 mmol, 107%) as a white solid.

R_f = 0.32 (1:3 EtOAc:hexanes)

E:Z = 100:0 in refluxing toluene

mp = 105 – 107 °C

¹H NMR (CDCl₃): δ 2.37 (s, 3H); 2.92 (dt, 2H, J = 7.2, 3 Hz); 3.70 (s, 3H); 3.87 (s, 3H); 4.40 (t, 2H, J = 7.2 Hz); 7.52 (m, 2H); 7.69 (t, 1H, J = 3Hz); 8.09 (m, 2H)

(E)-4'-(3-bromo-1,4-dimethoxynaphthalen-2-yl)-3-ethylidenetetrahydrofuran-2-one (58b):

Compound 58b was prepared from 38 (0.588 g, 1.99 mmol) as described above for 58a to give 0.307 g (0.845 mmol, 42%) of the product as a colorless oil following flash chromatography (3:17 EtOAc:hexanes) and recrystallization from Et₂O/hexanes.

R_f = 0.09 (1:9 EtOAc:hexanes)

E:Z = 3:1 in refluxing toluene

¹H NMR (CDCl₃): δ 2.92 (dt, 2H, J = 3, 7.2 Hz); 3.73 (s, 3H); 3.98 (s, 3H); 4.41 (t, 2H, J = 7.2 Hz); 7.59 (m, 2H); 7.74 (t, 1H, J = 3Hz); 8.12 (m, 2H)

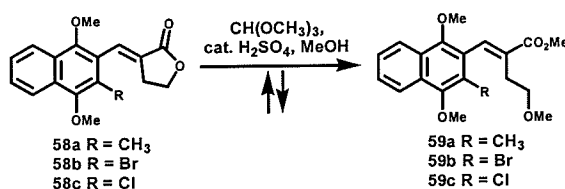
(E)-4'-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-3-ethylidenetetrahydrofuran-2-one (58c):

Compound 58c was prepared from 40 (0.484 g, 1.94 mmol) as described above for 58a to give 0.311 g (0.974 mmol, 51%) of the product as a colorless oil following flash chromatography (1:9 EtOAc:hexanes). (0.137 g E; 0.174 g E/Z)

$R_f = E = 0.13$; $Z = 0.07$ (3:37 EtOAc:hexanes, developed 4x)

E:Z = 9:1 in refluxing toluene.

$^1\text{H NMR}$ (CDCl_3): δ 2.94 (dt, 2H, $J = 7.2$, 3 Hz); 3.73 (s, 3H); 3.99 (s, 3H); 4.41 (t, 2H, $J = 7.2$ Hz); 7.58 (m, 2H); 7.77 (t, 1H, 3 Hz); 8.12 (m, 2H)



Methyl (E)-3-(1,4-dimethoxy-3-methylnaphthalen-2-yl)-2-methoxyethylpropenoate (59a):

According to a modified procedure by King et al.,²⁷ 58a (0.243 g, 0.815 mmol) was added to a flame-dried 10 mL round bottom flask under argon and a water-jacketed reflux condenser was attached. Anhydrous MeOH (3.0 mL) was then added, followed by H₂SO₄ (10 drops) and trimethyl orthoformate (0.65 mL, 8.5 mmol) at room temperature. The reaction was then heated under reflux for 12 hours, cooled to room temperature, and the solvent was removed under reduced pressure. The residue was dissolved in EtOAc, washed with saturated brine, dried over MgSO₄, filtered, and condensed. The resulting crude product was chromatographed (1:3 EtOAc:hexanes) and recrystallized from Et₂O/hexanes to provide 59a (0.249 g, 0.723 mmol, 59%) as tan crystals.

$R_f = 0.43$ (1:3 EtOAc:hexanes)

mp = 64 – 65 °C

$^1\text{H NMR}$ (CDCl_3): δ 2.28 (s, 3H); 2.55 (t, 2H, $J = 7.2$ Hz); 3.07 (s, 3H); 3.37 (t, 2H, $J = 7.2$ Hz); 3.75 (s, 3H); 3.85 (s, 3H); 3.86 (s, 3H); 7.48 (m, 2H); 7.71 (s, 3H); 8.07 (m, 2H)

Methyl (*E*)-3-(3-bromo-1,4-dimethoxynaphthalen-2-yl)-2-methoxyethylpropenoate (59b):

Compound 59b was prepared from 58b (0.257 g, 0.708 mmol) as described above for 59c to give 0.291 g (0.711 mmol, 100%) of the product as tan crystals following flash chromatography (1:3 EtOAc:hexanes) and recrystallization from Et₂O/hexanes.

$R_f = 0.42$ (1:3 EtOAc:hexanes)

mp = 66 – 67 °C

¹H NMR (CDCl₃): δ 2.57 (t, 2H, $J = 7.2$ Hz); 3.12 (s, 3H); 3.39 (t, 2H, $J = 7.2$ Hz); 3.77 (s, 3H); 3.86 (s, 3H); 3.97 (s, 3H); 7.42 (m, 2H); 7.65 (s, 1H); 8.10 (m, 2H)

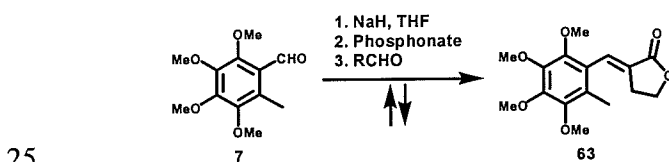
Methyl(*E*)-3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-methoxyethylpropenoate (59c):

Compound 59c was prepared from 58c (0.098 g, 0.30 mmol) as described above for 59a to give 0.064 g (0.17 mmol, 58%) of the product as tan crystals following flash chromatography (1:3 EtOAc:hexanes) and recrystallization from Et₂O/hexanes.

$R_f = 0.44$ (1:3 EtOAc:hexanes)

mp = 61 – 62 °C

¹H NMR (CDCl₃): δ 2.59 (t, 2H, $J = 7.2$ Hz); 3.12 (s, 3H); 3.39 (t, 2H, $J = 7.2$ Hz); 3.78 (s, 3H); 3.39 (s, 3H); 3.98 (s, 3H); 7.55 (m, 2H); 7.68 (s, 1H); 8.10 (m, 2H)



(*E*)-4'-(6-methyl-2,3,4,5-tetramethoxyphenyl)-3-ethylidenetetrahydrofuran-2-one (63):

According to the modified procedure of Murphy et al.,²⁶ NaH (0.210 g, 5.25 mmol) was added to a flame-dried 100 mL 3-neck round bottom flask connected to a water-jacketed reflux condenser. The flask was purged with Argon and a drying tube was attached to the top. Toluene (30.0 mL) was added to the flask followed by

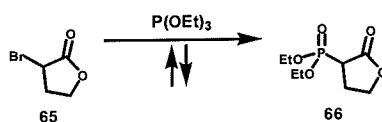
phosphonate (1.83 g, 8.2 mmol) dissolved in toluene (10.0 mL) at room temperature. The reaction was heated under reflux for 30 minutes, and the aldehyde (7, 0.501 g, 2.09 mmol) was dissolved in toluene (5.0 mL) and added slowly at reflux. The reaction was heated for another 8 h under reflux before being cooled to room temperature, diluted with ethyl acetate, and washed with brine. The organic layer was dried, filtered, and condensed. The resulting oil was purified via flash column chromatography (1:3 EtOAc:hexanes) to provide 63 (0.429 g, 1.39 mmol, 66%) as a white solid.

$R_f = 0.18$ (1:3 EtOAc:hexanes)

E:Z = 20:1 in refluxing toluene.

mp = 78 – 79 °C

$^1\text{H NMR}$ (CDCl_3): δ 2.12 (s, 3H); 2.85 (dt, 2H, $J = 7.2, 3$ Hz); 3.65 (s, 3H); 3.78 (s, 3H); 3.90 (s, 3H); 3.93 (s, 3H); 4.35 (t, 2H, $J = 7.2$ Hz); 7.48 (t, 1H, $J = 3$ Hz)



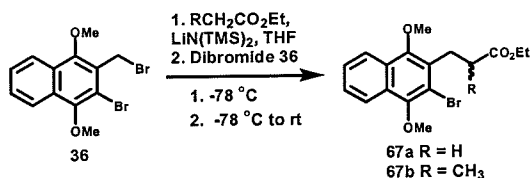
Diethyl 3-phosphonotetrahydrofuran-2-one (66):

Following the procedure by Murphy et al.²⁶ α -bromo- γ -butyro lactone (65, 3.0 mL, 32.2 mmol) was added to a flame-dried 25 mL round bottom flask followed by triethylphosphite (6.0 mL, 35 mmol). The mixture was refluxed for 4 hours and then ethyl bromide was removed under reduced pressure. The resulting oil was then purified by fractional distillation at reduced pressure to afford 66 (5.16 g, 23.2 mmol, 72%) as a colorless oil.

$R_f = 0.26$ (1:1 EtOAc:hexanes)

$^1\text{H NMR}$ (CDCl_3): δ 1.31 (dt, 6H, $J = 3, 7.2$ Hz); 2.54 (m, 2H); 3.02 (ddd, 1H, $J = 9.3, 6.3, 23.4$ Hz); 4.15 (m, 4H); 4.28 (m, 1H); 4.39 (m, 1H)

$^{31}\text{P NMR}$ (CDCl_3): δ 24.90 (s)



Ethyl 3-(3-bromo-1,4-dimethoxynaphthalen-2-yl)-propionate (67a):

Following a modified procedure of Clegg et al.,²⁸ lithium hexamethyldisilazide (LiHMDS, 1 M in THF, 1.5 ml, 1.5 mmol) was added to a flame-dried round bottom flask containing THF (20.0 mL) at -78 °C. Ethyl acetate (0.15 ml, 1.5 mmol) was then added slowly at -78 °C and stirred at -78 °C for 30 minutes. 36 (0.415 g, 1.15 mmol) was then dissolved in THF (10.0 mL) and added at -78 °C, at which point the reaction was allowed to warm to room temperature, and was stirred at room temperature for 4 h. The reaction was monitored by TLC (CH₂Cl₂) for disappearance of the less polar starting material. More LiHMDS (2.0 mL, 2.0 mmol) and EtOAc (0.70 mL, 0.70 mmol) were added and the reaction was monitored for the disappearance of starting material. When no starting material was present, 10 hours, the reaction was then poured into water, extracted with ethyl acetate, washed with brine, dried over MgSO₄, filtered, and condensed. The product was purified by column chromatography (CH₂Cl₂ to 1:19 EtOAc:CH₂Cl₂) to provide 67a (0.361g, 0.983 mmol, 86%) as a yellow oil.

$$R_f = 0.43 \text{ (CH}_2\text{Cl}_2\text{)}$$

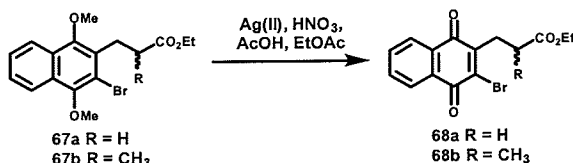
¹H NMR (CDCl₃): δ 1.26 (t, 3H, J = 7.2 Hz); 2.62 (m, 2H); 3.29 (m, 2H); 3.91 (s, 3H); 3.95 (s, 3H); 4.17 (q, 2H, J = 7.2 Hz); 7.51 (m, 2H); 8.02 (m, 1H); 8.07 (m, 1H)

Ethyl (2R/S)-3-(3-bromo-1,4-dimethoxynaphthalen-2-yl)-2-methylpropionate (67b):

Compound 67b was prepared from 36 (0.244 g, 0.678 mmol) as described above for 67a to give 0.258 g (0.678 mmol, 100%) of the product as a EtOAc following flash chromatography (1:1 to 3:1 CH₂Cl₂:hexanes).

$$R_f = 0.39 \text{ (3:1 CH}_2\text{Cl}_2\text{:hexanes)}$$

¹H NMR (CDCl₃): δ 1.15 (d, 3H, J = 7.2 Hz); 1.14 (t, 3H, J = 7.2 Hz); 2.92 (m, 1H); 3.12 (dd, 1H, J = 8.7, 13.2 Hz); 3.32 (dd, 1H, J = 6.3, 13.2 Hz); 3.87 (s, 3H); 3.95 (s, 3H); 4.09 (q, 2H, J = 7.2 Hz); 7.51 (m, 2H); 8.02 (m, 1H); 8.07 (m, 1H)



Ethyl (3-bromo-1,4-naphthoquinon-2-yl)-propionate (68a):

Following the general procedures by Shinkawa et al. and Flader et al.,^{16,22} 67a (0.361 g, 0.983 mmol) was dissolved in EtOAc (10.0 mL) and then AcOH (6 drops) and HNO₃ (1.0 mL) were added at room temperature. Then Ag(II)O (0.473 g, 3.82 mmol) was added in one portion at room temperature and stirred for 30 minutes at room temperature, the reaction was monitored by TLC (1:4 acetone:hexanes). After 30 minutes another addition of Ag(II)O (0.147 g, 1.19 mmol) was required, and the reaction stirred at room temperature for another 30 minutes. TLC showed the reaction to be complete, and the solvent was then separated from the silver solid by passing the reaction through a pipette with cotton plug, the solid was rinsed with EtOAc (4 x 5.0 mL), and then the solution was diluted with EtOAc (50.0 mL). The solution was then washed 2 times with saturated brine, dried over MgSO₄, filtered, and condensed. The crude yellow solid was recrystallized from acetone/hexane to provide 68a (0.135 g, 0.400 mmol, 41%) as a yellow solid.

$R_f = 0.44$ (1:4 acetone:hexanes)

mp = 78 – 79 °C

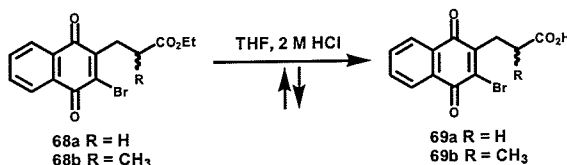
¹H NMR (CDCl₃): δ 1.23 (t, 3H, J = 7.2 Hz); 2.59 (t, 2H, J = 7.8 Hz); 3.16 (t, 2H, J = 7.8 Hz); 4.12 (q, 2H, J = 7.2 Hz); 7.74 (m, 2H); 8.13 (m, 2H)

Ethyl (2R/S)-3-(3-bromo-1,4-naphthoquinon-2-yl)-2-methylpropionate (68b):

Compound 68b was prepared from 67b (0.258 g, 0.678 mmol) as described above for 68a to give 0.064 g (0.18 mmol, 27%) of the product as a yellow solid following flash chromatography (3:1 CH₂Cl₂:hexane).

$R_f = 0.26$ (3:1 CH₂Cl₂:hexanes)

¹H NMR (CDCl₃): δ 1.12 (t, 3H, J = 7.2 Hz); 1.24 (d, 3H, J = 6.9 Hz); 2.94 (m, 2H); 3.23 (dd, 1H, J = 12.0, 7.5); 4.05 (m, 2H); 7.74 (m, 2H); 8.10 (m, 1H); 8.15 (m, 1H)



3-(3-Bromo-1,4-naphthoquinon-2-yl)-propionic acid (69a):

Ester 68a (0.108, 0.320 mmol) was dissolved in THF (5.0 mL) at room temperature and then 2 M HCl (4.0 mL) was added at room temperature. The homogeneous solution was then stirred vigorously and heated under reflux for 24 h, or until no starting material was observed by TLC (1:4 EtOAc:hexanes). The reaction was then cooled and diluted with EtOAc (30.0 mL), then washed 2 times with saturated brine, dried over MgSO_4 , filtered, and condensed. If any starting material ester was still present the resulting yellow oil was first purified via flash column chromatography (1:4 acetone:hexanes 0 to 0.5 % AcOH) followed by recrystallization from Et_2O /hexanes to provide 69a (0.077 g, 0.25 mmol, 78%) as fine yellow needles.

$R_f = 0.14$ (1:3 EtOAc:hexanes 0.5% AcOH)

Mp = 156 - 157 °C

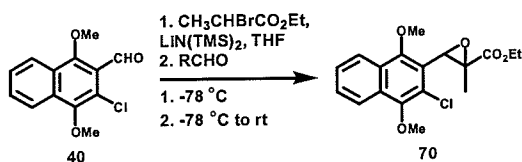
$^1\text{H NMR}$ (CDCl_3): δ 2.65 (t, 2H, $J = 7.5$ Hz); 3.15 (m, 2H); 7.74 (m, 2H); 8.13 (m, 2H)

(2R/S)-3-(3-bromo-1,4-naphthoquinon-2-yl)-2-methylpropionic acid (69b):

Compound 69b was prepared from racemic 68b (0.027 g, 0.08 mmol) as described above for 69a to give 0.016 g (0.05 mmol, 63%) of the product as a yellow solid following flash chromatography (1:4 acetone:hexanes 0 to 0.5 % AcOH) and recrystallization from Et_2O /hexanes.

$R_f = 0.10$ (1:4 acetone:hexanes 0.5% AcOH)

$^1\text{H NMR}$ (CDCl_3): δ 1.26 (d, 3H, $J = 6.3$ Hz); 3.00 (m, 2H); 3.25 (m, 1H); 7.74 (m, 2H); 8.10 (m, 1H); 8.14 (m, 1H)



Ethyl 3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-epoxy-2-methylpropionate (70):

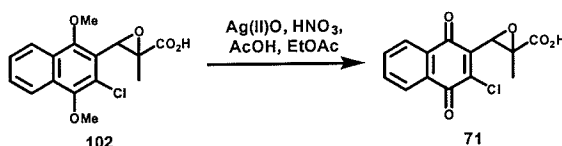
Following a modified procedure of Clegg et al.,²⁸ lithium hexamethyldisilazide (LiHMDS, 1 M in THF, 3.1 ml, 3.1 mmol) was added to a flame-dried round bottom flask containing THF (2.0 mL) at 78 °C. Ethyl 2-bromopropionate (0.28 ml, 2.1 mmol) was then added slowly at 78 °C and stirred at 78 °C for 30 minutes. 40 (0.518 g, 2.07 mmol) was then dissolved in THF (1.0 mL) and added at 78 °C, at which point the reaction was allowed to warm to room temperature, and was stirred at room temperature for 4 h. The reaction was then poured into water, extracted with ethyl acetate, washed with brine, dried over MgSO₄, filtered, and condensed. The product was purified by column chromatography (1:9 EtOAc:hexanes) to provide a racemic mixture of 4 diastereomers of 70 (0.646 g, 1.84 mmol, 89%) as a yellow oil.

$R_f = 0.12$ (1:9 EtOAc:hexanes)

¹H NMR (CDCl₃): δ

Enantiomer pair 1: 1.27 (t, 3H, J = 7.2 Hz); 1.83 (s, 3H); 3.94 (s, 3H); 4.04 (s, 3H); 4.14 (s, 1H); 4.19 (q, 2H, J = 7.2 Hz); 7.56 (m, 2H); 8.11 (m, 2H)

Enantiomer pair 2: 1.35 (t, 3 H, J = 7.2 Hz); 1.93 (s, 3H); 3.98 (s, 3H); 4.00 (s, 3H); 4.32 (q, 2H, J = 7.2 Hz); 4.43 (s, 1H); 7.56 (m, 2H); 8.11 (m, 2H)



3-(3-chloro-1,4-naphthoquinon-2-yl)-2-epoxy-2-methylpropionic acid (71):

Following a modified procedure of Shinkawa et al. and Flader et al.,^{16,22} the racemic acid mixture 102 (0.180 g, 0.558 mmol) was dissolved in ethyl acetate (10.0 mL) at room temperature, then HNO₃ (1.0 mL) and AcOH (5 drops) are added at room temperature. Silver (II) oxide (0.883 g, 7.13 mmol) was then added and the reaction was stirred vigorously at room temperature for 1 hour before being filtered through a cotton-plugged pipette, washing the solid with ethyl acetate, and then washing the organic layer with brine. The organic layer was dried over MgSO₄, filtered, and condensed. The yellow oil was then purified by either flash column

chromatography (1:1 EtOAc:hexanes 0.5% AcOH) or recrystallization from Et₂O/hexanes to afford 71 (0.033 g, 0.11 mmol, 20%) as a yellow solid.

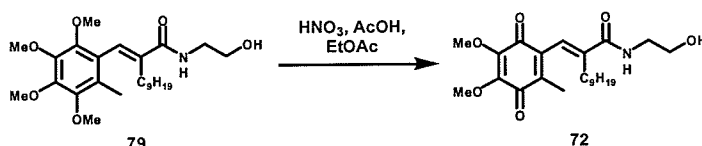
Alternatively the reaction can be run as a mixture of E and Z isomers under the same conditions. Separation of the E and Z isomers can be achieved by
5 flash chromatography (<1:1 Et₂O:hexanes 0.5% AcOH).

$R_f = 0.14$ (1:1 Et₂O:hexanes 0.5% AcOH)

¹H NMR (CDCl₃): δ

Enantiomer Pair 1: 2.15 (s, 3H); 4.28 (s, 1H); 7.80 (m, 2H); 8.12 (m, 1H); 8.18 (m, 1H)

10 Enantiomer Pair 2: 1.82 (s, 3H); 3.96 (s, 1H); 7.76 (m, 2H); 8.08 (m, 1H); 8.14 (m, 1H)



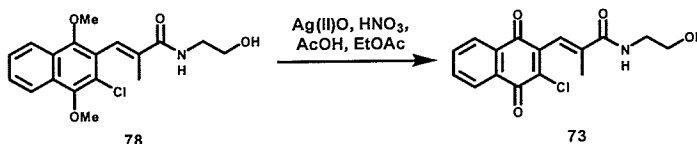
15 (E)-N-(2-hydroxyethyl)-3-(3,4-dimethoxy-2-methyl-3,6-dioxocyclohexa-1,4-dienyl)-2-nonylpropenamide (72):

Following a modified procedure of Shinkawa et al.,¹⁶ amide 79 (0.088 g, 0.20 mmol) was added to a flame-dried round bottom flask and dissolved in EtOAc (7.0 mL). Then AcOH (5 drops) and HNO₃ (0.5 mL) were added at rt and the reaction was stirred for 3 hours at room temperature. The colorless oil easily
20 dissolved in EtOAc and the reaction turned orange upon addition of HNO₃. The reaction was then diluted with EtOAc (40.0 mL), washed 3 times with brine, dried over MgSO₄, filtered, and condensed to provide an orange oil. The oil was then purified using flash chromatography (1:2 - 1:1 EtOAc:hexanes) and recrystallized from acetone/hexane to provide 72 (0.037 g, 0.09 mmol, 45%) as a red oil.

25 $R_f = 0.24$ (2:3 EtOAc:hexanes)

¹H NMR (CDCl₃): δ 0.84 (t, 3H, J = 6.6 Hz); 1.17 (m, 12 H); 1.33 (m, 2H); 1.93 (d, 3H, J = 1.2 Hz); 2.09 (t, 2H, J = 7.5 Hz); 2.51 (t, 1H, J = 5.1 Hz); 3.52 (q, 2H, J = 4.8 Hz); 3.79 (dd, 2H, J = 4.8 Hz); 3.98 (s, 3H); 4.02 (s, 3H); 6.48 (bs, 1H); 6.53 (s, 1H)

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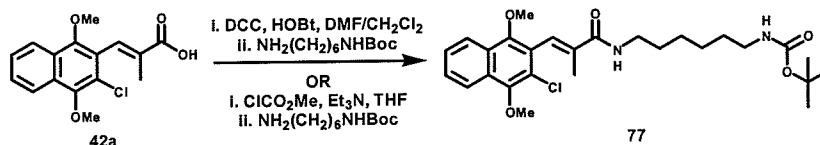
(E)-N-(2-hydroxyethyl)-3-(3-chloro-1,4-dioxonaphthoquinon-2-yl)-2-methylpropenamide (73):

Following a modified procedure of Shinkawa et al. and Flader et al.,^{16,22} amide 78 (0.050 g, 0.14 mmol) was added to a flame-dried round bottom flask and dissolved in EtOAc (15.0 mL). Then AcOH (6 drops) and HNO₃ (1.0 mL) were added at rt, followed by Ag(II)O (0.123 g, 0.993 mmol), and the reaction was stirred for 30 minutes at room temperature. The white solid did not dissolve until the addition of HNO₃, and the colorless solution immediately became a yellow/green suspension after adding Ag(II)O. The reaction was monitored by TLC (1:1 EtOAc:hexanes), after 30 minutes the reaction was not complete and more Ag(II)O (0.145 g, 1.17 mmol) was added, and the reaction was stirred for an additional 30 minutes at rt. The suspension was then filtered through a pasture pipette with a cotton plug, and the silver solid was rinsed with EtOAc. The filtrate was then diluted with EtOAc, washed 3 times with brine, dried over MgSO₄, filtered, and condensed to provide a yellow oil. The oil was then purified using flash chromatography (2:3 EtOAc:hexanes) and recrystallized from acetone/hexane to provide 73 (0.027 g, 0.084 mmol, 60%) as a yellow solid. A mixture of 5.2 mg of starting material and product also coeluted.

$R_f = 0.25$ (1:1 acetone:hexanes)

mp = 120 °C d

¹H NMR (CDCl₃): δ 1.87 (s, 3H); 2.51 (bs, 1H, OH); 3.56 (q, 2H, J = 5.1 Hz); 3.81 (m, 2H); 6.46 (bs, 1H, NH); 7.03 (s, 1H); 7.77 (m, 2H); 8.10 (m, 1H); 8.17 (m, 1H)



(E)-N-(N'-tert-butoxycarbonyl-6-aminohexyl)-3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-methylpropenamide (77):

Method A: DCC (0.070 g, 0.34 mmol) was added to a flame dried 10 mL round bottom flask under argon, and then CH_2Cl_2 (2.0 mL) was added at rt. In a second flame-dried flask under argon a solution of acid 42a (0.050 g, 0.16 mmol) and HOBt (0.006 g, 0.04 mmol) was prepared using DMF (3.0 mL) and CH_2Cl_2 (1.0 mL) at rt. The acid/HOBt solution was then added to the DCC solution at rt and stirred for 2 h before the amine (0.060 mL, 0.27 mmol) was added quickly at rt. The reaction was stirred for an additional 12 hours before being diluted with EtOAc, washed with brine, dried over MgSO_4 , filtered, and condensed. The resulting white solid, a combination of dicyclohexylurea, DCC, and product, was first suspended in approximately 5 mL CH_2Cl_2 . The suspension was then filtered through a pipette with cotton plug to remove the insoluble DCU, and the pipette was washed 2 times with 2 mL CH_2Cl_2 . The combined fractions were then purified via flash chromatography (2:3 EtOAc:hexanes) to provide 77 (E: 0.045 g, 0.089 mmol, 55%; Z: 0.020 g, 0.040 mmol, 25%) as a faint yellow oil.

Method B: Using a modified mixed anhydride procedure by Rajesh et al.,⁴¹ starting material (42a, 0.020 g, 0.064 mmol) was dissolved in THF (2.0 mL) at rt in a 10 mL round bottom flask to produce a yellow solution. Triethylamine (0.022 mL, 0.16 mmol) was added at rt and the reaction retained the same appearance, then methyl chloroformate (0.007 mL, 0.09 mmol) was added quickly at rt. The reaction immediately became cloudy and proceeded to change into a cloudy pink suspension within 15 seconds. After stirring for 2 minutes at room temperature N-Boc-1,6-diaminohexane (0.030 mL, 0.13 mmol) was added quickly. The reaction immediately lost the pink color and became an orange suspension. TLC (2:3 EtOAc:hexanes) indicated the reaction was complete in less than 30 minutes, resulting in minimal sideproduct formation. The reaction was then diluted with EtOAc, washed with brine, dried over MgSO_4 , filtered, and condensed. 0.025 g (0.050 mmol, 78%) of pure E 77 was obtained from chromatography.

Method C: Acid 42a (0.478 g, 0.156 mmol) and PyBOP (0.119 g, 0.229 mmol) were added to a flame-dried 10 mL round bottom flask and purged with Argon. CH_2Cl_2 (4.0 mL) was then added at room temperature followed by triethylamine (0.060 mL, 0.43 mmol). The clear/colorless solution was stirred at room temperature for 1 hour before N-Boc-1,6-diaminohexane (0.050 mL, 0.22 mmol) was added at room temperature. The faint yellow/clear solution was stirred for

an additional 4 hours at room temperature before being diluted with CH₂Cl₂ (70.0 mL), washed 3 times with dilute (0.25 M) NaOH, one time with brine, dried over MgSO₄, filtered, and condensed. The resulting yellow oil was then purified by flash chromatography (1:4 EtOAc:hexanes) to provide 77 (0.079 g, 0.16 mmol, 100%) as a faint yellow oil that began to solidify in the freezer.

R_f = 0.50 (2:3 EtOAc:hexanes)

¹H NMR (CDCl₃): δ 1.42 (s/m, 13H); 1.56 (s/m, 3H); 1.84 (d, 3H, J = 1.2 Hz); 3.11 (q, 2 H, J = 6.0 Hz); 3.39 (q, 2H, J = 6.9 Hz); 3.75 (s, 3H); 3.98 (s, 3H); 4.54 (bs, 1H); 6.06 (bs, 1H); 7.36 (s, 1H); 7.54 (m, 2H); 8.11 (m, 2H)

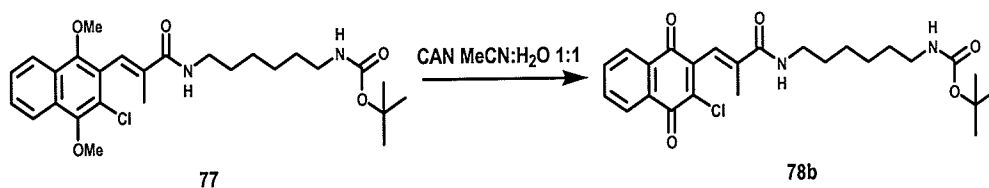
¹³C NMR (CDCl₃): δ 15.1, 26.2, 26.3, 28.4, 29.5, 30.0, 34.0, 39.7, 61.4, 61.8, 85.5, 122.2, 122.9, 123.4, 124.8, 126.7, 127.3, 127.5, 127.7, 128.7, 136.0, 148.6, 150.5, 156.1, 168.3

(Z)-N-(N'-tert-butoxycarbonyl-6-aminohexyl)-3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-methylpropenamide (Z-77):

R_f = 0.67 (2:3 EtOAc:hexanes)

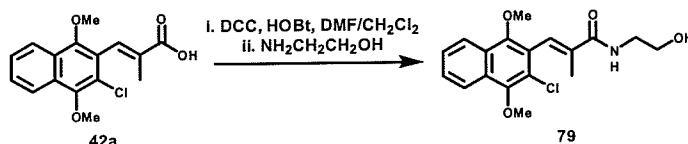
¹H NMR (CDCl₃): δ 1.24 (m, 10H); 1.55 (s/m, 2H); 1.69 (m, 3H); 1.80 (m, 1H); 1.85 (d, 3H, J = 1.5 Hz); 1.98 (m, 3H); 2.40 (q, 2H, J = 10.8 Hz); 3.69 (m, 1H); 3.84 (s, 3H); 3.99 (s, 3H); 4.05 (m, 1H); 6.64 (bs, 1H); 7.55 (m, 2H); 8.12 (m, 2H); 8.29 (d, 1H, J = 6.6 Hz);

¹³C NMR (CDCl₃): δ 16.5, 24.8, 25.2, 25.6, 26.5, 30.7, 28.5, 49.4, 53.4, 60.0, 61.4, 62.0, 122.1, 122.4, 122.9, 123.3, 123.6, 126.7, 127.4, 127.7, 138.7, 139.0, 148.5, 150.9, 153.9, 175.6



(E)-N-(N'-tert-butoxycarbonyl-6-aminohexyl)-3-(3-chloro-1,4-naphthoquinon-2-yl)-2-methylpropenamide (78b)

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(E)-N-(2-hydroxyethyl)-3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-methylpropenamide (79):

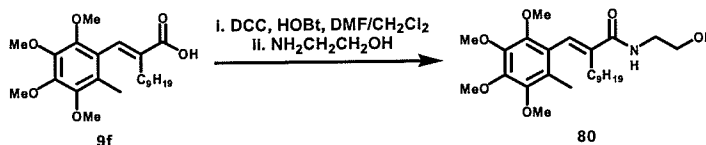
DCC (0.135 g, 0.654 mmol) was added to a flame dried 10 mL round
 5 bottom flask under argon, and then CH₂Cl₂ (2.0 mL) was added at rt. In a second
 flame-dried flask under argon a solution of acid 42a (0.117 g, 0.381 mmol) and HOBT
 (0.025 g, 0.19 mmol) was prepared using DMF (3.0 mL) and CH₂Cl₂ (1.0 mL) at rt.
 The acid/HOBT solution was then added at rt and stirred for 2 h before amine (0.024
 mL, 0.40 mmol) was added quickly at rt. The reaction was stirred for an additional 12
 10 hours before being diluted with EtOAc, washed with brine, dried over MgSO₄,
 filtered, and condensed. The resulting white solid, a combination of
 dicyclohexylurea, DCC, and product, was first suspended in approximately 5 mL
 CH₂Cl₂. The suspension was then filtered through a pipette with cotton plug to
 remove the insoluble DCU, and the pipette was washed 2 times with 2 mL CH₂Cl₂.
 15 The combined fractions were then purified via flash chromatography (2:3
 EtOAc:hexanes) to provide 79 (0.110 g, 0.314 mmol, 83%) as a white solid.

R_f = 0.28 (1:1 EtOAc:hexanes)

mp = 165 - 167 °C

¹H NMR (CDCl₃): δ 1.86 (d, 3H, J = 1.2 Hz); 2.68 (bs, 1H, OH); 3.60
 20 (q, 2H, J = 5.4 Hz); 3.75 (s, 3H); 3.84 (t, 2H, J = 4.8 Hz); 3.98 (s, 3H); 6.42 (bs, 1H,
 NH); 7.43 (s, 1H); 7.55 (m, 2H); 8.10 (m, 2H)

¹³C NMR (CDCl₃): δ 14.1, 15.0, 29.7, 43.0, 61.4, 61.9, 62.7, 122.2,
 122.9, 124.6, 126.7, 127.4, 128.5, 134.3, 135.3, 148.7, 150.5, 169.6



25

(E)-N-(2-hydroxyethyl)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-nonylpropenamide (80):

DCC (0.106 g, 0.514 mmol) was added to a flame dried 10 mL round
 bottom flask under argon, and then CH₂Cl₂ (2.0 mL) was added at rt. In a second

flame-dried flask under argon a solution of acid 9f (0.167 g, 0.409 mmol) and HOBt (0.008 g, 0.06 mmol) was prepared using DMF (3.0 mL) and CH₂Cl₂ (1.0 mL) at rt. The acid/HOBt solution was then added at rt and stirred for 2 h before amine (0.040 mL, 0.66 mmol) was added quickly at rt. The reaction was stirred for an additional 12 hours before being diluted with EtOAc, washed with brine, dried over MgSO₄, filtered, and condensed. The resulting white solid, a combination of dicyclohexylurea, DCC, and product, was first suspended in approximately 5 mL CH₂Cl₂. The suspension was then filtered through a pipette with cotton plug to remove the insoluble DCU, and the pipette was washed 2 times with 2 mL CH₂Cl₂. The combined fractions were then purified via flash chromatography (1:4 EtOAc:hexanes) to provide two compounds that appeared to be isomers: (*E*)-80 (0.088 g, 0.20 mmol, 48%, 2:3 EtOAc:hexanes R_f = 0.36) and (*Z*)-80 (0.063 g, 0.14 mmol, 33%, 2:3 EtOAc:hexanes R_f = 0.71, coluted with DCC), both as a colorless oils.

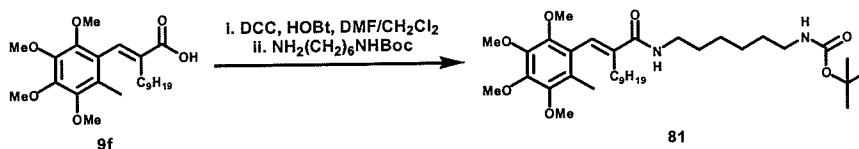
R_f = 0.36 (2:3 EtOAc:hexanes)

¹H NMR (CDCl₃): δ 0.83 (t, 3H, J = 6.9 Hz); 1.13 (m, 12H); 1.32 (m, 2H); 2.03 (s, 3H); 2.13 (m, 2H); 2.70 (t, 1H, J = 5.1 Hz); 3.55 (m, 2H); 3.69 (s, 3H); 3.78 (s, 3H); 3.80 (m, 2H); 3.88 (s, 3H); 3.92 (s, 3H); 6.31 (bs, 1H); 6.92 (s, 1H)
¹³C NMR (CDCl₃): δ 13.0, 14.1, 22.6, 27.8, 28.8, 29.3, 29.5, 29.6, 31.8, 42.8, 60.6, 60.9, 61.1, 61.2, 62.8, 124.9, 125.0, 128.0, 140.3, 144.6, 146.3, 146.8, 147.8, 170.4

(*Z*)-N-(2-hydroxyethyl)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-nonylpropenamide (*Z*-80):

R_f = 0.71 (2:3 EtOAc:hexanes)

¹H NMR (CDCl₃): δ LOWER REGION OBSCURED BY DCC 3.19 (s, 3H); 2.14 (m, 2H); 2.42 (m, 2H); 3.68 (m, 1H); 3.75 (s, 3H); 3.78 (s, 3H); 3.88 (s, 3H); 3.92 (s, 3H); 4.07 (m, 1H); 6.64 (s, 1H); 8.53 (d, 1H, J = 7.2 Hz)



(E)-N-(N'-tert-butoxycarbonyl-6-aminohexyl)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-methylpropenamide (81):

81 was prepared from 9f (0.439 g, 1.07 mmol) following method A for 88. E and Z isomers were separated using flash chromatography (1:4 acetone:hexanes). E isomer (0.360 g, 0.059 mmol, 55%); Z isomer (0.379 g, contaminated with DCC).

$R_f = 0.61$ (2:3 EtOAc:hexanes)

$^1\text{H NMR}$ (CDCl_3): δ 0.82 (t, 3H, $J = 6.6$ Hz); 1.12 (m, 12H); 1.22 (m, 3H); 1.35 (m, 7H); 1.41 (s, 9H); 1.46 (m, 2H); 1.56 (m, 3H); 2.02 (s, 3H); 2.11 (m, 2H); 3.08 (q, 2H, $J = 6.0$ Hz); 3.33 (q, 2H, $J = 6.6$ Hz); 3.68 (s, 3H); 3.76 (s, 3H); 3.87 (s, 3H); 3.91 (s, 3H); 4.54 (bs, 1H); 5.92 (bs, 1H); 6.83 (s, 1H)

$^{13}\text{C NMR}$ (CDCl_3): δ 13.0; 13.5; 22.6; 26.2; 26.4; 27.8; 28.4; 28.9; 29.3; 29.5; 29.6; 30.0; 31.8; 39.4; 40.3; 53.4; 60.6; 60.8; 61.1; 61.2; 125.1; 126.9; 141.1; 144.6; 146.2; 146.9; 147.8; 156.0; 169.2

15

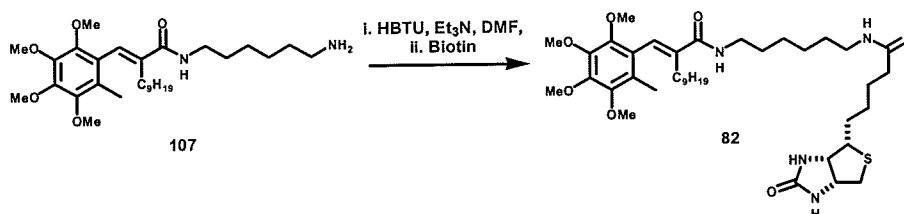
(Z)-N-(N'-tert-butoxycarbonyl-6-aminohexyl)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-methylpropenamide (Z-81):

$R_f = 0.75$ (2:3 EtOAc:hexanes)

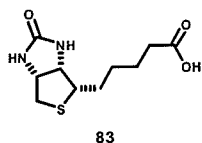
$^1\text{H NMR}$ (CDCl_3): δ 0.84 (t, 3H, $J = 6.9$ Hz); 1.38 – 1.17 (m, 28H); 1.42 (m, 1H); 1.57 (m, 2H); 1.72 (m, 7H); 1.93 (m, 3H); 2.08 (s, 3H); 2.14 (m, 2H); 2.42 (q, 2H, $J = 11.7$ Hz); 3.68 (m, 1H); 3.75 (s, 3H); 3.79 (s, 3H); 3.89 (s, 3H); 3.92 (s, 3H); 4.07 (m, 1H); 6.37 (s, 1H); 8.54 (d, 1H, $J = 7.5$ Hz);

$^{13}\text{C NMR}$ (CDCl_3): δ 13.0; 14.1; 22.6; 24.8; 25.2; 25.7; 26.5; 27.3; 29.3; 29.4; 29.7; 30.4; 30.8; 31.8; 32.9; 49.4; 60.7; 60.9; 61.1; 61.2; 65.0; 123.6; 124.1; 125.2; 142.1; 144.6; 146.4; 147.2; 147.7; 154.1; 176.0

25



(E)-N-[5-((1R,5S,6S)-3-oxo-7-thia-2,4-diazabicyclo[3.3.0]oct-6-yl)pentanoylamino]hexyl-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-methylpropenamide (82):



5

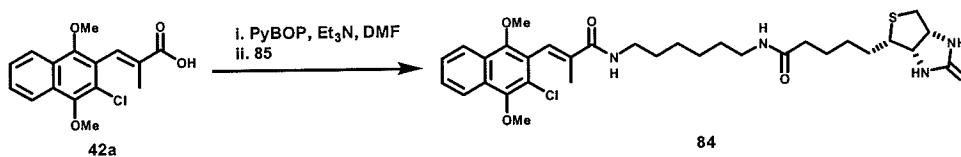
5-((1R,5S,6S)-3-oxo-7-thia-2,4-diazabicyclo[3.3.0]oct-6-yl)pentanoic acid D-(+)-Biotin (83, Aldrich):

¹H NMR (DMSO): δ 1.32 (m, 2H); 1.49 (m, 2H); 1.60 (m, 2H); 2.19 (t, 2H, J = 7.2 Hz); 2.56 (d, 1H, J = 12.6 Hz); 2.81 (dd, 1H, J = 12.6, 5.1 Hz); 3.09 (m, 1H); 4.12 (ddd, 1H; J = 7.5, 4.2, 1.5 Hz); 4.29 (dd, 1H, J = 7.5, 5.1 Hz); 6.35 (s, 1H); 6.42 (s, 1H); 11.93 (bs, 1H)

10

¹³C NMR (DMSO): δ 24.5, 28.0, 28.1, 33.48, 40.3, 55.4, 59.2, 61.0, 162.7, 174.4

15



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(E)-N-[5-((1R,5S,6S)-3-oxo-7-thia-2,4-bicyclo[3.3.0]oct-6-yl)pentanoylamino]hexyl-3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-methylpropenamide (84):

25

To a flame dried 10 mL round bottom flask was added 42a (0.015 g, 0.049 mmol) and PyBOP (0.031 g, 0.060 mmol), and then DMF (2.0 mL) was added to produce a yellow solution. Et₃N (0.020 mL, 0.14 mmol) was added at room temperature and the solution remained yellow/clear. After stirring at room temperature for 45 minutes amine 82 (0.1 M in DMF, 0.60 mL, 0.060 mmol) was added and the solution became a darker gold color but remained clear. After 20 minutes TLC (1:9 MeOH:CH₂Cl₂) indicated the starting material was no longer present and a new spot (R_f 0.29) appeared. The reaction stirred for 12 hours more before the solvent was stripped off under reduced pressure. The resultant gold oil was

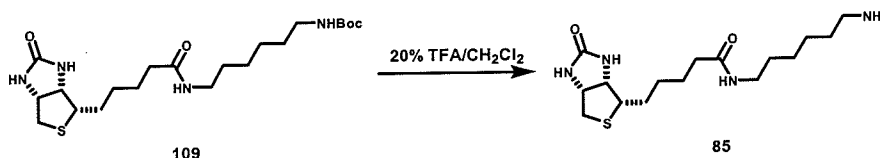
immediately chromatographed (1:9 MeOH:CH₂Cl₂) to provide two yellow bands corresponding to two spots on TLC (R_f 0.39 and 0.29). NMR of the higher spot indicated it was potentially the HOBT ester of the starting material. The lower spot was confirmed by NMR to be the coupled product, 84. The product was collected as a yellow oil that solidified in the freezer (0.031 g, 0.048 mmol, 99%).

R_f = 0.29 (1:9 MeOH:CH₂Cl₂)

¹H NMR (CDCl₃): δ 1.05 (m, 2H); 1.33 (obscured by MeOH); 1.49 (m, 3H); 1.61 (m, 6H); 1.82 (s, 6H); 2.20 (m, 2H); 2.72 (bd, 1H, J = 13.2 Hz); 2.86 (bd, 1H, J = 9.3 Hz); 3.36 (m, 2H); 3.73 (s, 3H); 3.96 (s, 3H); 4.33 (bs, 1H); 4.51 (bs, 1H); 5.28 (m, 0.5H); 5.72 (bs, 0.5H); 6.33 (m, 0.5H); 6.41 (bs, 0.5 H); 7.35 (s, 1H); 7.53 (m, 2H); 8.08 (m, 2H); 8.70 (bs, 0.5H)

¹H NMR (CD₃CN:D₂O 1:1): δ 1.70 (s, 3H); 2.10 (t, 3H, J = 7.2 Hz); 2.62 (d, 2 H, J = 11.1 Hz); 3.23 (t, 3 H, J = 7.8 Hz); 3.69 (s, 3H); 3.90 (s, 3H); 4.42 (m, 3H); 7.20 (s, 1H); 7.59 (m, 2H); 8.07 (m, 2H)

¹³C NMR (CDCl₃): δ 8.7, 15.0, 25.7, 26.0, 26.2, 27.7, 27.9, 29.1, 29.3, 35.7, 39.1, 39.7, 40.4, 55.4, 60.4, 61.4, 61.9, 62.0, 62.3, 122.1, 122.9, 123.2, 124.7, 126.7, 127.3, 127.6, 127.8, 128.7, 135.8, 148.5, 150.6, 168.6, 173.7, 192.8

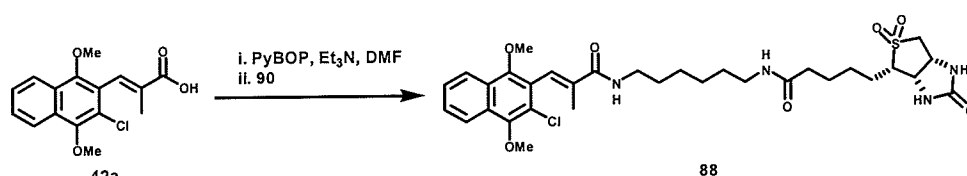


N-(6-aminohexyl)-5-((1R,5S,6S)-3-oxo-7-thia-2,4-diazabicyclo[3.3.0]oct-6-yl)pentanamide (85):

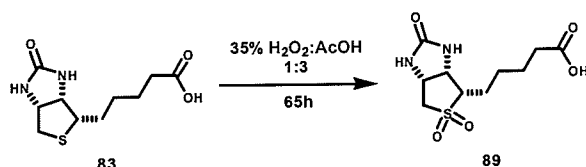
Boc protected amine 109 (0.034 g, 0.08 mmol) was dissolved in CH₂Cl₂ (2.0 mL) and TFA (0.4 mL, 5.2 mmol) was added at room temperature. The reaction stirred at room temperature for 20 minutes and then monitored by TLC (1:9 MeOH:CH₂Cl₂). When starting material was no longer observed by TLC the TFA/CH₂Cl₂ was removed under reduced pressure and the vial was placed under high vacuum for 2 hours. The tan residue was then taken up in DMF and used without purification. 85 was obtained quantitatively.

R_f = 0.00 (1:9 MeOH:CH₂Cl₂)

¹H NMR (DMSO): δ 1.18 – 1.65 (m, 14H); 2.03 (t, 2H, J = 7.2 Hz); 2.56 (d, 1H, J = 12.3 Hz); 2.76 (m, 2H); 2.81 (dd, 1H, J = 5.1, 12.6 Hz); 3.00 (q, 2H, J = 6.3 Hz); 3.08 (m, 1H); 4.11 (dd, 1H, J = 4.5, 7.5 Hz); 4.30 (dd, 1H, J = 4.8, 7.5 Hz); 6.42 (bs, 2H); 7.67 (bs, 1H); 7.75 (t, 1H, J = 5.1 Hz)



(*E*)-*N*-(*N'*-[5-((1*R*,5*S*,6*S*)-3,7,7-trioxo-7-thia-2,4-bicyclo[3.3.0]oct-6-yl)propanoylamino]hexyl-3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-methylpropenamide (88):



5-((1*R*,5*S*,6*S*)-3,7,7-trioxo-7-thia-2,4-diazabicyclo[3.3.0]oct-6-yl)pentanoic

acid (89):

Following the procedure of Sachon et al.,⁴² D-biotin (83, 0.304 g, 1.24 mmol) was suspended in AcOH (3.0 mL) and then H₂O₂ (35% in H₂O, 1.0 mL) was added at room temperature. The suspension became a colorless, clear solution after 10 min at room temperature, and biotin sulfoxide began to precipitate after 5 hours. The reaction was stirred at room temperature for 65 hours, then filtered. The white filter cake was then washed with 20 mL of ether and dried under reduced pressure to provide 89 as a white solid (0.298 g, 1.08 mmol, 87%).

Insoluble in CH₂Cl₂, acetone, MeOH, water.

Soluble in DMSO and NaOH aq.

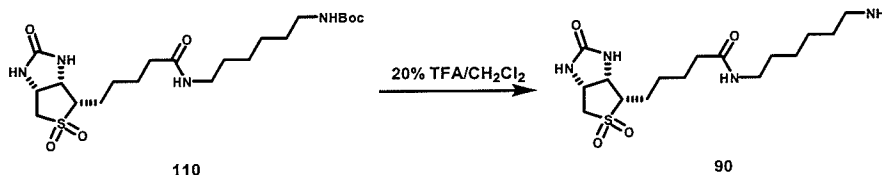
*R*_f =

Mp = 255 °C d (Lit. >260 °C)⁴²

¹H NMR (DMSO): δ 1.41 (m, 2H); 1.53 (m, 2H); 1.63 (m, 2H); 2.20 (t, 2H, *J* = 7.2 Hz); 3.01 (d, 1H, *J* = 13.8 Hz); 3.16 (q, 1H, *J* = 6.3 Hz); 3.30 (m, 3H); 4.38 (m, 2H); 6.59 (s, 1H); 6.69 (s, 1H)

¹³C NMR (DMSO): δ 21.1, 24.4, 25.5, 33.4, 49.0, 53.5, 54.2, 60.2, 161.6, 174.4

-104-

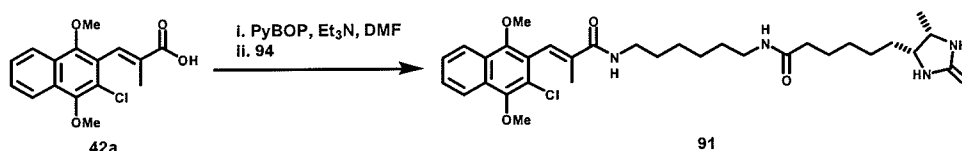


N-(6-aminohexyl)-5-((1*R*,5*S*,6*S*)-3,7,7-trioxo-7-thia-2,4-diazabicyclo[3.3.0]oct-6-yl)pentanamide (90):

N-Boc protected sulfonobiotin 110 (0.014 g, 0.03 mmol) was added to
 5 a flame-dried 5 ml round bottom flask and purged with argon. The white solid was
 suspended in CH₂Cl₂ (1.0 mL) and stirred at room temperature. TFA (0.2 mL) was
 added at room temperature and the white solid immediately dissolved to produce a
 clear, peach solution. The solution was stirred at room temperature for an additional
 45 minutes before the solvents were removed under reduced pressure to provide the
 10 product as a tan residue. The residue was insoluble in CH₂Cl₂, but soluble in DMF.
 Amine 90 was synthesized quantitatively.

$R_f = 0.00$ (1:9 MeOH:CH₂Cl₂)

¹H NMR (DMSO): δ 1.26 (m, 4H); 1.37 (m, 6H); 1.50 (m, 2H); 1.63
 (m, 2H); 2.05 (t, 2H, $J = 7.2$ Hz); 2.75 (m, 2H); 2.99 (m, 1H); 3.03 (m, 1H); 3.15 (m,
 15 1H); 3.30 (dd, 1H, $J = 6.3, 13.8$ Hz); 4.38 (m, 2H); 6.60 (s, 1H); 6.68 (s, 1H); 7.66
 (bs, 2H); 7.76 (t, 1H, $J = 5.4$ Hz)



20

(*E*)-*N*-(*N'*-[6-((4*R*,5*S*)-5-methyl-imidazolidin-2-on-6-yl)hexanoylamino]hexyl-3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-methylpropenamide (91):

Unsaturated acid 42a (0.033 g, 0.11 mmol) and PyBOP (0.690 g, 0.133
 25 mmol) were added to a flame-dried 10 mL round bottom flask and purged with argon.
 CH₂Cl₂ (2.0 mL) was then added resulting in a yellow solution, and then
 triethylamine (0.040 mL, 0.29 mmol) was added at room temperature and the yellow
 solution was stirred at room temperature for 40 minutes. Amine 94 (0.133 M in
 DMF/CH₂Cl₂ 1:5, 1.1 mL, 0.147 mmol) was added quickly at room temperature and

the reaction turned orange. The reaction was stirred for an additional 17 h before the solvents were removed under reduced pressure resulting in a red oil that was purified by flash chromatography (7:93 MeOH:CH₂Cl₂) to provide a yellow oil that was contaminated with triethylammoniumhexafluorophosphate. To remove the

5 contaminating salt the oil was dissolved in Et₂O/CH₂Cl₂ and washed 4 times with dilute NaOH, then one time with brine, and dried over Na₂SO₄. The resultant white foam 91 (0.044 g, 0.073 mmol, 68%) was free of ammonium salts.

Alternatively, upon completion the reaction is diluted with Et₂O and washed 3 times with dilute NaOH (0.1 M), one time with saturated brine, dried over

10 MgSO₄, filtered, and condensed under reduced pressure. The resulting gold oil was then purified by flash chromatography (7:93 MeOH:CH₂Cl₂).

R_f = 0.35 (1:9 MeOH:CH₂Cl₂)

HRMS (ESI) calc. 623.2976 M+Na found 623.2978 M+Na

HPLC (econosphere C8, 40:60 MeCN:H₂O) rt = 28.2 min

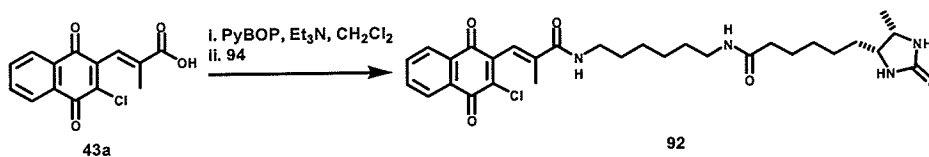
15 Elemental analysis: calculated C(63.93%), H(7.54%), N(9.32%); found C(63.55%), H(7.32%), N(9.06%)

¹H NMR (CDCl₃): δ 1.09 (d, 3H, J = 6.6 Hz); 1.23 (m, 2H); 1.38 (m, 9H); 1.50 (m, 3H); 1.63 (m, 4H); 1.73 (m, 2H); 1.83 (d, 3H, J = 1.2 Hz); 2.16 (t, 2H, J = 7.5 Hz); 3.23 (q, 2H, J = 6.6 Hz); 3.39 (m, 2H); 3.67 (m, 1H); 3.75 (s, 3H); 3.80 (m,

20 1H); 3.97 (s, 3H); 4.50 (s, 1H); 5.12 (s, 1H); 5.93 (t, 1H, J = 5.4 Hz); 6.21 (t, 1H, J = 5.4 Hz); 7.36 (d, 1H, J = 1.2 Hz); 7.54 (m, 2H); 8.09 (m, 2H)

¹³C NMR (CDCl₃): δ 15.0, 15.8, 25.4, 26.0, 28.8, 29.5, 30.9, 36.23, 38.9, 39.5, 51.4, 55.9, 61.4, 61.8, 122.2, 122.8, 123.3, 124.7, 126.7, 127.3, 127.5, 127.6, 128.7, 136.0, 148.6, 150.5, 163.3, 168.5, 172.9

25



(E)-N-(N'-[6-((4R,5S)-5-methyl-imidazolidin-2-on-6-

yl)hexanoylamino]hexyl-3-(3-chloro-1,4-naphthoquinon-2-yl)-2-methylpropenamide

30 (92):

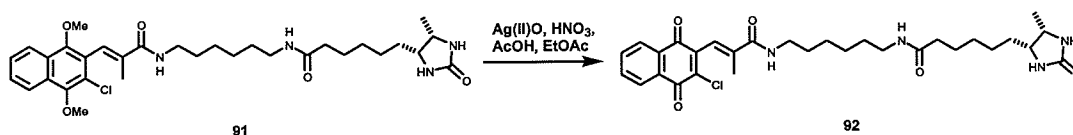
Method A: Quinone 43a (0.032 g, 0.11 mmol) and PyBOP (0.084 g, 0.16 mmol) were added to a 10 mL flame-dried round bottom flask and purged with Argon. CH₂Cl₂ (1.5 mL) was added at room temperature resulting in a yellow suspension. The suspension clarified to a yellow solution (sometimes a dark green solution) upon the addition of Et₃N (0.035 mL, 0.25 mmol) at room temperature,.
 5 The acid was allowed to activate for 10 minutes at room temperature before amine 94 (0.24 M in DMF, 0.50 mL, 0.12 mmol) was added at room temperature. The reaction was allowed to stir at room temperature for 30 minutes before being added to a column and purified (CH₂Cl₂ to 1:9 MeOH:CH₂Cl₂). 92 (0.052 g, 0.091 mmol, 80%)
 10 was collected as a dark gold oil and determined pure by NMR.

Method B: To a flame-dried 10 mL round bottom flask was added quinone 43a (9.921 mg, 0.0359 mmol), PyBOP (22.299 mg, 0.0428 mmol), and NaH (4.092 mg, 0.1705 mmol) and the flask was purged with argon for 10 minutes. The solid reagents were suspended in CH₂Cl₂ (2.0 mL) and then DMF was added slowly
 15 until the yellow suspension had become completely clear (0.4 mL). The reaction changed from golden/clear to light red/clear in 1 minute at room temperature, and after 10 minutes a solution of 94 (0.05 M in DMF, 0.68 mL, 0.034 mmol) was added to the reaction immediately changing the reaction to a yellow/clear solution. The reaction was allowed to stir at room temperature for 20 minutes before the clear
 20 yellow solution was stripped of CH₂Cl₂ under reduced pressure and then added directly to a column for purification (CH₂Cl₂ to 3:40 MeOH:CH₂Cl₂)

R_f = 0.34 (1:9 MeOH:CH₂Cl₂)

HRMS (MALDI) C₃₀H₃₉³⁷ClN₄O₅ Calc. 573.2657 Found 573.2684

HPLC (econosphere C8, 40:60 MeCN:H₂O) rt = 12.9 min

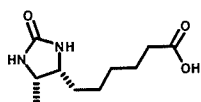


(E)-N-(N'-[6-((4R,5S)-5-methyl-imidazolidin-2-on-6-yl)hexanoylamino]hexyl-3-(3-chloro-1,4-naphthoquinon-2-yl)-2-methylpropenamide
(92):

35 Dimethoxynaphthalene 91 (0.104 g, 0.172 mmol) was combined with Ag(II)O (1.58 g, 1.28 mmol) in a 4 mL vial and suspended in dioxane (2.0 mL). The

suspension was sonicated until the starting material was completely dispersed (2 minutes). Nitric acid (6.0 M, 0.50 mL, 3.0 mmol) was added to the black suspension dropwise at room temperature and the suspension changed to a yellow solvent with yellow precipitate in less than one minute. The reaction was stirred at room temperature for 10 minutes before being added to a column and purified (0 to 1:9 MeOH:CH₂Cl₂). The fractions containing product and unhydrolyzed intermediate were combined in a separatory funnel and washed once with brine. The organic layer was separated, dried over MgSO₄, filtered, and condensed. The product was collected as a yellow residue (0.073 g, 0.13 mmol, 74%).

- 10 $R_f = 0.34$ (1:9 MeOH:CH₂Cl₂)
HRMS (MALDI) C₃₀H₃₉³⁷ClN₄O₅ Calc. 573.2657 Found 573.2684
HPLC (econosphere C8, 40:60 MeCN:H₂O) rt = 12.9 min
¹H NMR (CDCl₃): δ 1.11 (d, 3H, J = 6.3 Hz); 1.24 (m, 4 H); 1.37 (m, 9H); 1.48 (m, 5H); 1.61 (m, 11H); 1.86 (d, 3H, J = 1.2 Hz); 2.16 (t, 2H, J = 7.2 Hz);
15 3.24 (m, 2H); 3.35 (m, 2H); 3.68 (m, 1H); 3.83 (m, 1H); 4.45 (bs, 1H); 4.87 (bs, 1H);
5.74 (bs, 1H); 6.29 (bs, 1H); 6.99 (d, 1H, J = 1.2 Hz); 7.78 (m, 2H); 8.11 (m, 1H);
8.18 (m, 1H)
¹³C NMR (CDCl₃): δ 16.4, 25.4, 24.8, 26.0, 28.8, 29.3, 36.3, 39.0,
39.6, 51.4, 55.9, 57.8, 124.0, 127.2, 127.4, 131.3, 131.7, 134.3, 134.5, 140.0, 141.9,
20 142.6, 143.5, 146.3, 163.3, 167.1, 172.9, 177.5, 181.6, 185.4



93

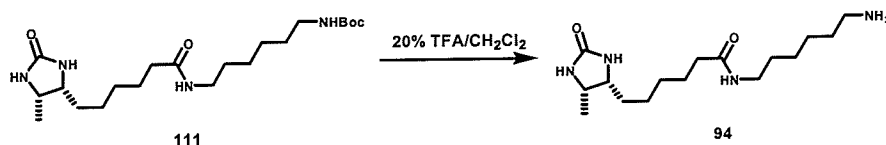
6-[(4R,5S)-5-methyl-imidazolidin-2-on-4-yl]hexanoic acid (93, Aldrich):

Insoluble: CH₂Cl₂, H₂O, acetone

- 25 Soluble: NaOH aq.

¹H NMR (DMSO): δ 0.94 (d, 3H, J = 6.3 Hz); 1.26 (m, 6H); 1.47 (m, 2H); 2.18 (t, 2H, J = 7.2 Hz); 3.47 (m, 1H); 3.59 (m, 1H); 6.10 (s, 1H); 6.30 (s, 1H)
¹³C NMR (DMSO): δ 15.5, 24.4, 25.5, 28.6, 29.5, 33.6, 50.2, 54.9,
162.8, 174.5

-108-



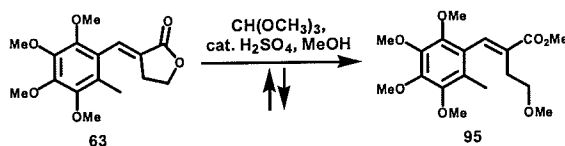
N-(6-aminohexyl)-6-[(4R,5S)-5-methyl-imidazolidin-2-on-4-yl]hexanamide

(94):

N-Boc protected desthiobiotinylating reagent 111 (0.082 g, 0.20 mmol) was added to a flame-dried 5 mL conical vial and purged with Argon before CH₂Cl₂ (1.0 mL) was added. The starting material dissolved in approximately 2 minutes at room temperature to provide a colorless, clear solution. TFA (0.2 mL) was added at room temperature and the reaction became opaque, pale yellow. The reaction was stirred at room temperature for an additional 45 minutes before the solvent was removed under reduced pressure to provide the product as a tan oil. The product was used without further purification. 94 was synthesized quantitatively. 1.0 mL of CH₂Cl₂ were added to the oil resulting in two layers, and then 0.2 mL of DMF were added and the oil dissolved to make a pale tan solution.

¹H NMR (CDCl₃): δ 0.94 (d, 3H, J = 6.6Hz); 1.29 (m, 12 H); 1.48 (m, 5H); 2.02 (t, 2H, J = 7.2 Hz); 2.53 (t, 1H, J = 5.4 Hz); 2.74 (m, 2H); 3.00 (m, 2H); 3.46 (m, 1H); 3.60 (m, 1H); 7.76 (m, 4H)

¹³C NMR (CDCl₃): δ 15.5, 25.3, 25.5, 25.9, 27.0, 28.7, 29.0, 29.5, 34.3, 35.4, 38.3, 50.3, 55.1, 158.2, 158.67, 163.0, 172.0



20

Methyl (E)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-methoxyethylpropenoate (95):

According to a modified procedure by King et al.,²⁷ 63 (0.084 g, 0.27 mmol) was added to a flame-dried 10 mL round bottom flask under argon and a water-jacketed reflux condenser was attached. Anhydrous MeOH (2.0 mL) was then added, followed by H₂SO₄ (4 drops) and trimethyl orthoformate (0.31 mL, 4.0 mmol) at room temperature. The reaction was then heated under reflux for 12 hours, cooled to room temperature, and the solvent was removed under reduced pressure. The residue was dissolved in EtOAc, washed with saturated brine, dried over MgSO₄,

filtered, and condensed. The resulting crude product was purified via flash column chromatography (1:3 EtOAc:hexanes) to provide 95 (0.073 g, 0.20 mmol, 76%) as a faint yellow solid.

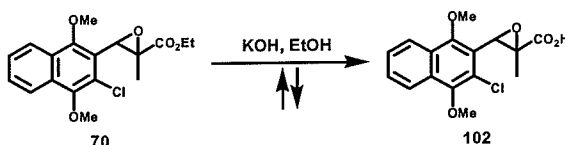
$R_f = 0.25$ (1:3 EtOAc:hexanes)

5

mp = 35 – 37 °C

$^1\text{H NMR}$ (CDCl_3): δ 2.02 (s, 3H); 2.47 (t, 2H, $J = 7.2$ Hz); 3.17 (s, 3H); 3.37 (t, 2H, $J = 7.2$ Hz); 3.69 (s, 3H); 3.78 (s, 3H); 3.81 (s, 3H); 3.88 (s, 3H); 3.92 (s, 3H); 7.49 (s, 1H)

10



3-(3-chloro-1,4-dimethoxynaphthalen-2-yl)-2-methoxy-2-methylpropyl propionate

(102):

Darzens esters 70 (0.193 g, 0.550 mmol) were dissolved in EtOH (10.0 mL) and then KOH (0.200 g, 3.56 mmol) was added to the reaction. The reaction was heated to boiling and stirred at this temperature for 30 minutes. The reaction was then cooled, acidified, and extracted with ethyl acetate. The organic layer was washed with brine, dried over MgSO_4 , filtered, and condensed. The resulting acid was then used as crude, or can be purified via flash chromatography (1:3 EtOAc:hexanes 0.5% AcOH) or recrystallization from Et_2O /hexanes to provide 102 (0.179 g, 0.555 mmol, 101%) as a yellow oil made up of 4 diastereomers.

20

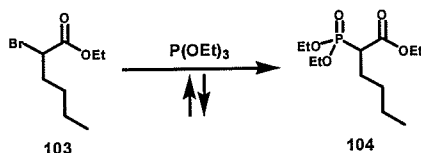
$R_f = 0.07$ (1:3 EtOAc:hexanes 0.5% AcOH)

$^1\text{H NMR}$ (CDCl_3): δ

Enantiomer pair 1: 1.87 (s, 3H); 3.98 (s, 3H); 4.00 (s, 3H); 4.47 (s, 1H); 7.57 (m, 2H); 8.11 (m, 2H)

25

Enantiomer pair 2: 2.03 (s, 3H); 3.96 (s, 3H); 4.04 (s, 3H); 4.35 (s, 1H); 7.57 (m, 2H); 8.11 (m, 2H)



Triethyl 2-phosphonohexanoate (104):

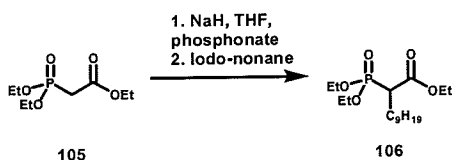
Method A: Following a modified procedure by Kirschleger et al.,⁴³ NaH (0.762 g, 19.0 mmol) was added to a flame-dried 250 mL round bottom flask under argon and a drying tube. THF (75.0 mL) was then added at room temperature followed by triethyl phosphonoacetate (4.20 mL, 21.0 mmol) added dropwise at room temperature. After 30 minutes at room temperature iodobutane (2.10 mL, 18.4 mmol) was added quickly and the reaction was stirred for 7 days at room temperature. The reaction was then washed with brine, dried over MgSO₄, filtered, and condensed. The resulting oil was then purified by either flash column chromatography (1:3 acetone:hexanes) or fractional distillation at reduced pressure to provide 104 (4.29 g, 15.3 mmol, 83%) as a colorless oil.

Method B: Following a modified procedure by Murphy et al.,²⁶ ethyl α -bromohexanoate (103, 1 eq) was added to a flame-dried round bottom flask followed by triethylphosphite (1 eq). The mixture was refluxed for 4 hours and then ethyl bromide was removed under reduced pressure. The resulting oil was then purified by fractional distillation at reduced pressure to afford 104 as a colorless oil.

$R_f = 0.34$ (1:3 EtOAc:hexanes)

¹H NMR (CDCl₃): δ 0.86 (t, 3H, J = 7.2 Hz); 1.23 (t, 3H, J = 7.2 Hz); 1.28 (m, 12H); 2.89 (dddd, 1H, J = 33.6, 22.5, 11.1, 3.9 Hz); 4.09 (q, 2H, J = 7.2 Hz); 4.14 (m, 4H)

³¹P NMR (CDCl₃): δ 26.98 (s)

Triethyl 2-phosphonoundecanoate (106):

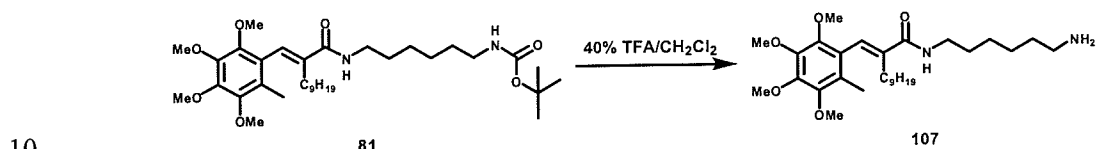
Following a slightly modified procedure by Kirschleger et al.,⁴³ NaH (1.00 g, 25.1 mmol) was added to a flame-dried 250 mL round bottom flask under argon and a drying tube. THF (100.0 mL) was then added at room temperature followed by triethyl phosphonoacetate (4.0 mL, 20.0 mmol) added dropwise at room temperature. After 30 minutes at room temperature iodononane (4.25 mL, 20.5 mmol) was added quickly and the reaction was stirred for 7 days at room temperature.

The reaction was then washed with brine, dried over MgSO_4 , filtered, and condensed. The resulting oil was then purified by either flash column chromatography (1:3 acetone:hexanes) or fractional distillation at reduced pressure to provide 106 (4.73 g, 13.5 mmol, 67%) as a colorless oil.

5 $R_f = 0.30$ (1:3 acetone:hexanes)

$^1\text{H NMR}$ (CDCl_3): δ 0.85 (t, 3H, $J = 6.6$ Hz); 1.26 (m, 23H); 1.81 (bs, 1H); 1.94 (bs, 1H); 2.90 (dddd, 1H, $J = 33.6, 22.5, 11.1, 3.3$ Hz); 4.15 (m, 6H)

$^{31}\text{P NMR}$ (CDCl_3): δ 26.87 (s)

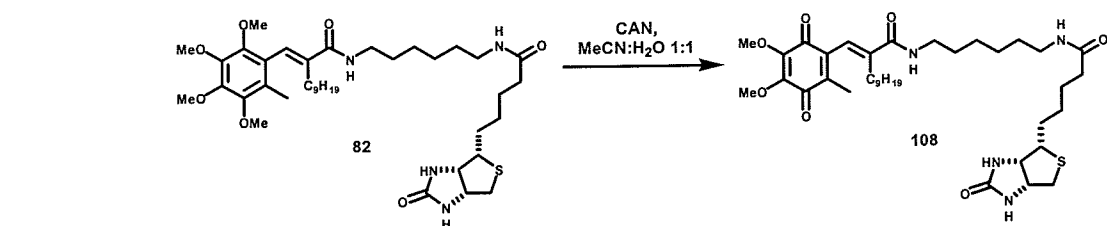


(E)-N-(6-aminohexyl)-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-methylpropenamide (107):

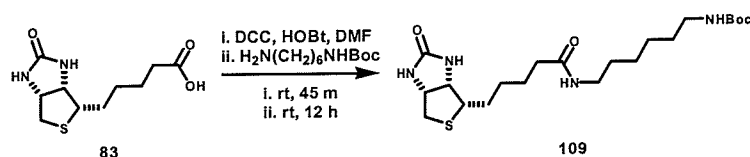
Boc protected amine 81 (0.097 g, 0.16 mmol) was dissolved in CH_2Cl_2 (1.0 mL) and TFA (0.43 mL, 5.5 mmol) was added at rt. The reaction stirred at room temperature for 1 hour and the TFA/ CH_2Cl_2 was then removed under reduced pressure. The residue was then taken up in DMF and used without purification. 107 was synthesized quantitatively.

$R_f = 0.00$ (1:9 MeOH: CH_2Cl_2)

20 $^1\text{H NMR}$ (CDCl_3): δ 0.82 (t, 3H, $J = 6.9$ Hz); 1.11 (m, 12H); 1.23 (m, 3H); 1.39 (m, 4H); 1.56 (m, 2H); 1.68 (m, 3H); 2.01 (s, 3H); 2.09 (m, 2H); 2.96 (m, 2H); 3.30 (q, 2H, $J = 6.9$ Hz); 3.67 (s, 3H); 3.77 (s, 3H); 3.87 (s, 3H); 3.91 (s, 3H); 6.04 (bs, 1H); 6.84 (s, 1H); 8.11 (bs, 2H)



(E)-N-[5-((1R,5S,6S)-3-oxo-7-thia-2,4-diazabicyclo[3.3.0]oct-6-yl)pentanoylamino]hexyl-3-(3,4-dimethoxy-2-methyl-3,6-dioxocyclohexa-1,4-dienyl)-2-methylpropenamide (108):



N-(*N*-*tert*-butoxycarbonyl-6-aminohexyl)-5-((1*R*,5*S*,6*S*)-3-oxo-7-thia-2,4-diazabicyclo[3.3.0]oct-6-yl)pentanamide (109):

5 Following a significantly modified procedure by Sabatino et al.,⁴⁴
 Biotin (83, 0.527 g, 2.16 mmol) and PyBOP (1.24 g, 2.39 mmol) were added to a
 flame-dried 50 mL round bottom flask, to which DMF (10.0 mL) was added at rt. To
 the white suspension was added Et₃N (0.70 mL, 5.0 mmol) at rt and the suspension
 cleared to a light yellow, clear solution. The reaction was stirred at rt for 45 minutes
 10 before the amine (0.55 mL, 2.5 mmol) was added at rt. The yellow clear reaction was
 stirred at rt for 10 hours and then the solvent was removed under reduced pressure.
 The resulting yellow oil was then suspended in water (30.0 mL) and sonicated for 10
 minutes. The white suspension was then filtered to produce a light tan filter cake.
 The filter cake was taken up in boiling acetone (200.0 mL) and recrystallized using
 15 acetone. The resulting white powder was collected by filtration, NMR showed pure
 109 (0.655 g, 1.48 mmol, 69%).

$R_f = 0.24$ (1:9 MeOH:CH₂Cl₂, Hanessian stain)

MP = 163 – 164 °C (Literature 174 – 176 °C)⁴⁴

¹H NMR (DMSO): δ 1.10 – 1.40 (m, 19H); 1.47 (m, 2H); 1.58 (m,
 20 2H); 2.03 (t, 2H, $J = 7.5$ Hz); 2.79 (d, 1H, $J = 5.4$ Hz); 2.86 (m, 2H); 2.99 (q, 2H, $J =$
 6.3 Hz); 3.08 (m, 1H); 4.11 (m, 1H); 4.29 (m, 1H); 6.35 (s, 1H); 6.41 (s, 1H); 6.76 (t,
 1H, $J = 5.1$ Hz); 7.71 (t, 1H, $J = 5.4$ Hz)

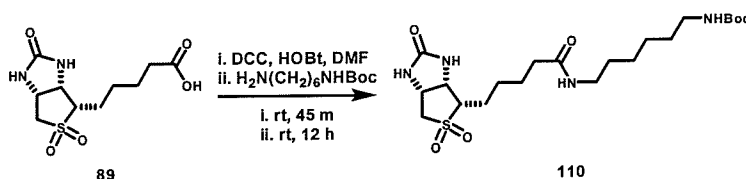
¹H NMR (CDCl₃/CD₃OD): δ 1.14 (m, 4H); 1.25 (s, 9H); 1.28 (m, 5H);
 1.47 (m, 4H); 2.00 (dt, 2H, $J = 7.5$ and 1.5 Hz); 2.55 (d, 1H, $J = 12.9$ Hz); 2.74 (dd,
 25 1H, $J = 5.1$ and 12.9 Hz); 2.88 (q, 2H, $J = 6.6$ Hz); 2.99 (q, 3H, $J = 5.7$ Hz); 4.12 (dd,
 1H, $J = 8.1, 4.5$ Hz); 4.32 (dd, 1H, $J = 7.8, 4.8$ Hz); 5.20 (bs, 1H); 6.99 (bs, 1H) (2
 protons exchange)

¹H NMR (CD₃CN:D₂O 1:1): δ 1.21 (m, 4H); 1.26 – 1.43 (m, 15 H);
 1.53 (m, 4H); 2.09 (t, 2H, $J = 7.2$ Hz); 2.64 (d, 1H, $J = 12.9$ Hz); 2.85 (dd, 1H, $J = 4.8,$
 30 12.9 Hz); 2.92 (m, 2H); 3.04 (t, 2H, 6.6 Hz); 3.14 (m, 1H); 4.34 (d, 1H, $J = 19.6$
 ppm); 4.44 (dd, 1H, $J = 5.1, 6.6$ Hz); 5.90 (bs, 1H); 7.382 (bs, 1H)

^{13}C NMR ($\text{CDCl}_3/\text{CD}_3\text{OD}$): δ 25.3, 25.9, 26.0, 27.8, 28.0, 28.1, 28.8, 29.4, 35.5, 38.9, 40.0, 55.3, 59.9, 61.7, 79.0, 156.6, 163.9, 173.9

^{13}C NMR (DMSO): δ 25.3, 26.0, 26.1, 28.0, 28.3, 29.2, 29.5, 30.7, 35.2, 38.3, 55.4, 59.2, 61.0, 77.3, 155.6, 162.7, 171.78

5



N-(*N'*-*tert*-butoxycarbonyl-6-aminohexyl)-5-((1*R*,5*S*,6*S*)-3,7,7-trioxo-7-thia-2,4-diazabicyclo[3.3.0]oct-6-yl)pentanamide (110):

10 Biotinsulfone (89, 0.165 g, 0.597 mmol) was added to a flame-dried 10 mL round bottom flask followed by PyBOP (0.395 g, 0.759 mmol). The flask was purged with argon and then DMF (2.5 mL) was added resulting in a white suspension. Triethylamine (0.200 mL, 1.42 mmol) was then added at room temperature and the solution became clear and colorless. The reaction was stirred for 15 minutes at room temperature before a white precipitate began to form. *N*-Boc-1,6-diaminohexane (0.78 M in DMF, 0.90 mL, 0.70 mmol) was added quickly at room temperature resulting in an opaque white suspension. The reaction was stirred for an additional 4 hours at room temperature before the suspension was diluted with water (80.0 mL) and stirred for 10 minutes before the white precipitate was collected by filtration. The white precipitate was washed with dilute NaOH to remove biotinsulfone and then washed with CH_2Cl_2 to remove PyBOP, HOBT, and Et_3NHCl . Compound 110 (0.236 g, 0.497 mmol, 83%) was collected as a white solid and determined to be pure by NMR.

Insoluble: CH_2Cl_2 , acetone, NaOH aq.

25 Mildly Soluble: MeOH, EtOH

Soluble: DMSO

R_f = 0.15 (1:9 MeOH: CH_2Cl_2)

MP = 213 – 215 °C

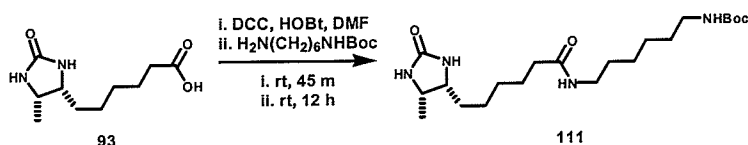
^1H NMR (DMSO): δ 1.21 (m, 4 H); 1.36 (s, 15H); 1.51 (m, 2H); 1.63 (m, 2H); 2.05 (t, 2H, J = 7.5 Hz); 2.73 (m, 2H); 2.99 (m, 3H); 3.15 (m, 1H); 3.30 (m,

30

¹H); 4.38 (m, 2H); 6.59 (s, 1H); 6.68 (s, 1H); 6.75 (t, 1H, J = 5.4 Hz); 7.73 (t, 1H, J = 5.4 Hz)

¹³C NMR (DMSO): δ 21.1, 25.2, 25.6, 26.0, 26.1, 28.3, 29.1, 29.4, 35.0, 38.3, 48.9, 53.4, 54.2, 60.3, 77.3, 85.1, 155.6, 161.6, 171.7

5



N-(*N*⁷-*tert*-butoxycarbonyl-6-aminohexyl)-6-[(4*R*,5*S*)-5-methyl-imidazolidin-2-on-4-yl]hexanamide (111):

Desthiobiotin (93, 0.288 g, 1.34 mmol) and PyBOP (0.792 g, 1.52 mmol) were added to a flame-dried 10 mL round bottom flask and purged with Argon. DMF (2.5 mL) was then added at room temperature producing a clear, colorless solution, to which was added triethylamine (0.420 mL, 2.99 mmol). The reaction was stirred at room temperature for 15 min before N-Boc-1,6-diaminohexane (0.78 M in DMF, 2.0 mL, 1.6 mmol) was added at room temperature. The reaction became a clear yellow solution and was stirred at room temperature for 14 hours before having the solvents removed under reduced pressure. The resulting yellow oil was taken up in CH₂Cl₂ and washed with brine 4 times, dried over MgSO₄, filtered, and condensed. The yellow oil was then purified by flash chromatography (7:93 MeOH:CH₂Cl₂) to yield 111 (0.405 g, 0.982 mmol, 73%) as a white solid/foam. Recrystallization was performed in acetone/hexane to further purify the product.

Insoluble: EtOAc, Et₂O, H₂O, NaOH aq.

Soluble: acetone, CH₂Cl₂

R_f = 0.29 (1:9 MeOH:CH₂Cl₂)

MP = 85 – 87 °C

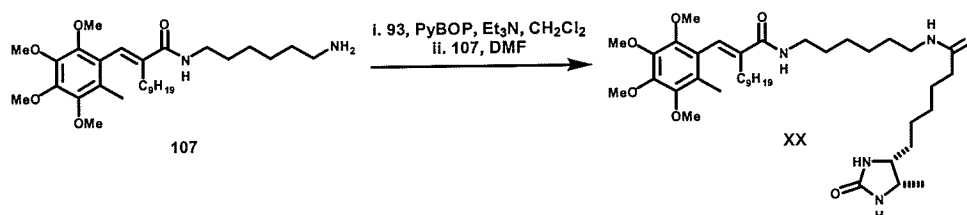
¹H NMR (CDCl₃): δ 1.11 (d, 3H, J = 6.6 Hz); 1.31 (m, 8H); 1.42 (s, 9H); 1.46 (m, 6H); 1.63 (m, 2H); 2.15 (t, 2H, J = 7.2 Hz); 3.09 (m, 2H); 3.21 (m, 2H); 3.68 (m, 1H); 3.83 (m, 1H); 4.31 (bs, 1H); 4.55 (bs, 1H); 4.65 (bs, 1H); 5.65 (bs, 1H)

¹H NMR (DMSO): δ 0.94 (d, 3H, J = 6.3 Hz); 1.20 (m, 8H); 1.32 (m, 6H); 1.36 (s, 9H); 1.46 (m, 2H); 2.02 (t, 2H, J = 7.2 Hz); 2.87 (m, 2H); 2.99 (m, 2H); 3.46 (m, 1H); 3.59 (m, 1H); 6.10 (s, 1H); 6.28 (s, 1H); 6.75 (bs, 1H); 7.69 (bs, 1H)

^{13}C NMR (CDCl_3): δ 15.8, 25.4, 26.1, 28.4, 28.9, 29.5, 30.0, 36.4, 39.1, 40.2, 51.4, 53.4, 56.0, 79.1, 156.1, 163.2, 172.8

^{13}C NMR (DMSO): δ 15.5, 25.2, 25.5, 26.0, 26.1, 28.3, 28.7, 29.1, 29.4, 29.5, 35.2, 38.3, 45.7, 50.2, 54.9, 77.3, 155.6, 162.7, 171.8

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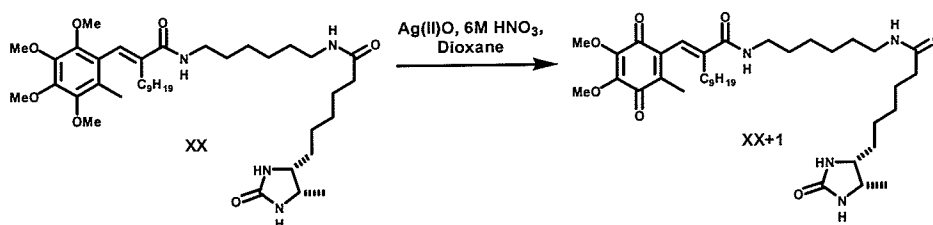
(E)-N-(N'-[6-((4R,5S)-5-methyl-imidazolidin-2-on-6-yl)hexanoylamino]hexyl-3-(6-methyl-2,3,4,5-tetramethoxyphenyl)-2-methylpropenamide (XX):

Desthiobiotin (93, 0.066 g, 0.306 mmol) was added to a flame-dried 10 mL round bottom flask followed by PyBOP (0.164 g, 0.314 mmol) and the flask was purged with Argon. CH_2Cl_2 (3.0 mL) was added to the flask making a white suspension, and then triethylamine (0.10 mL, 0.71 mmol) was added and the suspension quickly clarified to a clear, colorless solution. After stirring for 25 minutes at room temperature a solution of 107 (0.47 M in $\text{DMF}:\text{CH}_2\text{Cl}_2$ 1:1, 0.60 mL, 0.28 mmol) was added at room temperature, the flask containing 107 was rinsed with CH_2Cl_2 (0.5 mL) and added to the reaction. The reaction stirred at room temperature for 3 hours before being diluted with CH_2Cl_2 (20 mL), washed twice with dilute NaOH, washed once with brine, dried over MgSO_4 , filtered, and condensed. The colorless oil was then purified by flash chromatography (CH_2Cl_2 to 3:40 MeOH: CH_2Cl_2) to provide XX (0.115 g, 0.16 mmol, 58%) as a colorless oil.

$R_f = 0.43$ (1:9 MeOH: CH_2Cl_2)

^1H NMR (CDCl_3): δ 0.82 (t, 3H, $J = 6.9$ Hz); 1.09 (d, 3H, $J = 6.3$ Hz); 1.12 (m, 12 H); 1.20 (m, 2H); 1.34 (m, 10H); 1.46 (m, 2H); 1.55 (m, 2H); 1.65 (m, 2H); 2.01 (s, 3H); 2.10 (m, 2H); 2.16 (t, 2H, $J = 7.2$ Hz); 3.20 (m, 2H); 3.33 (m, 2H); 3.65 (m, 1H); 3.68 (s, 3H); 3.76 (s, 3H); 3.81 (m, 1H); 3.86 (s, 3H); 3.90 (s, 3H); 4.81 (s, 1H); 5.49 (s, 1H); 6.14 (bs, 2H); 6.83 (s, 1H)

30



5 (E)-N-(N'-[6-((4R,5S)-5-methyl-imidazolidin-2-on-6-yl)hexanoylamino]hexyl-3-(3,4-dimethoxy-2-methyl-3,6-dioxocyclohexa-1,4-dienyl)-2-methylpropenamide (XX+1):

Tetramethoxybenzene XX (0.018 g, 0.026 mmol) was dissolved in dioxane (0.5 mL) in a 4 mL vial at room temperature, and then Ag(II)O (0.021 g, 0.16 mmol) was added to make a black suspension. At room temperature 6 M HNO₃ (0.12 mL, 0.72 mmol) was added slowly until the reaction became a clear orange solution. The reaction was stirred for ten minutes at room temperature, and then water (1.0 mL) was added to hydrolyze the formed intermediate. After stirring for 5 minutes at room temperature the reaction was extracted three times with CH₂Cl₂ (0.4 mL each) and the resulting orange organic layers were added to a column and purified (CH₂Cl₂ to 3:40 MeOH:CH₂Cl₂). XX was collected as a gold oil and determined pure by NMR (0.007 g, 0.010 mmol, 37%).

R_f = 0.43 (1:9 MeOH:CH₂Cl₂)

¹H NMR (CDCl₃): δ 0.84 (t, 3H, J = 7.2 Hz); 1.16 (m, 15H); 1.34 (m, 12H); 1.48 (m, 2H); 1.55 (m, 4H); 1.92 (s, 3H); 2.08 (m, 2H); 2.15 (m, 2H); 3.21 (m, 2H); 3.30 (m, 2H); 3.72 (m, 1H); 3.841 (m, 1H); 3.97 (s, 3H); 4.01 (s, 3H); 4.66 (bs, 1H); 5.75 (bs, 1H); 6.25 (bs, 2H); 6.48 (s, 1H)

¹³C NMR (CDCl₃): δ 13.7; 14.1; 22.6; 25.5; 26.1; 27.7; 29.3; 29.4; 31.8; 36.3; 39.0; 39.5; 52.8; 54.0; 56.0; 61.2; 122.5; 137.5; 140.3; 144.2; 144.8; 168.7; 172.9; 183.3; 184.0 XX

The term C₁-C₉ alkyl refers to substituted or unsubstituted, straight and branched aliphatic hydrocarbon chains, containing from 1 to 9 carbon atoms, including 1 to 6 carbon atoms. For example, methyl, ethyl, propyl, isopropyl, butyl, i-butyl and t-butyl are encompassed by the term alkyl. Specifically included within the definition of alkyl are those aliphatic hydrocarbon chains that are optionally substituted. Representative optional substituents include, but are not limited to,

hydroxy, acyloxy, alkoxy, amino, amino substituted by one or two alkyl groups of from 1 to 6 carbon atoms, aminoacyl, acylamino, thioalkoxy of from 1 to 6 carbon atoms, substituted thioalkoxy of from 1 to 6 carbon atoms, and trihalomethyl. The term alkoxy as used herein, refers to the group —OR wherein R is an alkyl group as
5 defined above. Halo is defined to include fluoro, chloro and bromo.

The present invention is also directed to the use of the compounds described herein for inhibiting the redox of Ape1/Ref1, by administering to a subject in need thereof such a quinone derivative, as well as inhibiting a physiological disorder associated with altered angiogenesis or cancer by administering to a subject
10 in need thereof an effective amount of a quinone derivative of the invention.

Selective inhibition includes specific inhibition, or, in other words, where there is no or no appreciable effect on the BER function of APE1/Ref-1, as well as where the predominant effect is on the redox function, vis-à-vis the BER function. Also encompassed by the invention is the use of the quinone derivatives
15 of the invention in combination with additional chemotherapeutic/therapeutic agents. It is preferable that the other agents work on a subject in a different way to that of the quinone derivatives. Such other therapeutic agents include, but are not limited to, Avastin, melphalan, gemcitabine, cisplatin, methoxyamine, thalidomide and its derivatives, and retinoic acid, as well as other therapies including radiation.

20 Physiological disorders associated with altered angiogenesis encompass those disorders associated with inappropriate angiogenesis, which are directly or indirectly deleterious to the subject. Altered angiogenesis contributes to pathological conditions related to, among others, cancer (including growth, survival, migration, metastasis, and microenvironment effects), cardiovascular disease, chronic
25 inflammatory disease, rheumatoid arthritis, diabetic retinopathy, degenerative maculopathy, retrolental fibroplasias, idiopathic pulmonary fibrosis, acute adult respiratory distress syndrome, asthma, endometriosis, psoriasis, keloids, and systemic sclerosis.

Examples of types of cancers in the methods of the invention include,
30 among others, breast, prostate, pancreas, colon, cervical, germ cell tumors, adult and pediatric gliomas, osteosarcomas, rhabdomyosarcomas, non-small cell lung cancer, leukemias, and multiple myeloma.

The term subject includes vertebrate animals, and preferably is a human subject. The term inhibit, and derivatives thereof, includes its generally accepted meaning, which includes prohibiting, preventing, restraining, and slowing, stopping, or reversing progression or severity. Thus, the present methods include
5 both medical therapeutic and prophylactic administration, as appropriate. As such, a subject in need thereof, as it relates to the therapeutic uses herein, is one identified to require or desire medical intervention. An effective amount is that amount of an agent necessary to inhibit the pathological diseases and disorders herein described. When at least one additional therapeutic agent is administered to a subject, such
10 agents may be administered sequentially, concurrently, or simultaneously, in order to obtain the benefits of the agents.

An important aspect of the invention is the ability to protect "normal" cells, while still providing therapeutic value. By administering the compounds of the invention, it is possible to administer lower amounts of other therapeutics to the
15 subject, while retaining the same outcomes. Also, by enhancing the apoptosis of cancer cells without a concomitant apoptosis in normal cells, a more targeted therapeutic approach may be taken.

The compounds used in the methods of this invention may form pharmaceutically acceptable acid and base addition salts with a wide variety of
20 organic and inorganic acids and bases and include the physiologically acceptable salts which are often used in pharmaceutical chemistry. Such salts are also part of this invention. Typical inorganic acids used to form such salts include hydrochloric, hydrobromic, hydroiodic, nitric, sulfuric, phosphoric, hypophosphoric and the like. Salts derived from organic acids, such as aliphatic mono and dicarboxylic acids,
25 phenyl substituted alkanoic acids, hydroxyalkanoic and hydroxyalkandioic acids, aromatic acids, aliphatic and aromatic sulfonic acids, may also be used. Such pharmaceutically acceptable salts thus include acetate, phenylacetate, trifluoroacetate, acrylate, ascorbate, benzoate, chlorobenzoate, dinitrobenzoate, hydroxybenzoate, methoxybenzoate, methylbenzoate, o-acetoxybenzoate, naphthalene-2-benzoate,
30 bromide, isobutyrate, phenylbutyrate, B-hydroxybutyrate, butyne-1,4-dioate, hexyne-1,4-dioate, caprate, caprylate, chloride, cinnamate, citrate, formate, fumarate, glycollate, heptanoate, hippurate, lactate, malate, maleate, hydroxymaleate, malonate, mandelate, mesylate, nicotinate, isonicotinate, nitrate, oxalate, phthalate,

teraphthalate, phosphate, monohydrogenphosphate, dihydrogenphosphate, metaphosphate, pyrophosphate, propiolate, propionate, phenylpropionate, salicylate, sebacate, succinate, suberate, sulfate, bisulfate, pyrosulfate, sulfite, bisulfite, sulfonate, benzene-sulfonate, p-bromophenylsulfonate, chlorobenzenesulfonate, ethanesulfonate, 2-hydroxyethanesulfonate, methanesulfonate, naphthalene-1-sulfonate, naphthalene-2-sulfonate, p-toluenesulfonate, xylenesulfonate, tartarate, and the like.

The pharmaceutically acceptable acid addition salts are typically formed by reacting a compound of formula I with an equimolar or excess amount of acid. The reactants are generally combined in a mutual solvent such as diethyl ether or benzene. The salt normally precipitates out of solution within about one hour to 10 days and can be isolated by filtration or the solvent can be stripped off by conventional means.

Bases commonly used for formation of salts include ammonium hydroxide and alkali and alkaline earth metal hydroxides, carbonates and bicarbonates, as well as aliphatic and primary, secondary and tertiary amines, aliphatic diamines and hydroxy alkylamines. Bases especially useful in the preparation of addition salts include ammonium hydroxide, potassium carbonate, sodium bicarbonate, calcium hydroxide, methylamine, diethylamine, ethylene diamine, cyclohexylamine and ethanolamine.

The pharmaceutically acceptable salts generally have enhanced solubility characteristics compared to the compound from which they are derived, and thus are often more amenable to formulation as liquids or emulsions.

Where subject applications, particularly human clinical use, are contemplated, it will be necessary to prepare pharmaceutical compositions in a form appropriate for the intended application. Generally, this will entail preparing compositions that are essentially free of impurities that could be harmful to a subject.

The agents can be administered orally, intravenously, intramuscularly, intrapleurally or intraperitoneally at doses based on the body weight and degree of disease progression of the subject, and may be given in one, two or even four daily administrations.

For example, the compounds can be formulated with common excipients, diluents, or carriers, and formed into tablets, capsules, suspensions,

powders, and the like. Examples of excipients, diluents, and carriers that are suitable for such formulations include the following: fillers and extenders such as starch, sugars, mannitol, and silicic derivatives; binding agents such as carboxymethyl cellulose and other cellulose derivatives, alginates, gelatin, and polyvinyl pyrrolidone; 5 moisturizing agents such as glycerol; disintegrating agents such as calcium carbonate and sodium bicarbonate; agents for retarding dissolution such as paraffin; resorption accelerators such as quaternary ammonium compounds; surface active agents such as cetyl alcohol, glycerol monostearate; adsorptive carriers such as kaolin and bentonite; and lubricants such as talc, calcium and magnesium stearate, and solid polyethyl 10 glycols.

One will generally desire to employ appropriate salts and buffers to render agents stable and allow for uptake by target cells. Aqueous compositions of the present invention comprise an effective amount of the agent, dissolved or dispersed in a pharmaceutically acceptable carrier or aqueous medium. Such compositions also are 15 referred to as innocuously. The phrase pharmaceutically or pharmacologically acceptable refers to molecular entities and compositions that do not produce adverse, allergic, or other untoward reactions when administered to a subject. As used herein, pharmaceutically acceptable carrier includes any and all solvents, dispersion media, coatings, antibacterial and antifungal agents, isotonic and absorption delaying agents 20 and the like. The use of such media and agents for pharmaceutically active substances is well known in the art. Supplementary active ingredients also can be incorporated into the compositions.

Compositions for use in the present invention may include classic pharmaceutical preparations. Administration of these compositions according to the 25 present invention will be via any common route so long as the target tissue is available via that route. This includes oral, nasal, buccal, rectal, vaginal or topical. Alternatively, administration may be by orthotopic, intradermal, subcutaneous, intramuscular, intraperitoneal or intravenous injection. Such compositions would normally be administered as pharmaceutically acceptable compositions, described 30 supra.

The active compounds may also be administered parenterally or intraperitoneally. Solutions of the active compounds as free base or pharmacologically acceptable salts can be prepared in water suitably mixed with a

surfactant, such as hydroxypropylcellulose. Dispersions can also be prepared in glycerol, liquid polyethylene glycols, and mixtures thereof and in oils. Under ordinary conditions of storage and use, these preparations contain a preservative to prevent the growth of microorganisms.

5 The pharmaceutical forms suitable for injectable use include sterile aqueous solutions or dispersions and sterile powders for the extemporaneous preparation of sterile injectable solutions or dispersions. In all cases the form must be sterile and must be fluid to the extent that easy syringability exists. It must be stable under the conditions of manufacture and storage and must be preserved against the
10 contaminating action of microorganisms, such as bacteria and fungi. The carrier can be a solvent or dispersion medium containing, for example, water, ethanol, polyol (for example, glycerol, propylene glycol, and liquid polyethylene glycol, and the like), suitable mixtures thereof, and vegetable oils. The proper fluidity can be maintained, for example, by the use of a coating, such as lecithin, by the maintenance of the
15 required particle size in the case of dispersion and by the use of surfactants. The prevention of the action of microorganisms can be brought about by various antibacterial and antifungal agents, for example, parabens, chlorobutanol, phenol, sorbic acid, thimerosal, and the like. In many cases, it will be preferable to include isotonic agents, for example, sugars or sodium chloride. Prolonged absorption of the
20 injectable compositions can be brought about by the use in the compositions of agents delaying absorption, for example, aluminum monostearate and gelatin.

 Sterile injectable solutions are prepared by incorporating the active compounds in the required amount in the appropriate solvent with various of the other ingredients enumerated above, as required, followed by filtered sterilization.
25 Generally, dispersions are prepared by incorporating the various sterilized active ingredients into a sterile vehicle which contains the basic dispersion medium and the required other ingredients from those enumerated above. In the case of sterile powders for the preparation of sterile injectable solutions, the preferred methods of preparation are vacuum-drying and freeze-drying techniques which yield a powder of
30 the active ingredient plus any additional desired ingredient from a previously sterile-filtered solution thereof.

 For oral administration agents of the present invention may be incorporated with excipients and used in the form of non-ingestible mouthwashes and

dentifrices. A mouthwash may be prepared incorporating the active ingredient in the required amount in an appropriate solvent, such as a sodium borate solution (Dobell's Solution). Alternatively, the active ingredient may be incorporated into an antiseptic wash containing sodium borate, glycerin and potassium bicarbonate. The active
5 ingredient may also be dispersed in dentifrices, including gels, pastes, powders and slurries. The active ingredient may be added in a therapeutically effective amount to a paste dentifrice that may include water, binders, abrasives, flavoring agents, foaming agents, and humectants.

The compositions for use in the present invention may be formulated
10 in a neutral or salt form, as described above.

Upon formulation, solutions will be administered in a manner compatible with the dosage formulation and in such amount as is therapeutically effective. The formulations are easily administered in a variety of dosage forms such as injectable solutions, drug release capsules and the like. For parenteral
15 administration in an aqueous solution, for example, the solution should be suitably buffered if necessary and the liquid diluent first rendered isotonic with sufficient saline or glucose. These particular aqueous solutions are especially suitable for intravenous, intramuscular, subcutaneous and intraperitoneal administration. In this connection, sterile aqueous media which can be employed will be known to those of
20 skill in the art in light of the present disclosure. For example, one dosage could be dissolved in 1 ml of isotonic NaCl solution and either added to 1000 ml of hypodermoclysis fluid or injected at the proposed site of infusion, (see for example, "Remington's Pharmaceutical Sciences" 15th Edition, pages 1035-1038 and 1570-1580). Some variation in dosage will necessarily occur depending on the condition of
25 the subject being treated. The person responsible for administration will, in any event, determine the appropriate dose for the individual subject. Moreover, for human administration, preparations should meet sterility, general safety and purity standards as required by FDA and foreign counterpart agencies.

30 Enzymatic Redox Assays

Following a modified procedure of Gius et al., EMSA assays were performed on all compounds to determine redox IC₅₀ values.³⁴ Briefly, purified Apel protein (10 mg / mL) was reduced with DTT (1.0 mM) at 37 °C for 10 min and then

diluted with PBS buffer to final concentrations of Ape1 and DTT of 2 mg / mL and 0.2 mM respectively. A final volume of 18 mL was prepared from EMSA buffer (10 mM Tris [pH 7.5], 50 mM NaCl, 1 mM MgCl₂, 1 mM EDTA, 5% [vol/vol] glycerol) to which was added two mL of reduced Ape1 protein and 6 mg of oxidized nuclear
5 extracts (Hey-C2 cells, treated with 0.01 mM diamide for 10 min); and the reaction was incubated at room temperature for 30 min.

One mL of poly(dI-dC) · poly(dI-dC) (1 mg / μL, Amersham Biosciences, Piscataway, NJ) was added for 5 min followed by one mL of the 5' hexachloro-fluorescein phosphoramidite (HEX)-labeled double-stranded
10 oligonucleotide DNA (0.1 pmol, The Midland Certified Reagent Company, Midland, TX) containing the AP-1 consensus sequence (5'CGCTTGATGACTCAGCCGGAA-3'), and the mixture was further incubated for 30 min. at room temperature. The final concentration of DTT in the redox reactions was 0.02 mM.

Samples were loaded on a 5% nondenaturing polyacrylamide gel and
15 subjected to electrophoresis in 0.5X TBE buffer (200 V for 1 h at 4°C) and detected using the Hitachi FMBio II Fluorescence Imaging System (Hitachi Genetic Systems, South San Francisco, CA). The HEX fluorophore is excited by a solid-state laser at 532 nm (Perkin-Elmer) and emits a fluorescent light signal at 560 nm, which is then measured using a 585 nm filter.

20 If the compound does not affect the redox function of Ape1, oxidized AP1 will become reduced by Ape1 and bind DNA, thus retarding the migration of DNA. (Figure 10, lane 3) If the drug blocks the ability of Ape1 to reduce AP1, then AP1 will remain oxidized, no binding will take place between AP1 and DNA, and DNA migration will not be retarded. (Figure 10, lane 1) A later experiment used
25 Ape1 and purified, oxidized AP1 rather than a cell lysate to confirm a direct relationship between the inhibitors and the interaction between Ape1 and AP1.

Growth Inhibition Assays

Growth inhibitory data was also collected for all the compounds tested
30 in the redox assay. Following the procedure of Fishel et al, cells were aliquoted into 96 well plates at a concentration of 2 – 4,000 cells/well in triplicate and allowed to adhere overnight. Cells were then treated with compound for either 24 or 72 h. 3-(4-5-Dimethylthiazol-2-yl)-5-(3-carboxymethoxyphenyl)-2-(4-sulfophenyl)-2H-

tetrazolium salt (MTS) was added to the cells following compound treatment and the cells were incubated for an additional 4 hours at 37 °C. After incubation with MTS the plates were measured for absorbance at 490 nm.. The values were standardized to wells containing media alone.

5 The benzoquinone series results are found in Table 1. The benzoquinone series included derivatives that varied either in the olefin sidechain adjacent to the carbonyl or the 2-substituent of the ring. Sidechain variants including methyl (10b), butyl (10e), and nonyl (1) showed redox IC₅₀ values in the range of 3 – 15 µM, with the methyl derivative having the lowest IC₅₀. The GI₅₀ values for the
10 same three compounds showed an inverse relationship to the IC₅₀ values. The range for GI₅₀ was 35 – 130 µM, where the nonyl derivative had the greatest activity. A rationale for the inverse relationship between redox and growth inhibition data rests on transportation of the drug molecules across the cell and nuclear membranes to interact with Ape1. The longer aliphatic chain may mediate transport through the
15 lipophilic membranes resulting in greater activity in cell-based assays.

 The hydrocarbon sidechain was also studied by replacing the butyl sidechain with a methoxyethyl group (67). In redox assays the compounds showed similar activity, 15 µM for the hydrocarbon and 10 µM for ether 67. Cell-based growth inhibition data again was in opposition to the enzymatic redox assay, where
20 the ether derivative 67 has a GI₅₀ of 200 µM and the butyl derivative 10e has a GI₅₀ of 85 µM. Further exploration of the sidechain was undertaken utilizing unsubstituted derivative 10a, where the sidechain is completely removed. Both redox and cell-based growth inhibition activities decreased upon removal of the sidechain. The redox IC₅₀ for the unsubstituted derivative was 40 µM compared to 3 µM for the
25 methyl substituted derivative 10b. Growth inhibition was similarly affected, where the GI₅₀ for the methyl sidechain was 130 µM the unsubstituted derivative had a GI₅₀ of 250 µM. The unsubstituted derivative shows the significance of the sidechain for retaining activity in the benzoquinone series. Representative EMSA data are shown in Figure 10 and Figure 11. In Figure 10 the nonyl derivative 1 (E3330) is compared
30 to the unsubstituted derivative 10a and the methoxyethyl derivative 67. Figure 11 shows two different samples of E3330 (1) compared to the n-butyl derivative 10e.

 The 2-position methyl group of the benzoquinone ring in E3330 was explored by synthesizing the 2-chloro derivative 23. The chloro derivative with a

methyl sidechain had equal activity to the 2-methyl derivative 10b in enzymatic redox assays (2.5 and 3.0 μM respectively). In cell-based assays, the 2-chloro derivative was superior to the methyl derivative by a factor of 3, where the alkyl substituted 10b has a GI_{50} of 130 μM and the halogenated derivative 23 had a GI_{50} of 45 μM .

- 5 One significant advance from the benzoquinone series was the realization that truncating the n-nonyl sidechain to a methyl substituent did not affect redox inhibition, but completely removing the sidechain had negative effects. (Table 1).

10 Table 1: Benzoquinone derivatives: Side chain variation and 3-position substitution

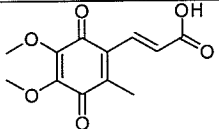
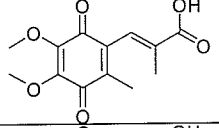
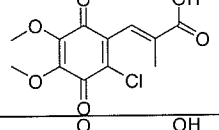
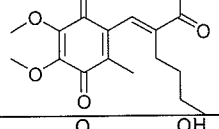
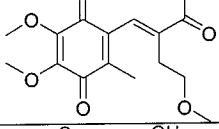
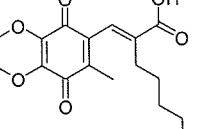
Structure	Name	3-Substituent	Side chain	Redox/ μM	Cell Killing/ μM
	10a	Methyl	Unsubstituted	40	250
	10b	Methyl	Methyl	3	130
	23	Chloro	Methyl	2.5	45
	10e	Methyl	nButyl	15	85
	64	Methyl	Methoxyethyl	10	200
	1	Methyl	nNonyl	10	35

Figure 10: EMSA data for E3330 (1) and derivatives 10a (unsubstituted double bond) and 64 (methoxyethyl substituted double bond). Lanes:

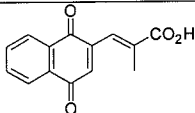
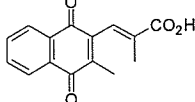
1) oxidized Ape1, oxidized AP1, DNA probe; 2) 0.02 mM DTT, oxidized AP1, DNA probe; 3-15) Inhibitor (μM), reduced Ape1, oxidized AP1, DNA probe.

Figure 11: EMSA data for E3330 (1) and derivative 10e (nbutyl substituted olefin). Lanes: 1) oxidized Ape1, oxidized AP1, DNA probe; 2) 0.02 mM DTT, oxidized AP1, DNA probe; 3-18) Inhibitor (μM), reduced Ape1, oxidized AP1, DNA probe.

The naphthoquinone derivatives showed little variation in activity when the substituent on the double bond was changed from a methyl to a n-butyl or even a methoxyethyl substituent. The more significant activity changes came from modifying the 3-position substituent. The 3-methyl derivatives, which are structurally most similar to E3330, showed the worst redox inhibition of the naphthoquinone derivatives at 10 – 25 μM (Tables 2 and 3). The 3-unsubstituted derivative possessed the potential to have an alternative mechanism of action from the substituted derivatives, where addition to the quinone can be imagined.

The other 3-position derivatives all had redox IC_{50} values below 5 μM , and discerning among them based on structure was difficult. One conclusion from the data is that having an electronegative substituent at the 3 position greatly enhances the redox inhibition of the compound. The chloro, bromo, methoxy, and methylthio derivatives all inhibited redox function between 7.5 and 30 times more than the 3-methyl derivative (Table 2). The 3-fluoro derivative still inhibited redox function at 4 μM ; however, with such an electronegative atom it was expected to significantly enhance the effects observed in the other 3-halo derivatives. Size of the substituent at the 3-position did not seem to have an effect either, where the small chloro and bulky methoxy and methylthio derivatives were nearly identical in activity.

Table 2: Naphthoquinone Derivatives: 3-position substitution

Structure	Name	3-Substituent	Redox/ μM	Cell Killing/ μM
	30a	Unsubstituted	2.5	20
	35a	Methyl	15	45

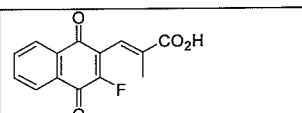
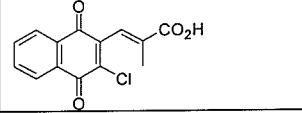
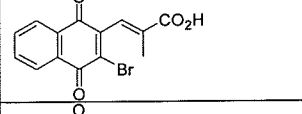
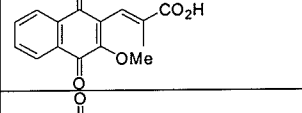
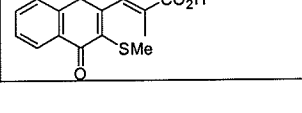
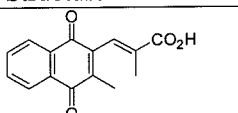
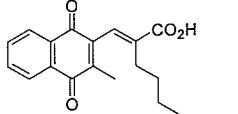
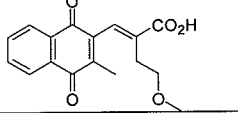
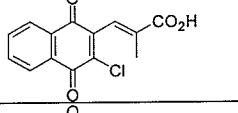
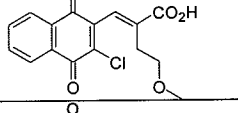
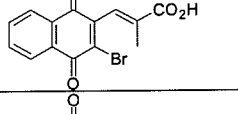
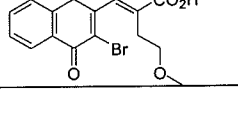
	52	Fluoro	4	50
	43a	Chloro	1.0	15
	39a	Bromo	2.0	12.5
	55	Methoxy	0.5	40
	58	Thiomethyl	1.0	30

Table 3: Naphthoquinone Derivatives: Sidechain variation

Structure	Name	3- position	Side Chain	Redox/ μM	Cell Killing/ μM
	35a	Methyl	Methyl	15	45
	35b	Methyl	nButyl	25	40
	62a	Methyl	Methoxy Ethyl	10	30
	43a	Chloro	Methyl	1.0	15
	62c	Chloro	Methoxy Ethyl	3.0	30
	39a	Bromo	Methyl	2.0	12.5
	62b	Bromo	Methoxy Ethyl	0.5	25

Further derivatives considered all have a degree of modification to the unsaturated acid moiety (Table 4). The double bond was modified first by saturating the olefin to modify the 3-dimensional orientation of the acid and alpha substituent. Two saturated derivatives of 3-bromo 39a were tested, with either unsubstituted (69a) or methyl substitution (69b) alpha to the carbonyl. The methyl substituted derivatives 69b (*R/S*) were tested as a racemic mixture and were equal in activity to the unsubstituted derivative. With an IC_{50} of 5 μ M and a GI_{50} of 15 μ M, the saturated derivatives were not much different in activity than the parent unsaturated derivative 39a (IC_{50} = 2.0 μ M, GI_{50} = 12.5 μ M). The olefin was also epoxidized to keep a rigid structure that possessed a new polar contact and different 3-dimensional shape. A mixture of four diastereomers (71a,b) was tested in enzymatic and cell-based assays. The mixture had an IC_{50} of 4.0 μ M in the redox assay and a GI_{50} of 10 μ M in the cell-based assay. The related unsaturated derivative 43a has an IC_{50} of 1.0 μ M and a GI_{50} of 15 μ M.

Because the mixtures of methyl-substituted saturated derivatives (69b *R/S*) were so similar in activity to the unsubstituted single compound (69a) and the related unsaturated derivative (39a) it was hypothesized there was no need to test the enantiomers separately. The epoxide mixture (71a/b) was also not separated because the activity of the four component mixture was equivalent to that of the unsaturated derivative 43a.

Derivatives of inhibitors with modifications to the carboxyl moiety including esters and amides were synthesized. 3-Chloro acid 43a showed equal activity to the methyl ester (*E*-44a, IC_{50} = μ M, GI_{50} = μ M) and the hydroxyethylamide (76b, IC_{50} = μ M, GI_{50} = μ M). Ester derivatives could possibly be hydrolyzed in cellular experiments; however, the stable amides provided further evidence that the carboxylic acid functional group may not play a role in binding. The most dramatic derivative examined was the *Z* isomer *Z*-43a, where the double bond geometry is reversed. Enzymatic and growth inhibition experiments showed little difference in activity between the *E* (IC_{50} = 1.0 μ M, GI_{50} = 15 μ M) and *Z* (IC_{50} = 1.5 μ M, GI_{50} = 30 μ M) isomers (Table 4).

Table 4: Naphthoquinone Derivatives: Miscellaneous modifications

Structure	Name	3-Substituent	Double Bond	Carbonyl	Redox/ μM	Cell Killing/ μM
	E-43a	Chloro	E	Acid	1.0	15
	Z-43a	Chloro	Z	Acid	1.5	30
	E-44a	Chloro	E	Methyl ester	1.0	17.5
	Z-44a	Chloro	Z	Methyl Ester	2.0	20
	73	Chloro	E	Amide	1.0	7.5
	71	Chloro	Epoxide	Acid	4.0	10
	39a	Bromo	E	Acid	2.0	12.5
	69a	Bromo	Saturated	Acid	5	15
	69b	Bromo	Saturated	Acid	5	15
	1	Methyl	Unsaturated	Acid	10	35
	72	Methyl	Unsaturated	Amide	10	35

The biological analyses of the benzoquinone and naphthoquinone derivatives provide a glimpse into the preferences of the redox active site on Ape1. First, the naphthoquinone derivatives show an increase in activity of an order of magnitude over the benzoquinone derivatives. Second, the nonyl sidechain of E3330 can be reduced to a methyl substituent without a significant loss of activity. In the benzoquinone series a preferred requirement for retention of activity was at least a

methyl substituent on the double bond. Third, in both the benzoquinone and naphthoquinone series an electronegative ring-substituent ortho to the double bond showed increased activity compared to the methyl derivatives. Fourth, the saturation, epoxidation, and geometry reversal of the double bond in the naphthoquinone series
5 showed no decrease in activity. Finally, amidation of the carboxylate in both the benzoquinone and naphthoquinone series showed activity retention.

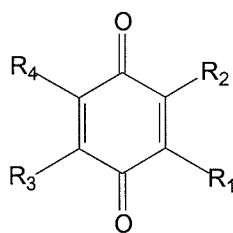
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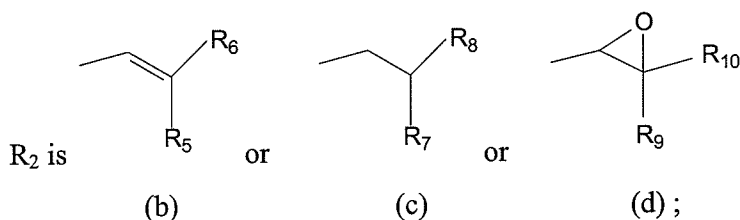
WE CLAIM:

1. A compound of the formula (a)

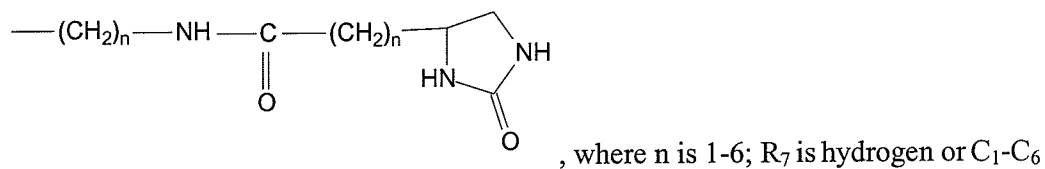
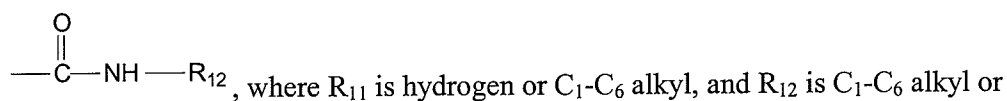


(a)

wherein R₁ is hydrogen, C₁-C₆ alkyl, halo, C₁-C₆ alkoxy, or thio(C₁-C₆ alkyl);



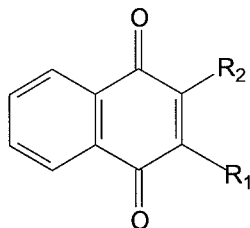
where R₅ is hydrogen or C₁-C₉ alkyl; R₆ is C₁-C₆ alkyl, -COOR₁₁, or



alkyl; R₈ is C₁-C₆ alkoxy, C₆H₅CO-, or -COOR₁₁; R₉ is hydrogen or C₁-C₆ alkyl; R₁₀ is -COOR₁₁; and

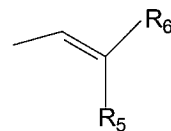
R₃ and R₄ are each, independently C₁-C₆ alkoxy, or together with the carbons to which they are attached form a 6-membered carbon ring; and salts thereof, with the proviso that when R₃ and R₄ are each C₁-C₆ alkoxy, R₁ is not hydrogen, C₁-C₆ alkyl, or C₁-C₆ alkoxy, and R₆ is not -COOR₁₁.

2. The compound of Claim 1 wherein it is of the formula



(e),

or a salt thereof.

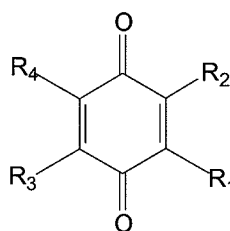
3. The compound of Claim 1 wherein R_1 is halo or thio(C_1 - C_6 alkyl).4. The compound of Claim 2 wherein R_1 is halo or thio(C_1 - C_6 alkyl).5. The compound of Claim 2 wherein R_2 is

(b).

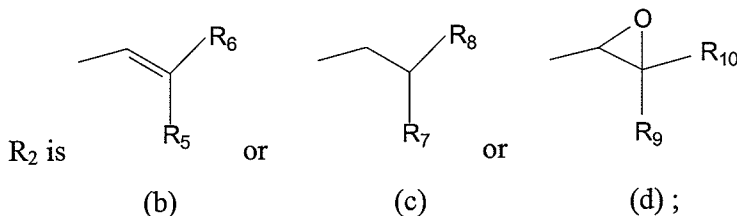
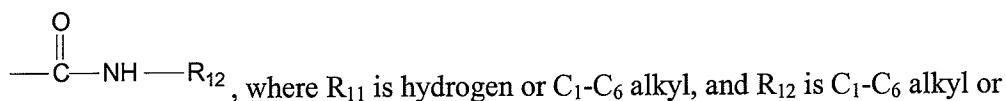
6. The compound of Claim 5 wherein R_6 is $-COOR_{11}$.7. The compound of Claim 6 wherein R_1 is halo or thio(C_1 - C_6 alkyl).

8. A pharmaceutical composition comprising a compound of any of Claims 1 through 7, or a pharmaceutically acceptable salt thereof, in combination with a pharmaceutically acceptable carrier, diluent, or excipient.

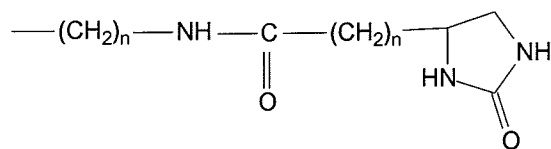
9. A method of inhibiting the redox function of Ape1/Ref1 comprising administering to a subject in need thereof a compound of the formula (a)



(a)

wherein R_1 is hydrogen, C_1 - C_6 alkyl, halo, C_1 - C_6 alkoxy, or thio(C_1 - C_6 alkyl);where R_5 is hydrogen or C_1 - C_9 alkyl; R_6 is C_1 - C_6 alkyl, $-COOR_{11}$, or

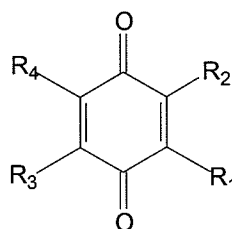
-135-



, where n is 1-6; R₇ is hydrogen or C₁-C₆ alkyl; R₈ is C₁-C₆ alkoxy, C₆H₅CO-, or -COOR₁₁; R₉ is hydrogen or C₁-C₆ alkyl; R₁₀ is -COOR₁₁; and

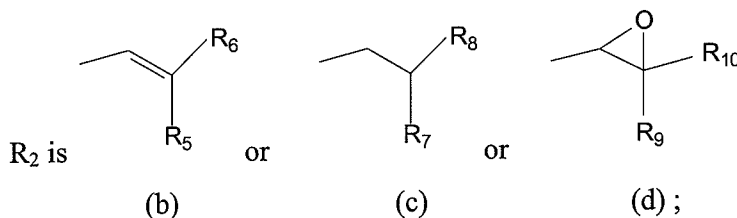
R₃ and R₄ are each, independently C₁-C₆ alkoxy, or together with the carbons to which they are attached form a 6-membered carbon ring; and pharmaceutically acceptable salts thereof.

10. A method for inhibiting a physiological disorder associated with altered angiogenesis comprising administering to a subject in need thereof an effective amount of a compound of formula (a)

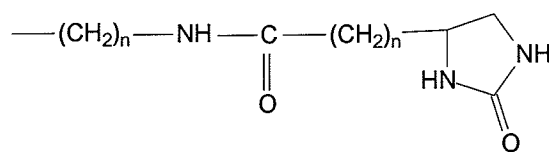
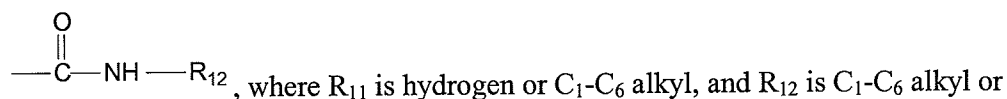


(a)

wherein R₁ is hydrogen, C₁-C₆ alkyl, halo, C₁-C₆ alkoxy, or thio(C₁-C₆ alkyl);



where R₅ is hydrogen or C₁-C₉ alkyl; R₆ is C₁-C₆ alkyl, -COOR₁₁, or



, where n is 1-6; R₇ is hydrogen or C₁-C₆ alkyl; R₈ is C₁-C₆ alkoxy, C₆H₅CO-, or -COOR₁₁; R₉ is hydrogen or C₁-C₆ alkyl; R₁₀ is -COOR₁₁; and

R_3 and R_4 are each, independently C_1 - C_6 alkoxy, or together with the carbons to which they are attached form a 6-membered carbon ring; and salts thereof.

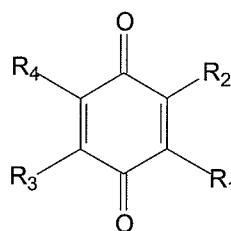
11. The method of Claim 11 wherein said disorder is selected from cancer, cardiovascular disease, chronic inflammatory disease, rheumatoid arthritis, diabetic retinopathy, degenerative maculopathy, retrolental fibroplasias, idiopathic pulmonary fibrosis, acute adult respiratory distress syndrome, asthma, endometriosis, psoriasis, keloids, and systemic sclerosis.

12. The method of Claim 11 wherein said disorder is cancer.

13. The method of Claim 10 wherein at least one additional therapeutic agent is administered to said subject.

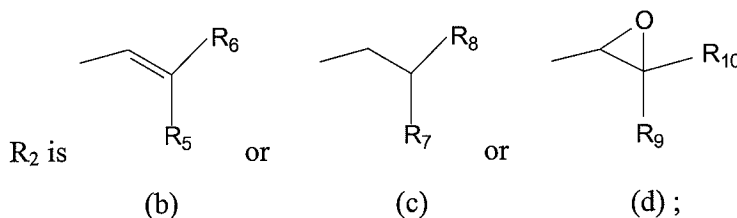
14. The method of Claim 13 wherein said additional therapeutic agent is Avastin.

15. A method for inhibiting cancer comprising administering to a subject in need thereof an effective amount of a compound of the formula (a)

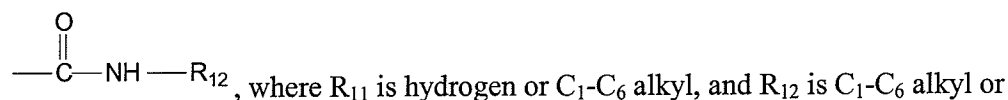


(a)

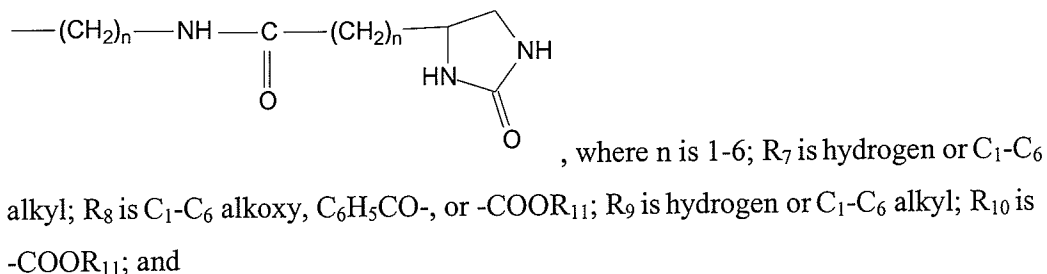
wherein R_1 is hydrogen, C_1 - C_6 alkyl, halo, C_1 - C_6 alkoxy, or thio(C_1 - C_6 alkyl);



where R_5 is hydrogen or C_1 - C_9 alkyl; R_6 is C_1 - C_6 alkyl, $-COOR_{11}$, or



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R₃ and R₄ are each, independently C₁-C₆ alkoxy, or together with the carbons to which they are attached form a 6-membered carbon ring; and pharmaceutically acceptable salts thereof.

16. The method of Claim 15 wherein said cancer is selected from breast, prostate, pancreas, colon, cervical, germ cell tumors, adult and pediatric gliomas, osteosarcomas, rhabdomyosarcomas, non-small cell lung cancer, leukemias, and multiple myeloma.

17. The method of Claim 15 wherein at least one additional therapeutic agent is administered to said subject.

18. The method of Claim 17 wherein said additional therapeutic agent is selected from melphalan, gemcitabine, cisplatin, thalidomide and its derivatives, and retinoic acid.

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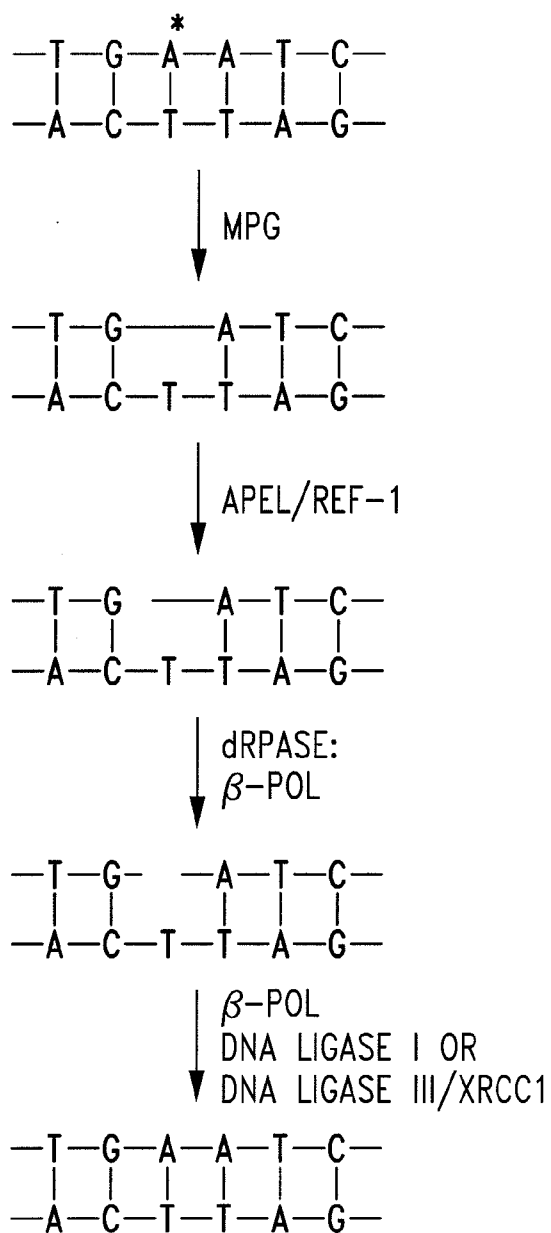


Fig. 1A

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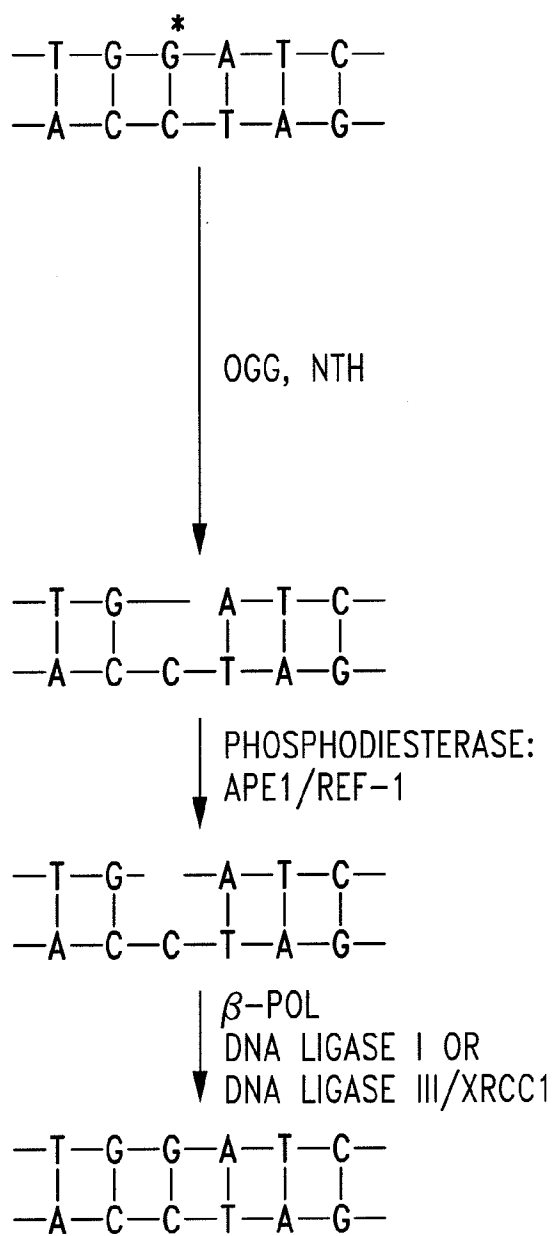


Fig. 1B

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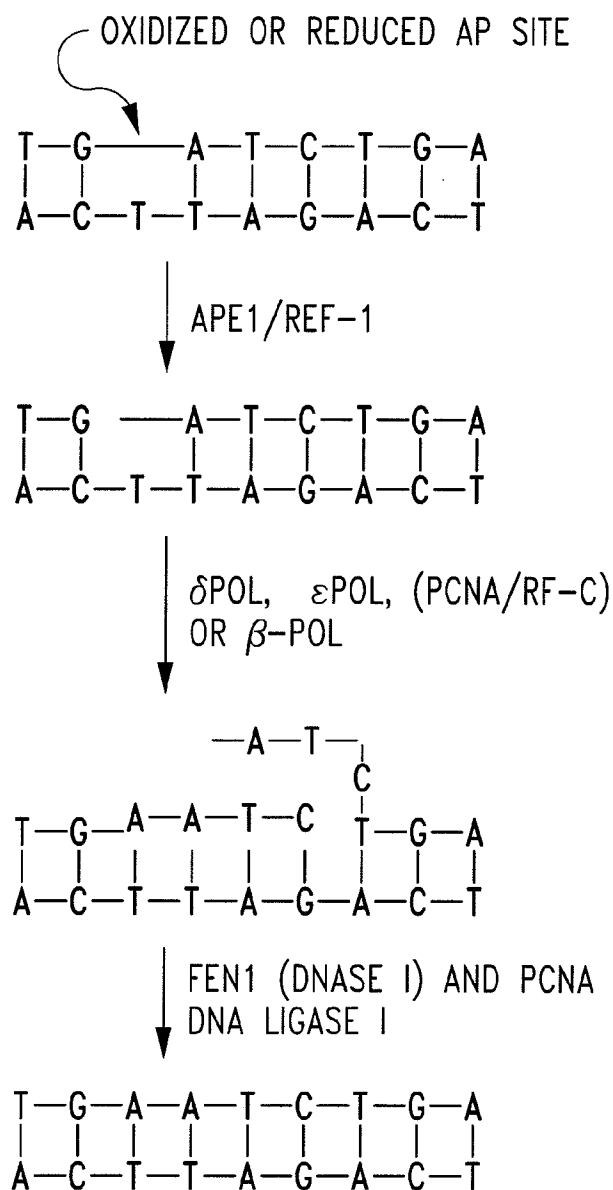


Fig. 1C

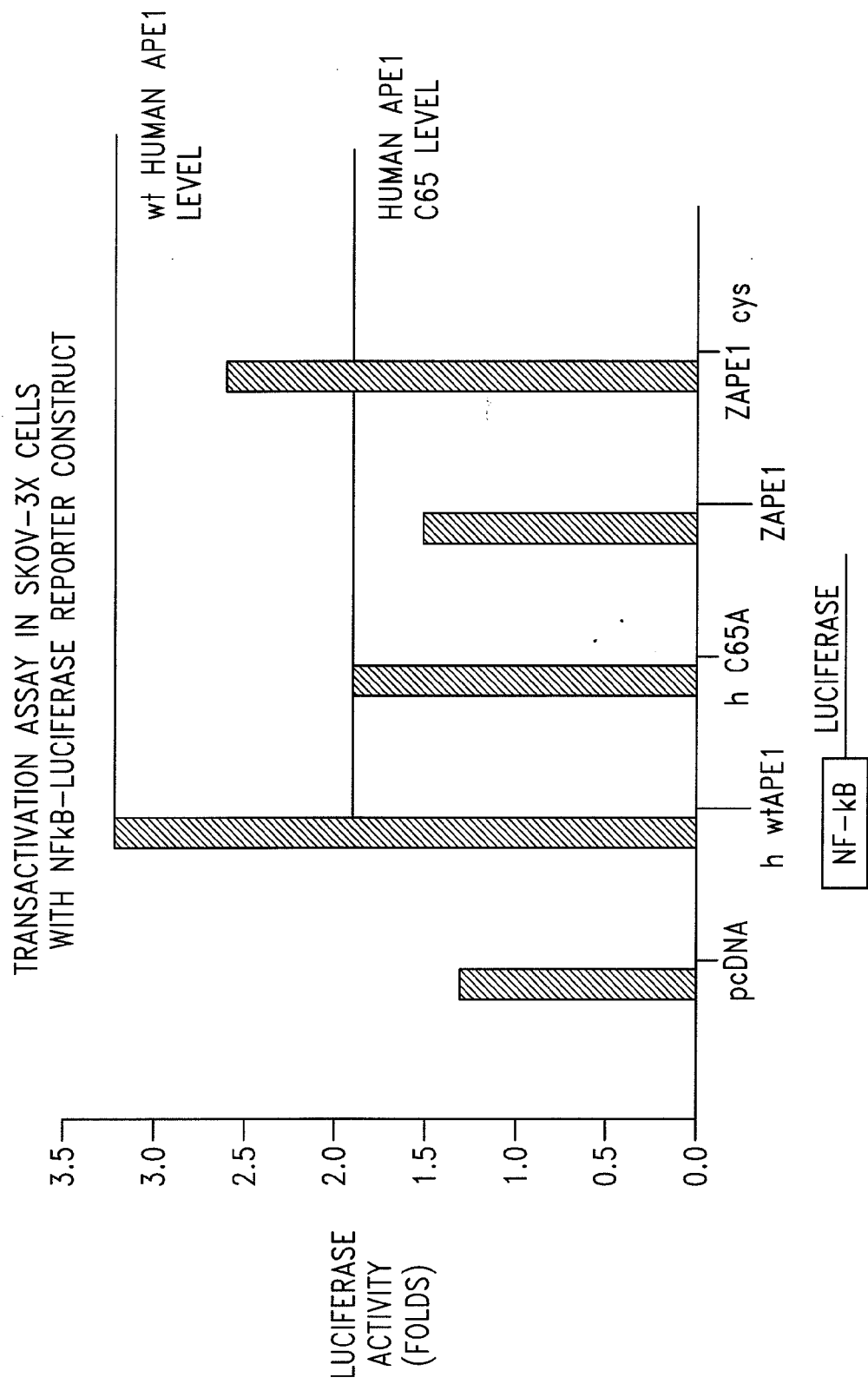


Fig. 2

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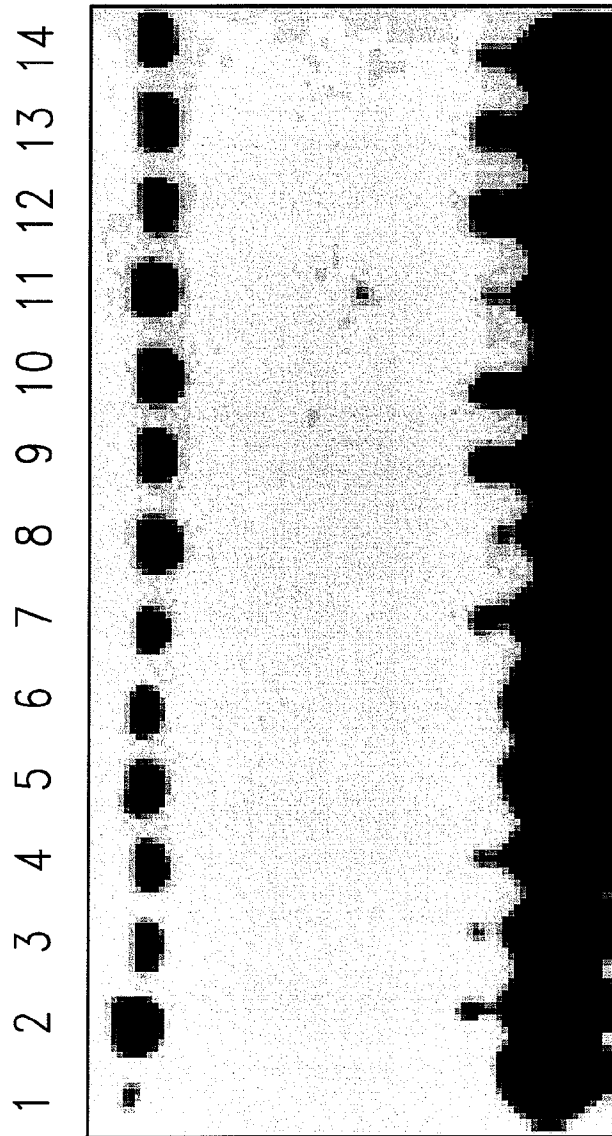


Fig. 3

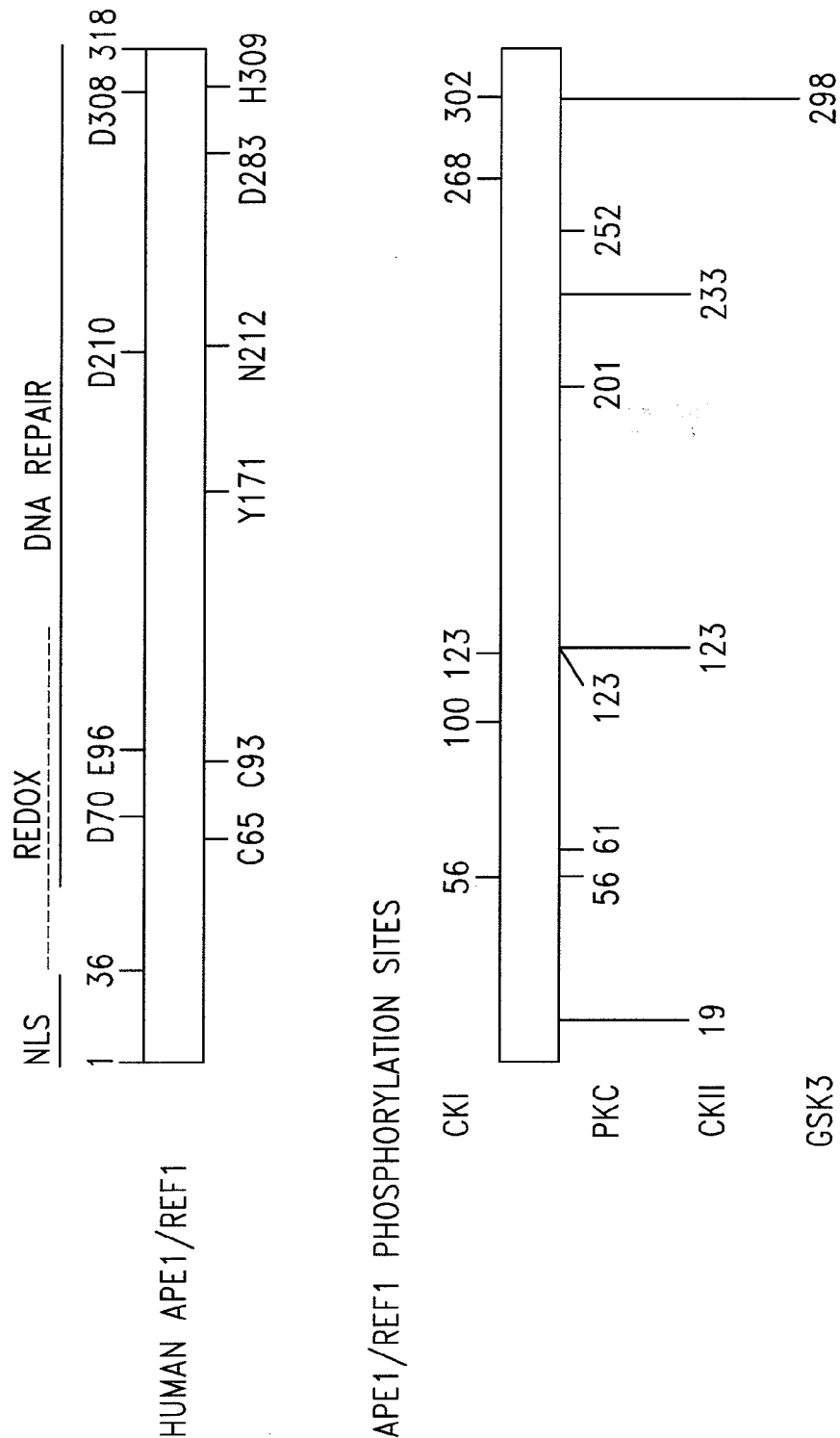


Fig. 4

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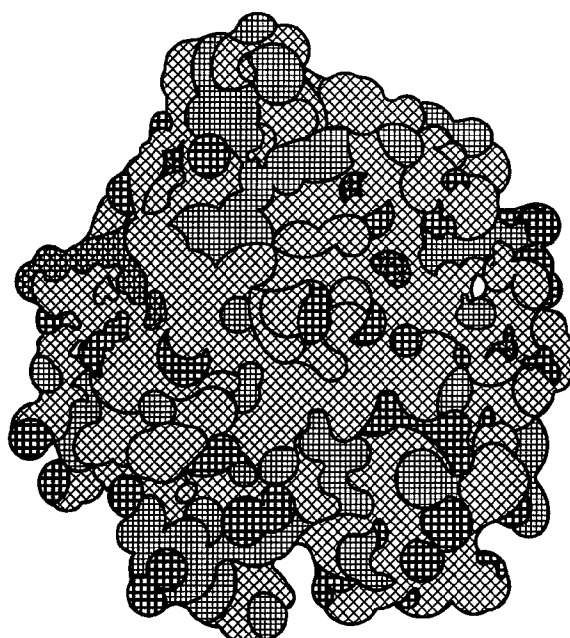


Fig. 5B

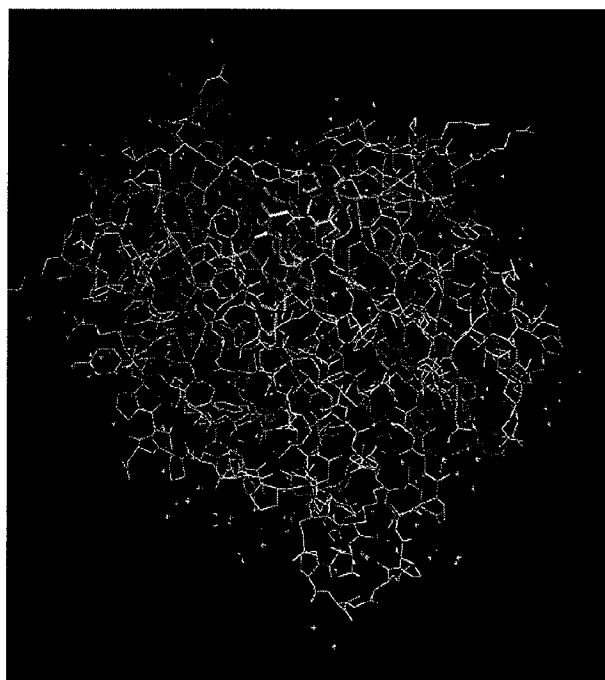
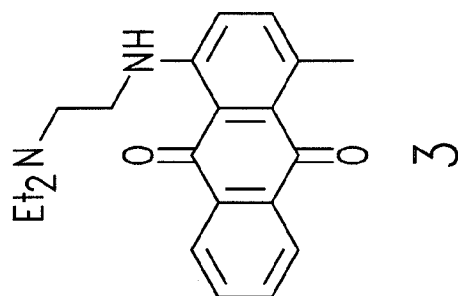


Fig. 5A

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NH_2OMe

2

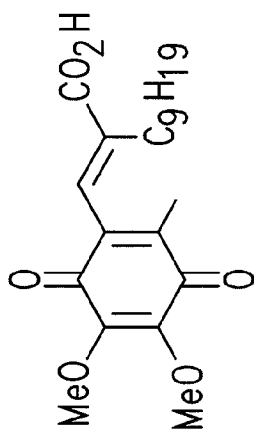


Fig. 6

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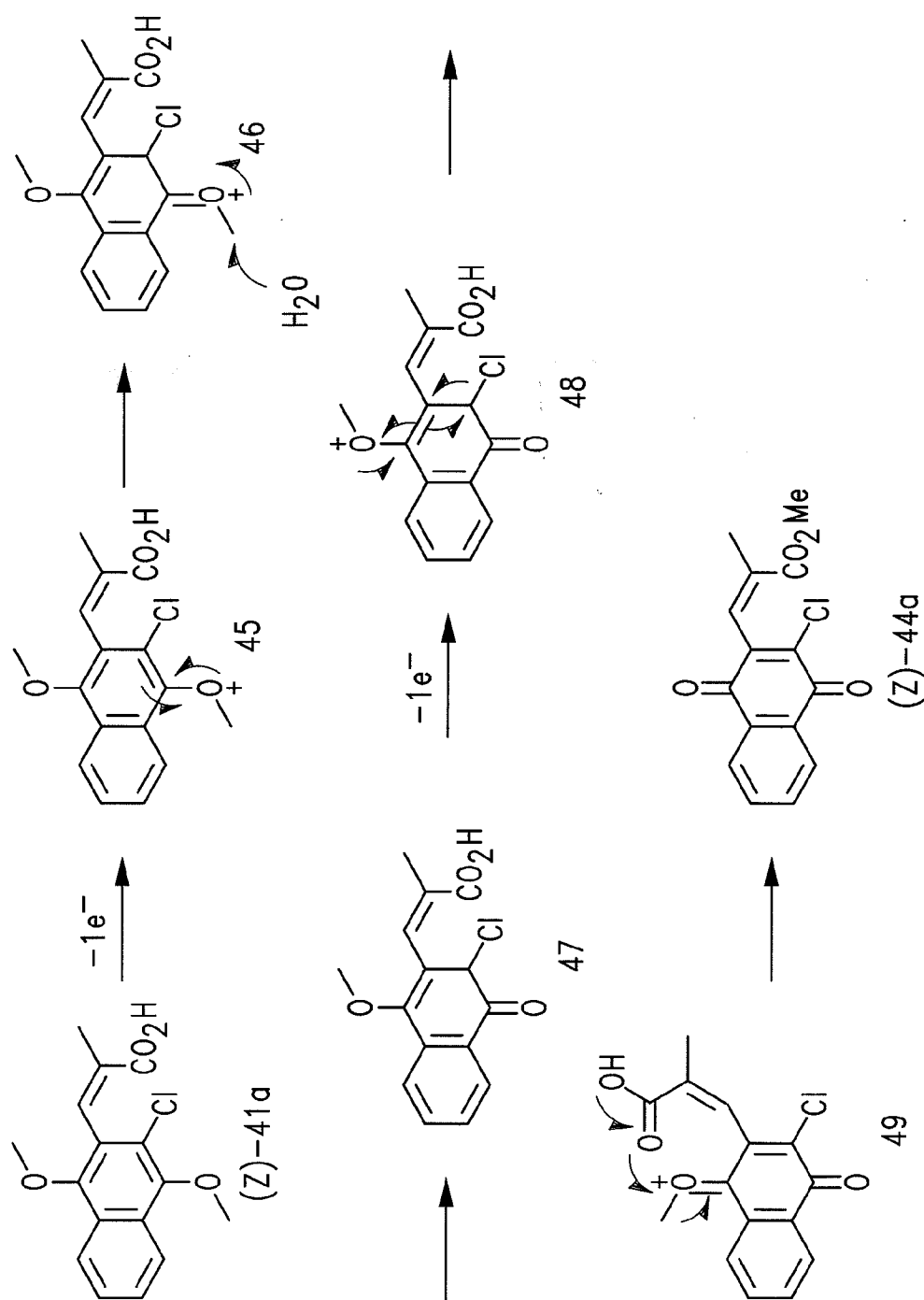
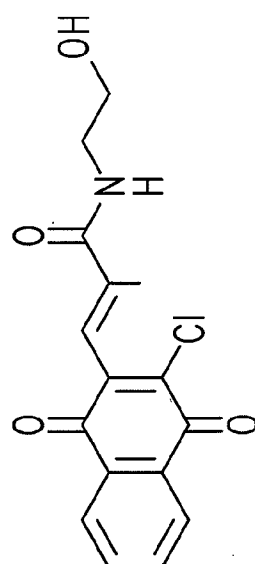
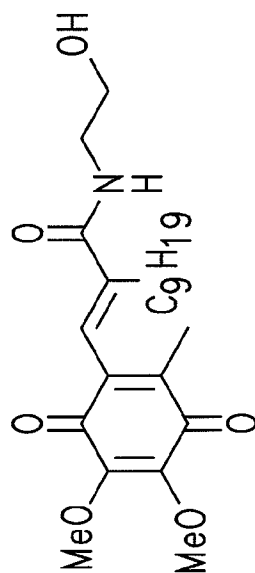


Fig. 7

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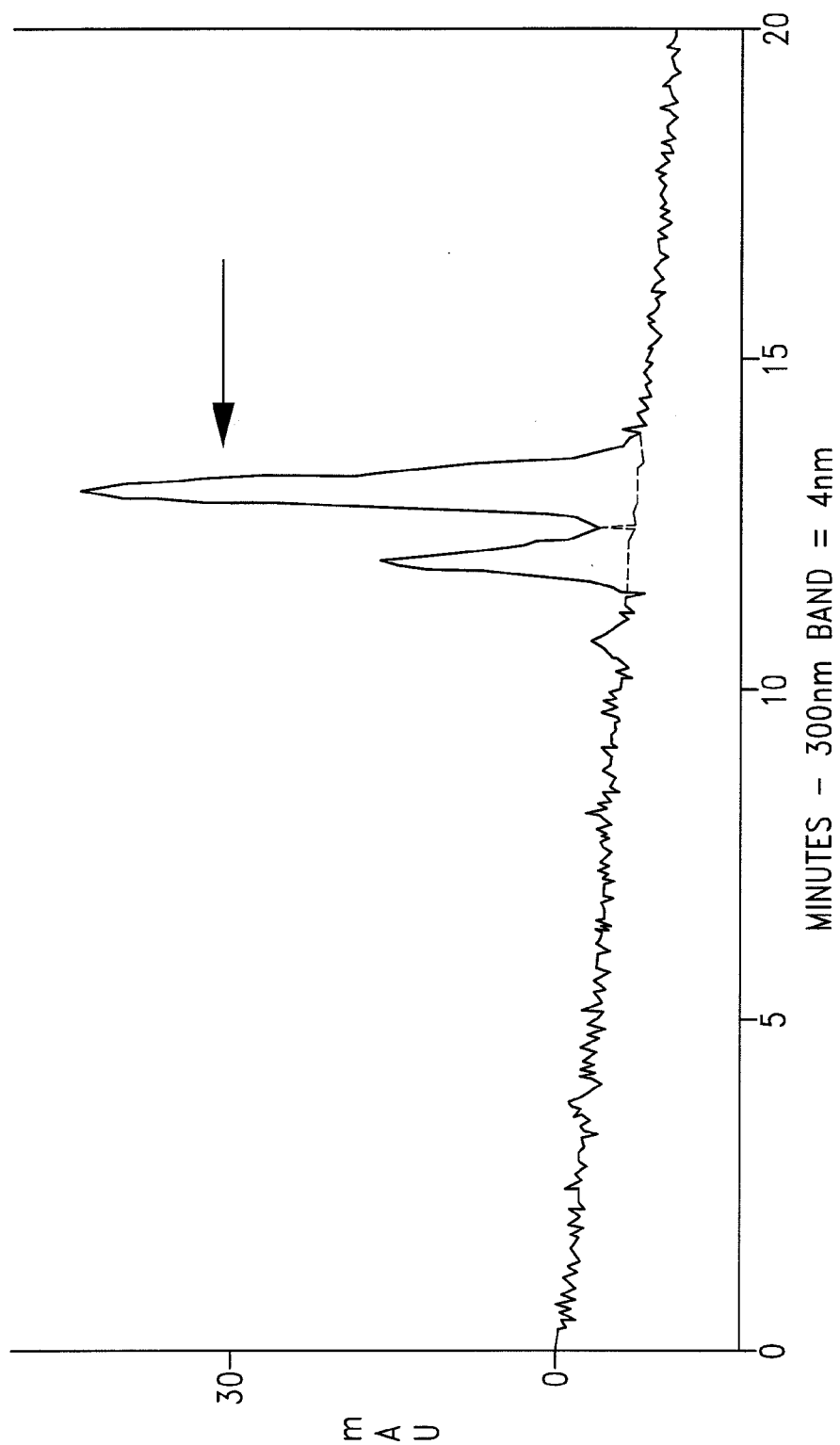
73



72

Fig. 8

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MINUTES - 300nm BAND = 4nm

Fig. 9A

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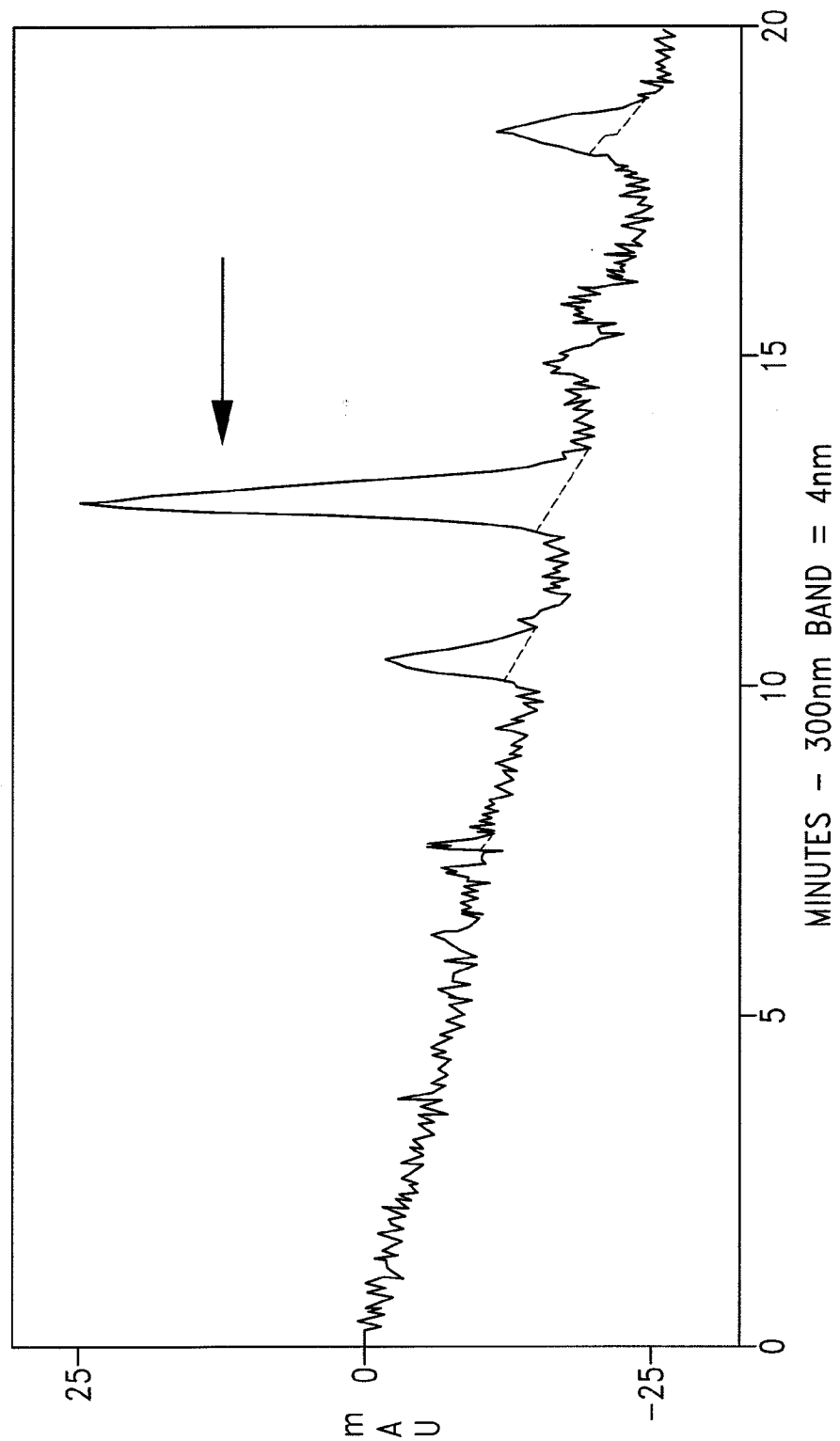


Fig. 9B

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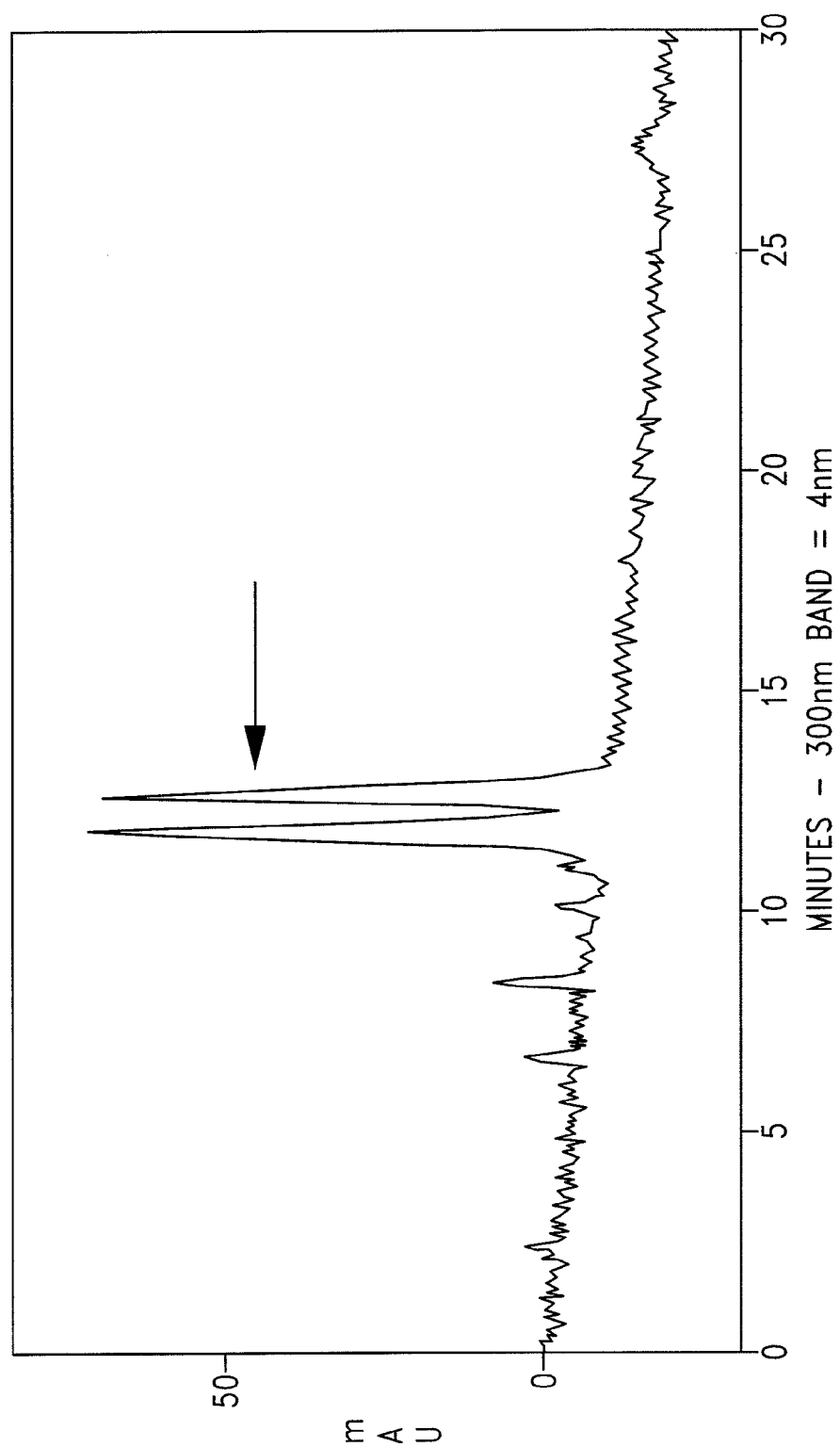


Fig. 9C

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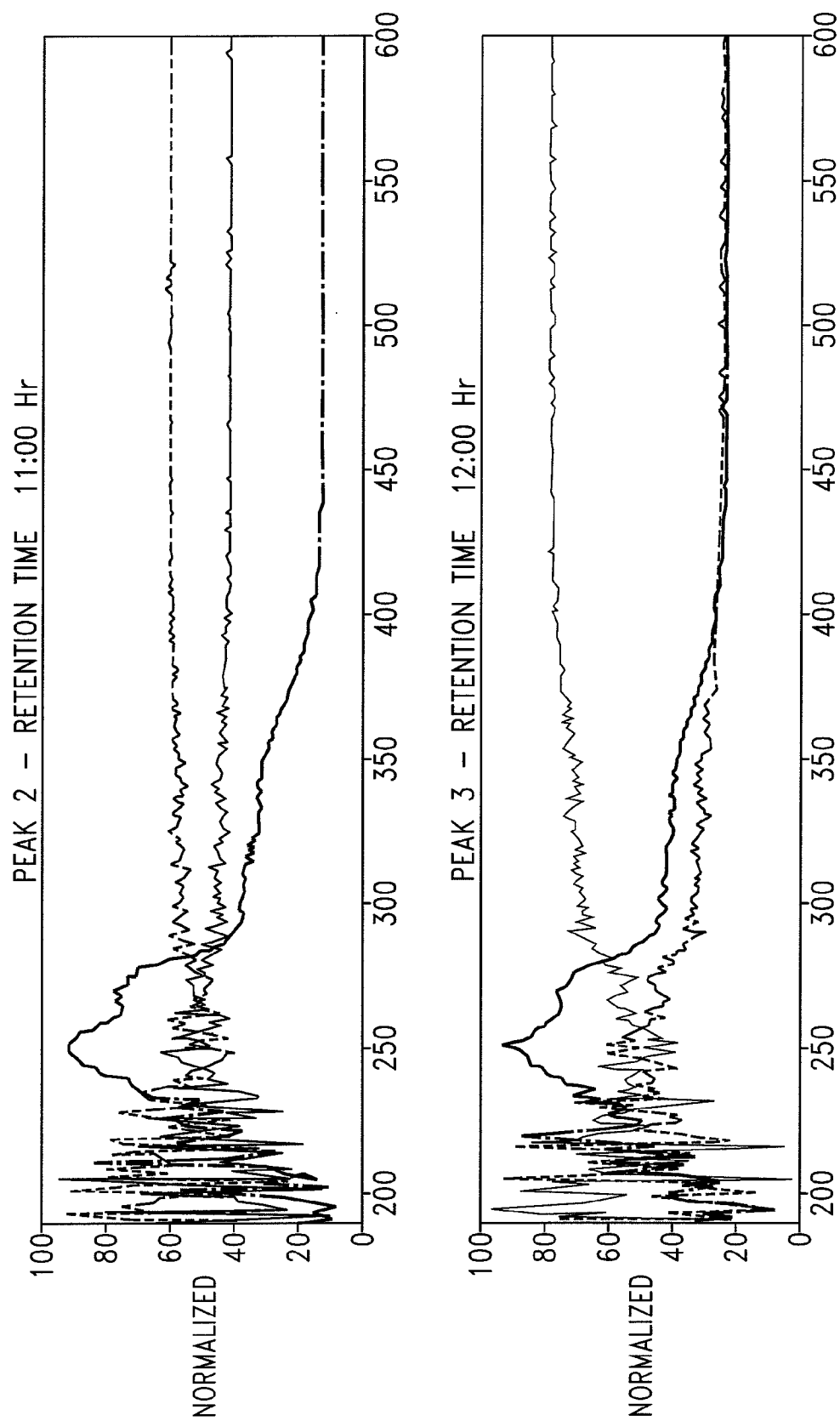


Fig. 9D

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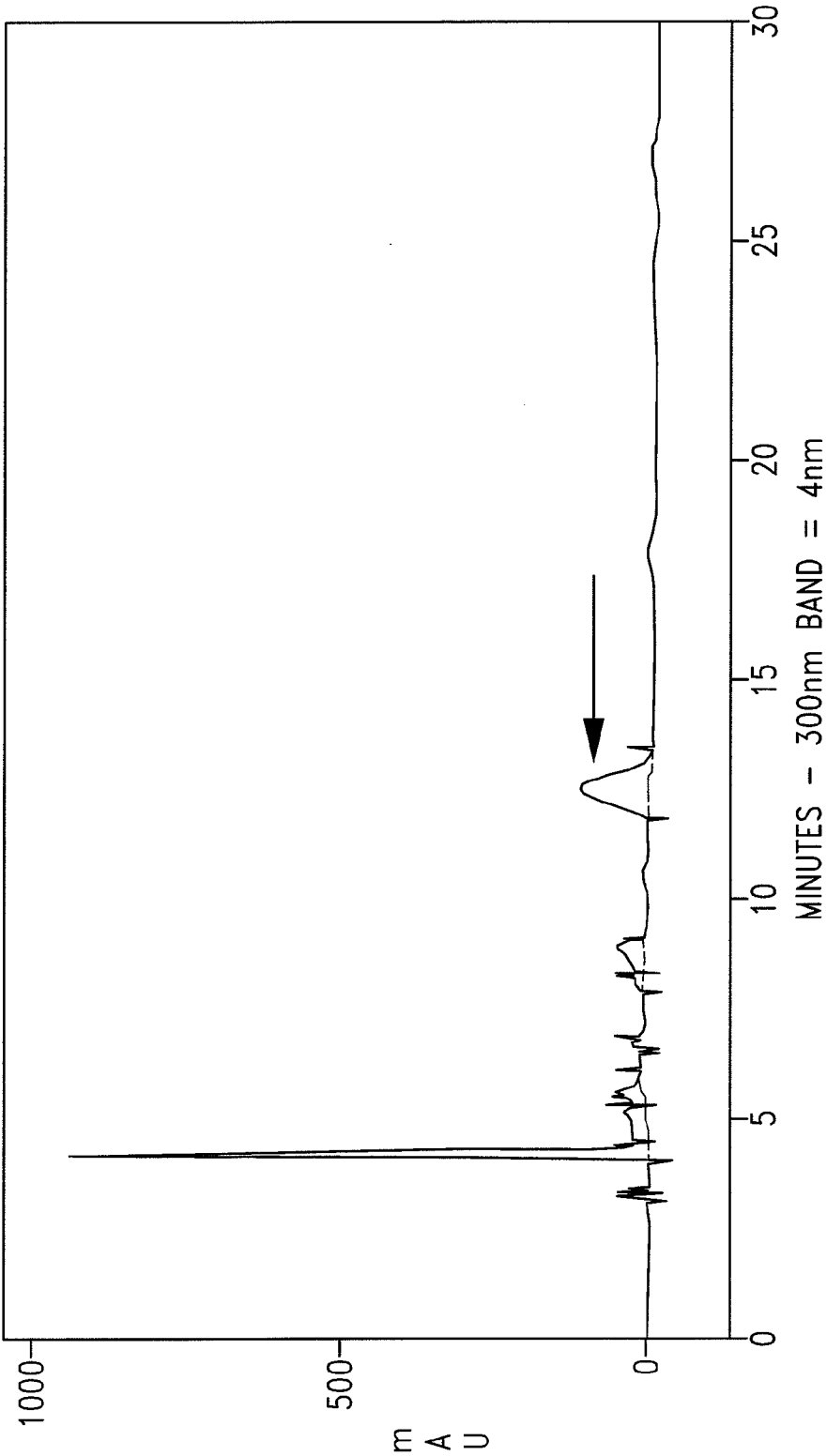


Fig. 9E

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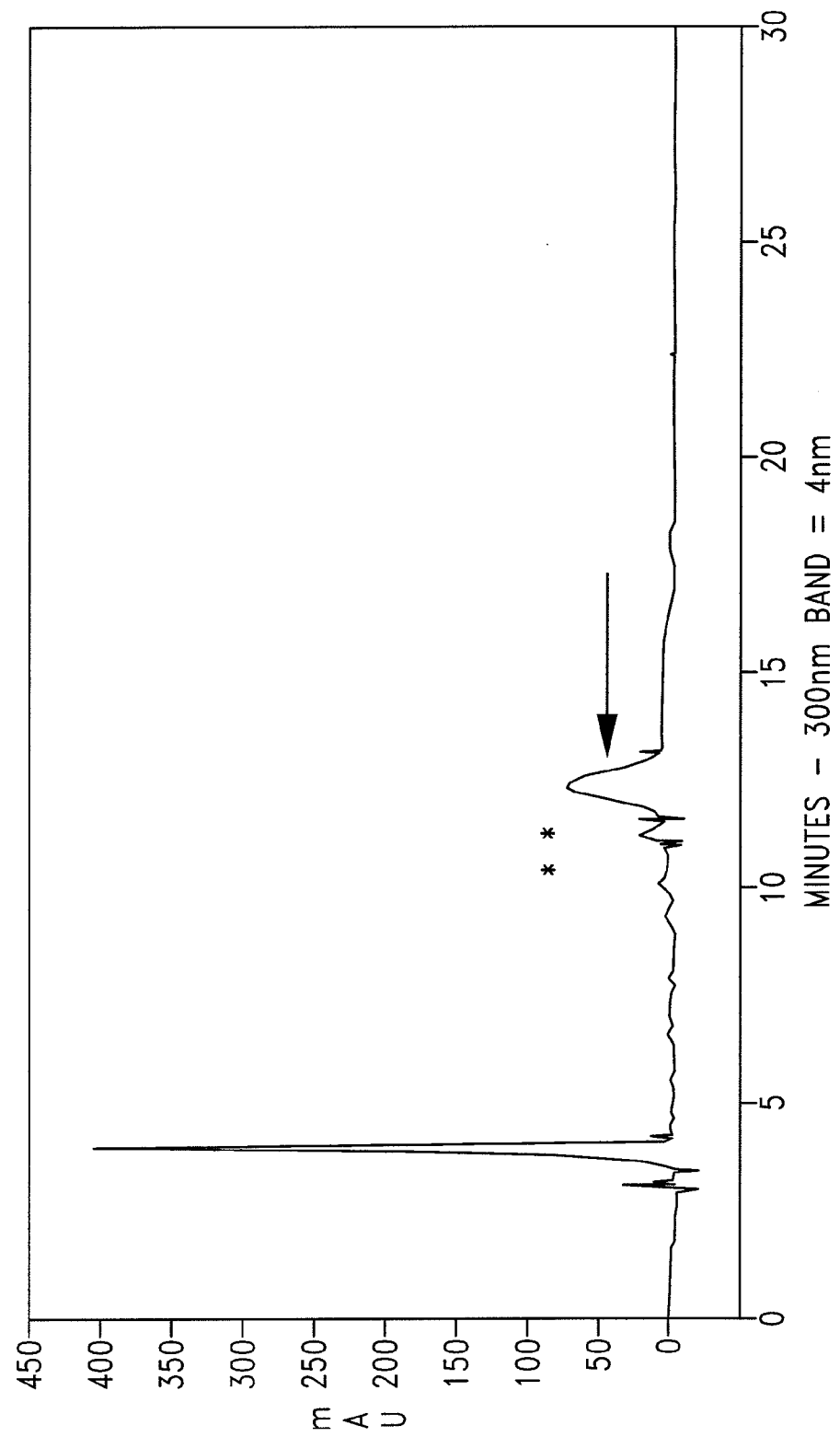


Fig. 9F

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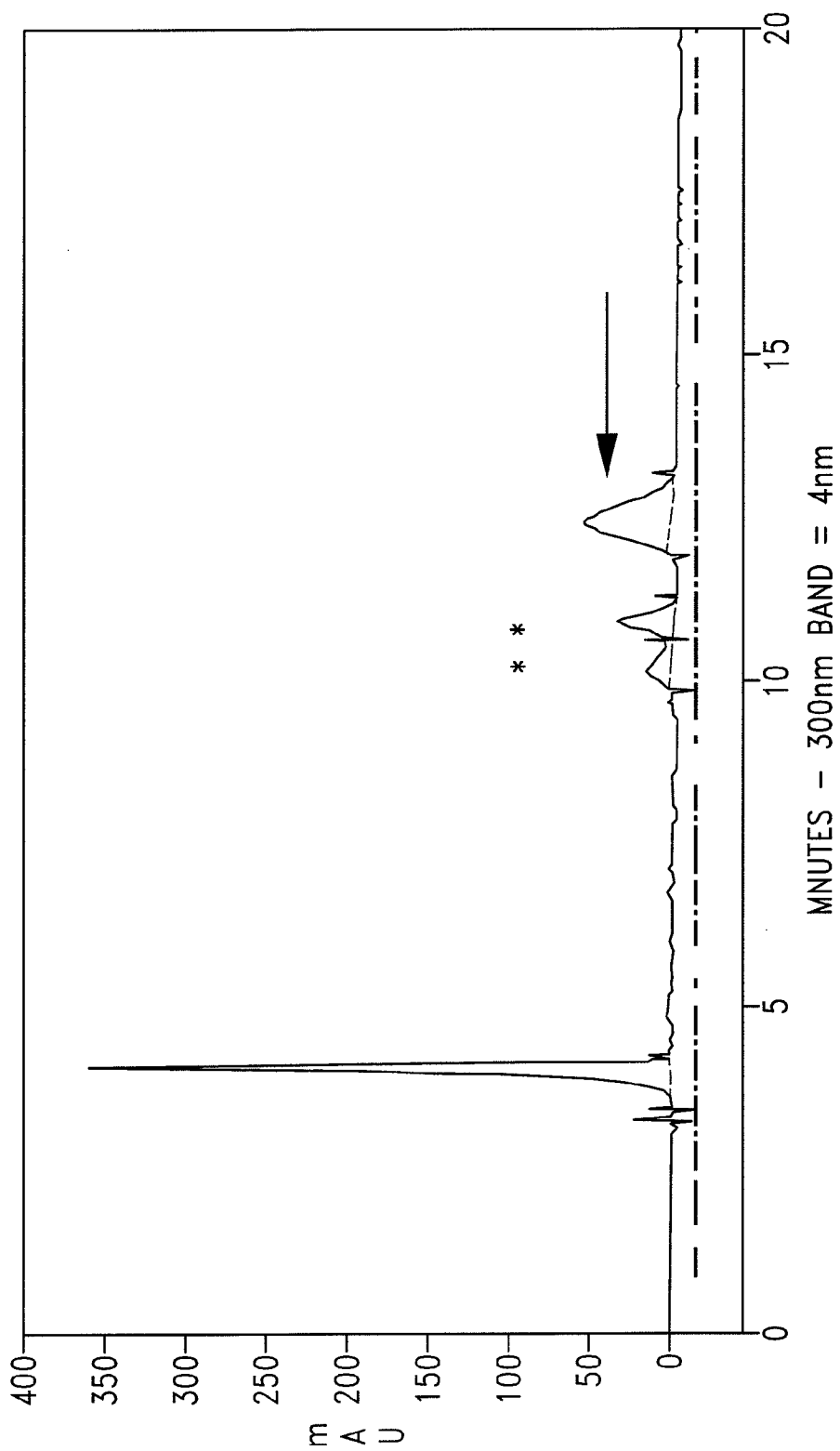


Fig. 9G

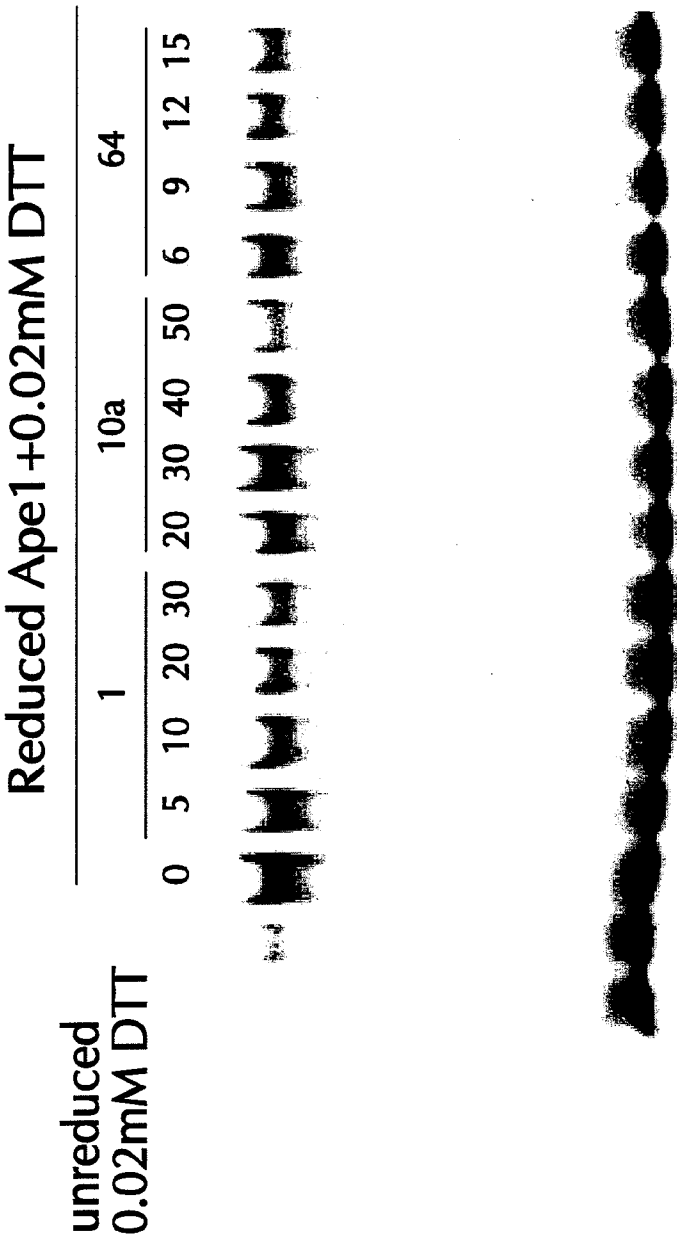


Figure 10: EMSA data for E3330 (1) and derivatives 10a (unsubstituted double bond) and 64 (methoxyethyl substituted double bond).

Fig. 10

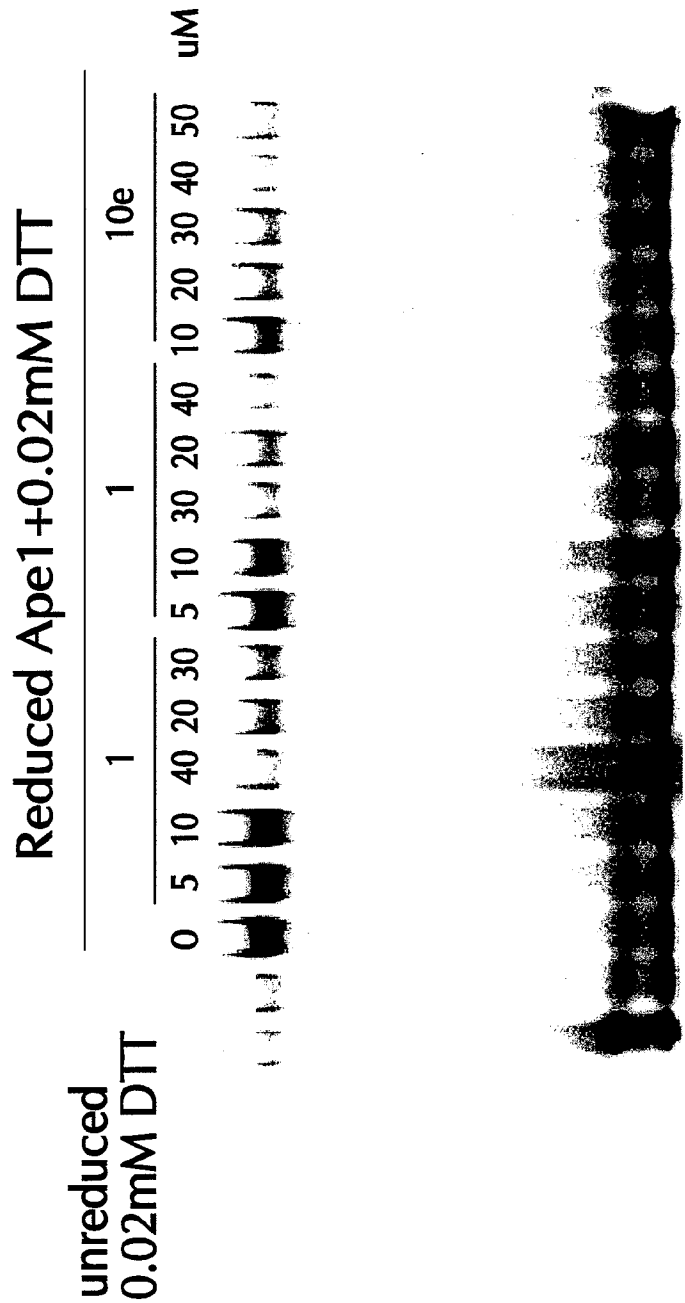


Figure 11: EMSA data for E3330 (1) and derivatives 10e (nbutyl substituted olefin)

Fig. 11

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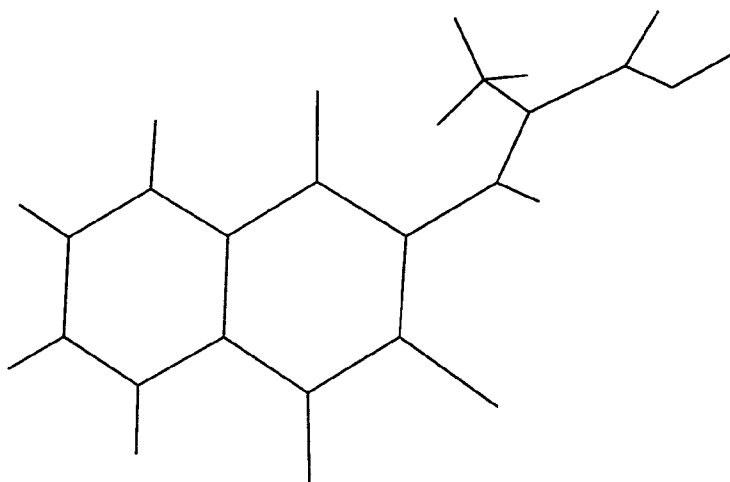


Figure 12: A. Crystal of inhibitor 43a used for X-ray diffraction study. B. Structure generated from data collected from X-ray diffraction studies on 43a.

Fig. 12

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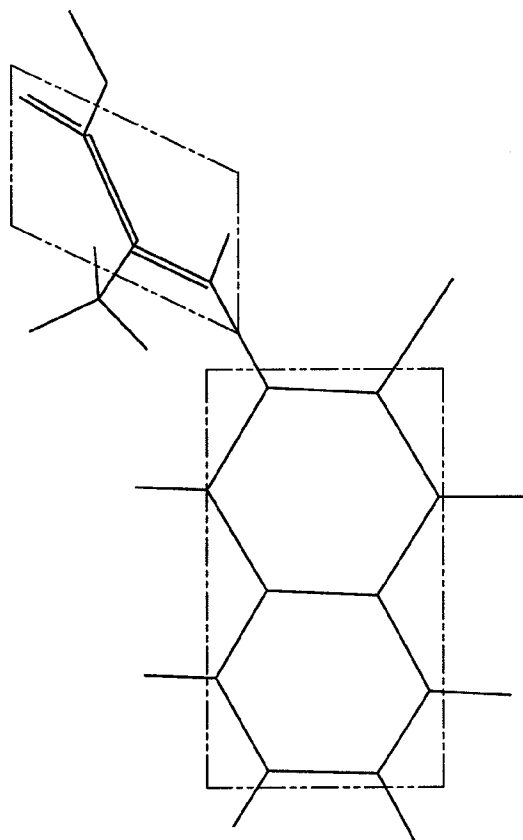


Figure 13: Structure derived from X-ray diffraction study shows both the relationship between quinone and unsaturated acid planes as well as trans-diene like unsaturated acid conformation.

Fig. 13

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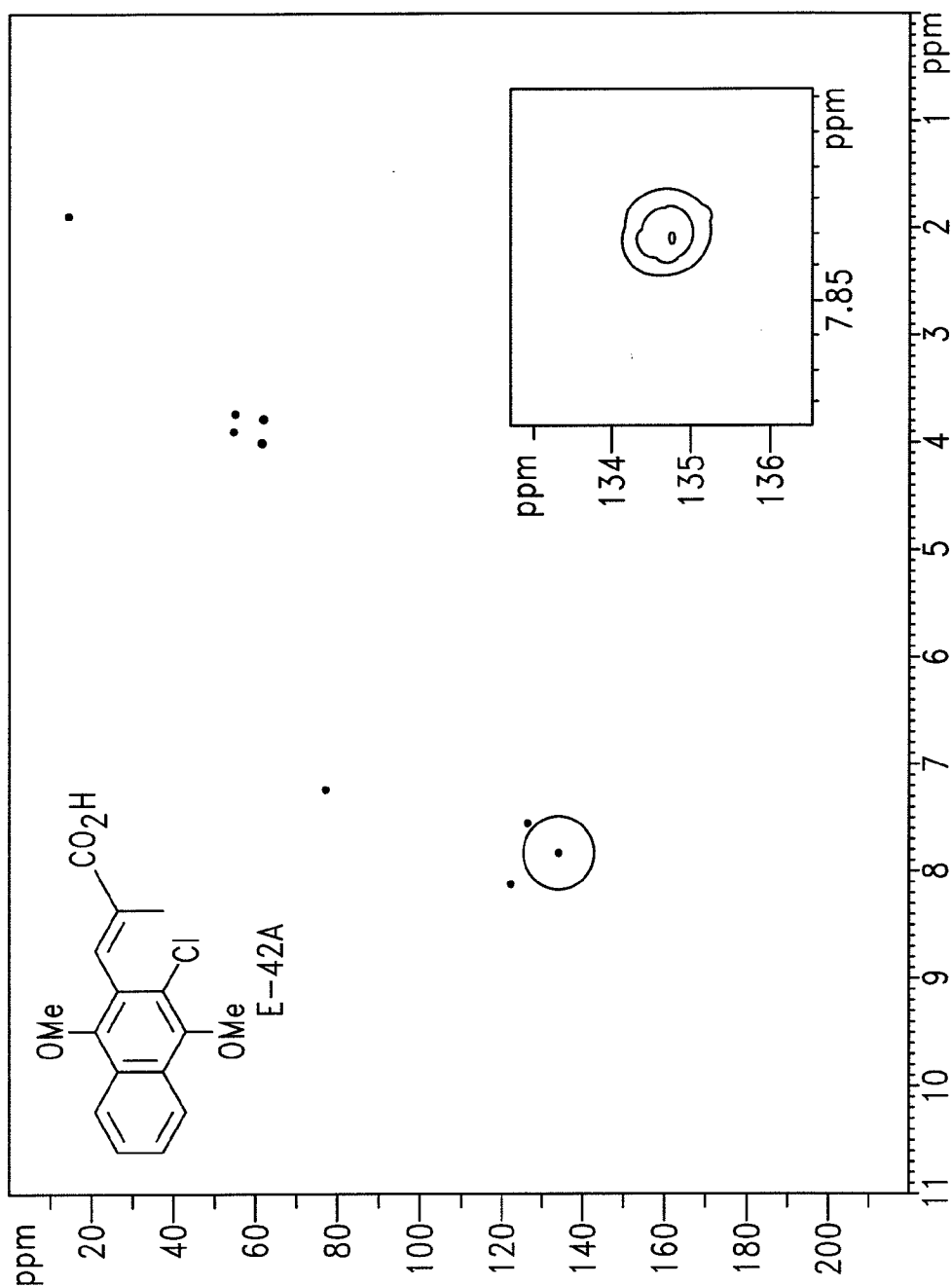


Fig. 14A

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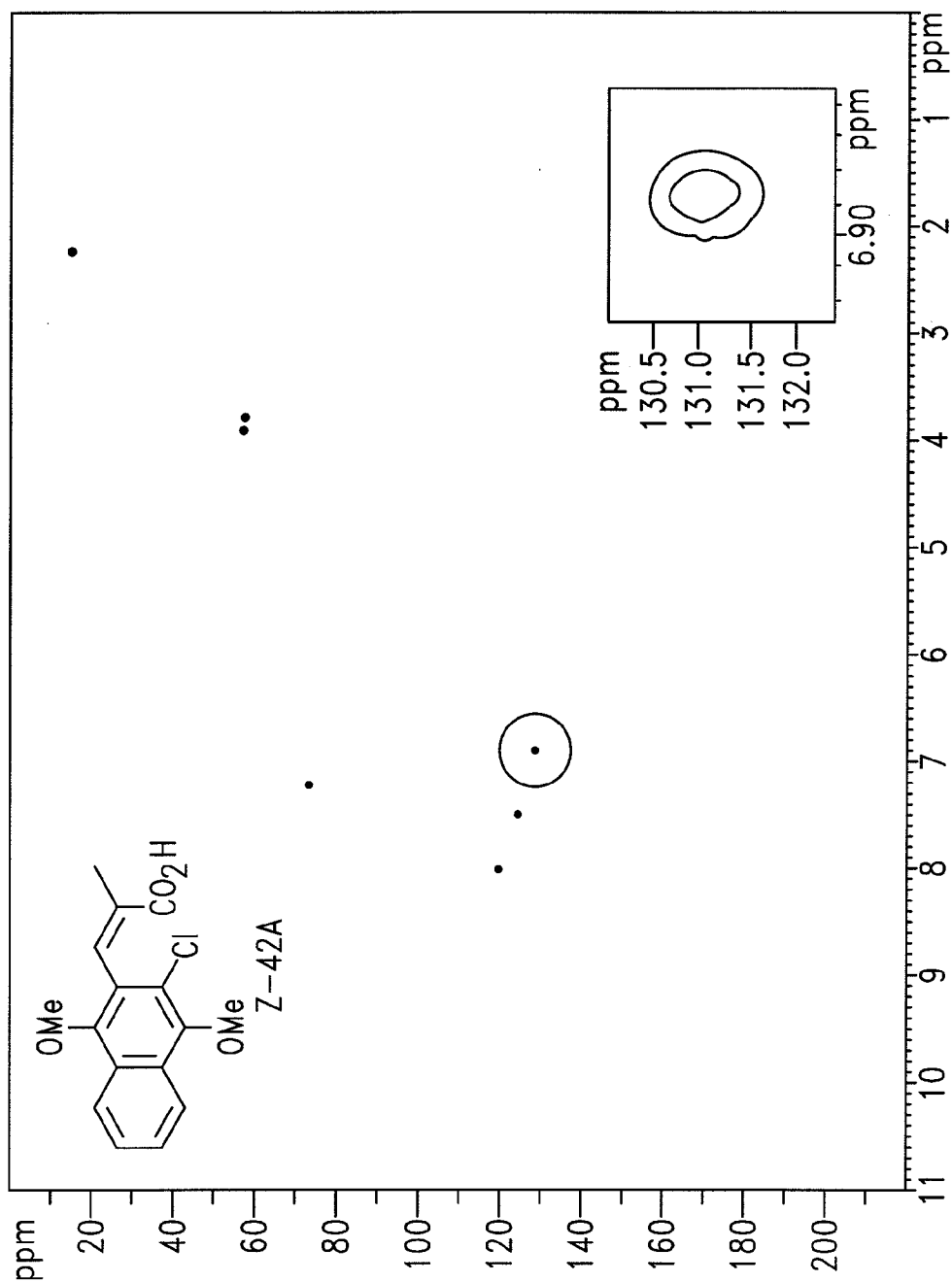


Fig. 14B

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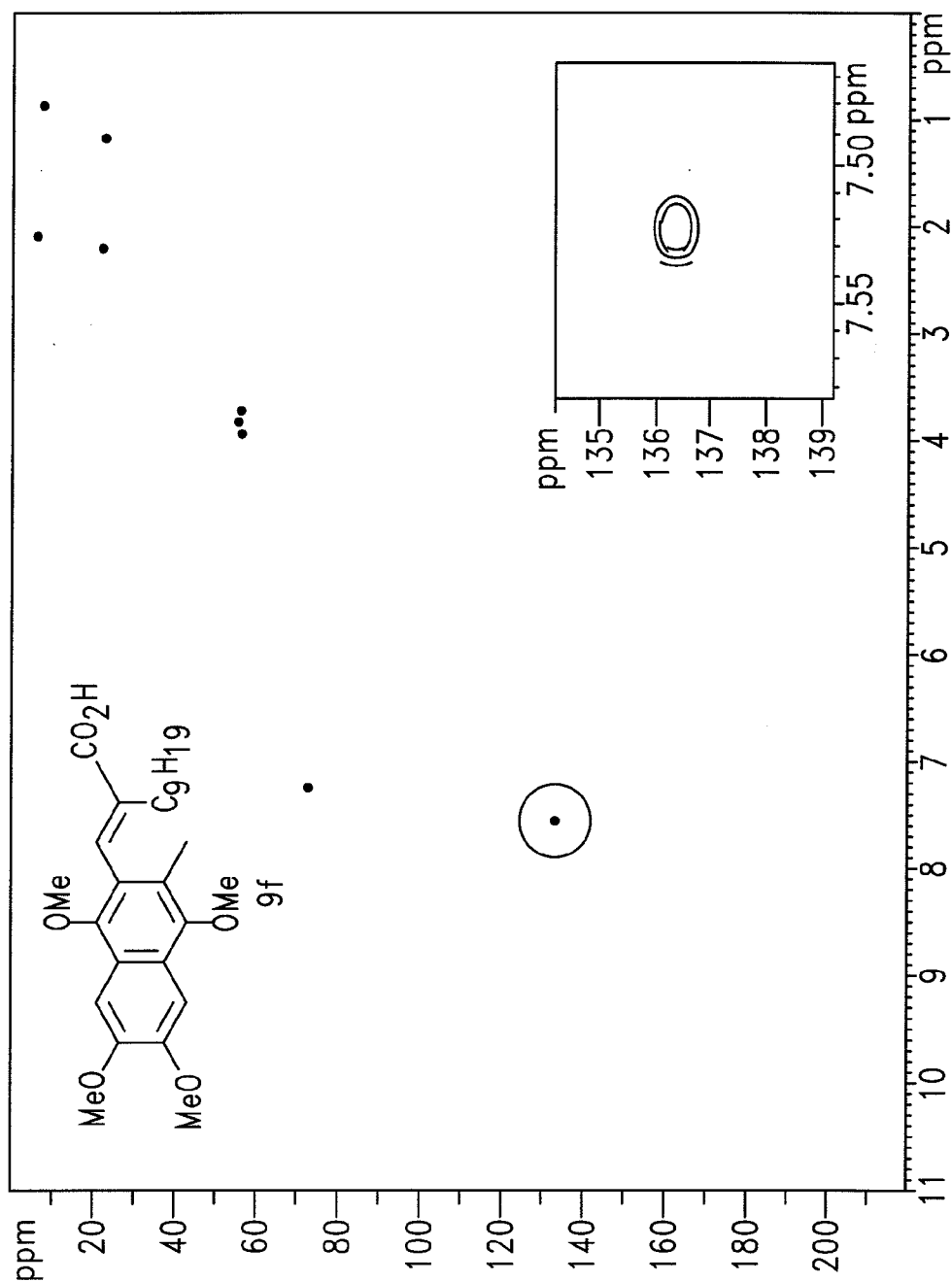


Fig. 14C

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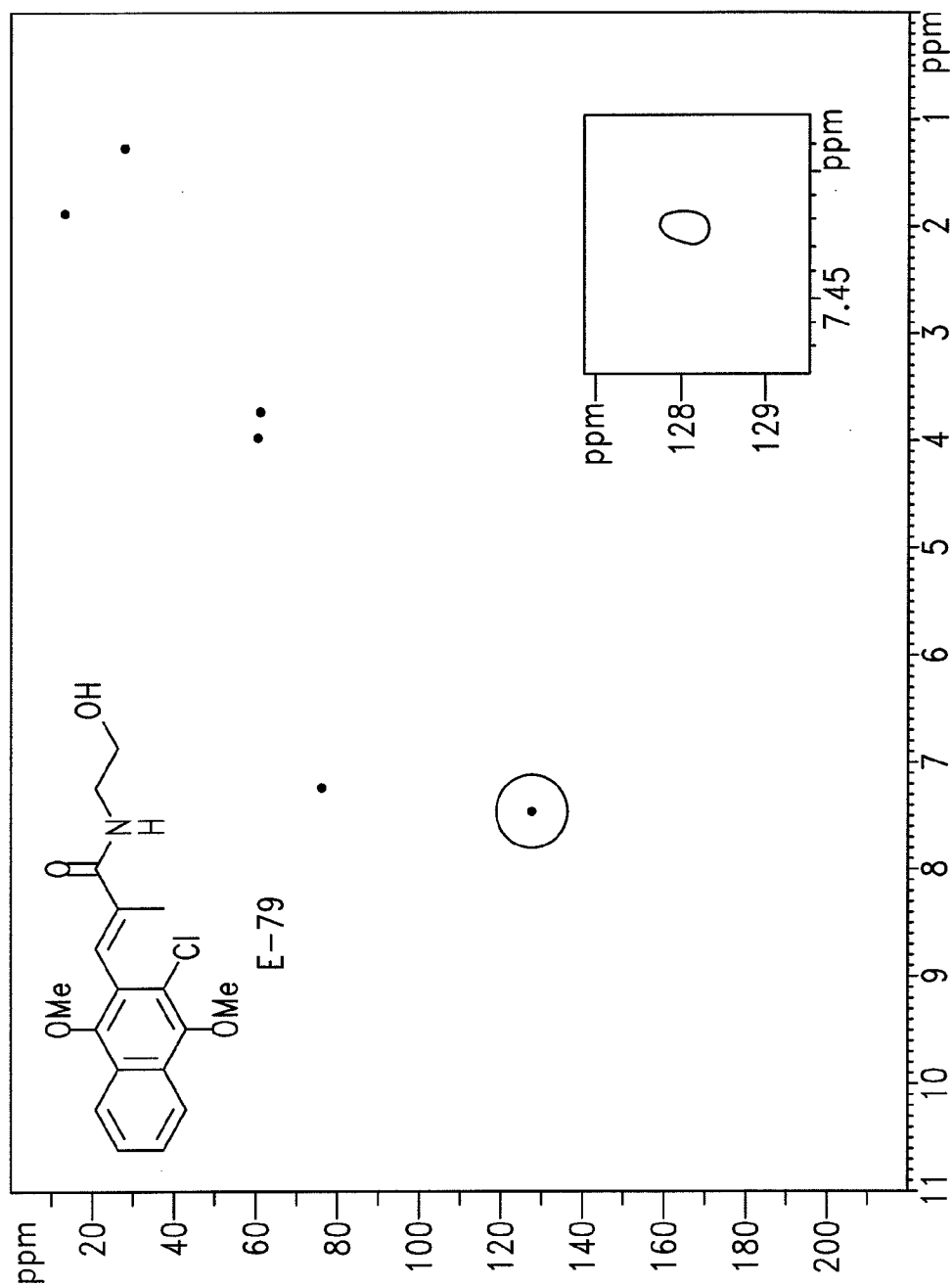


Fig. 14D

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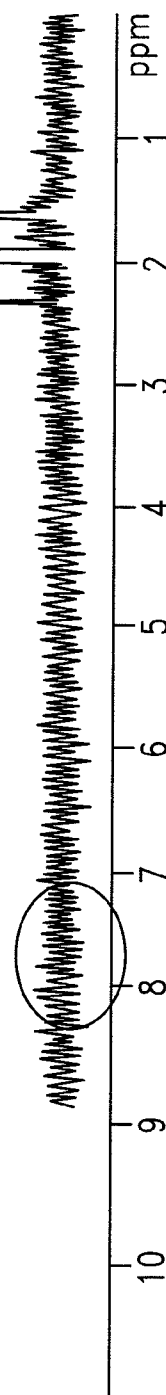
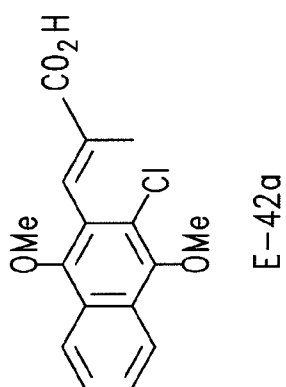


Fig. 15A

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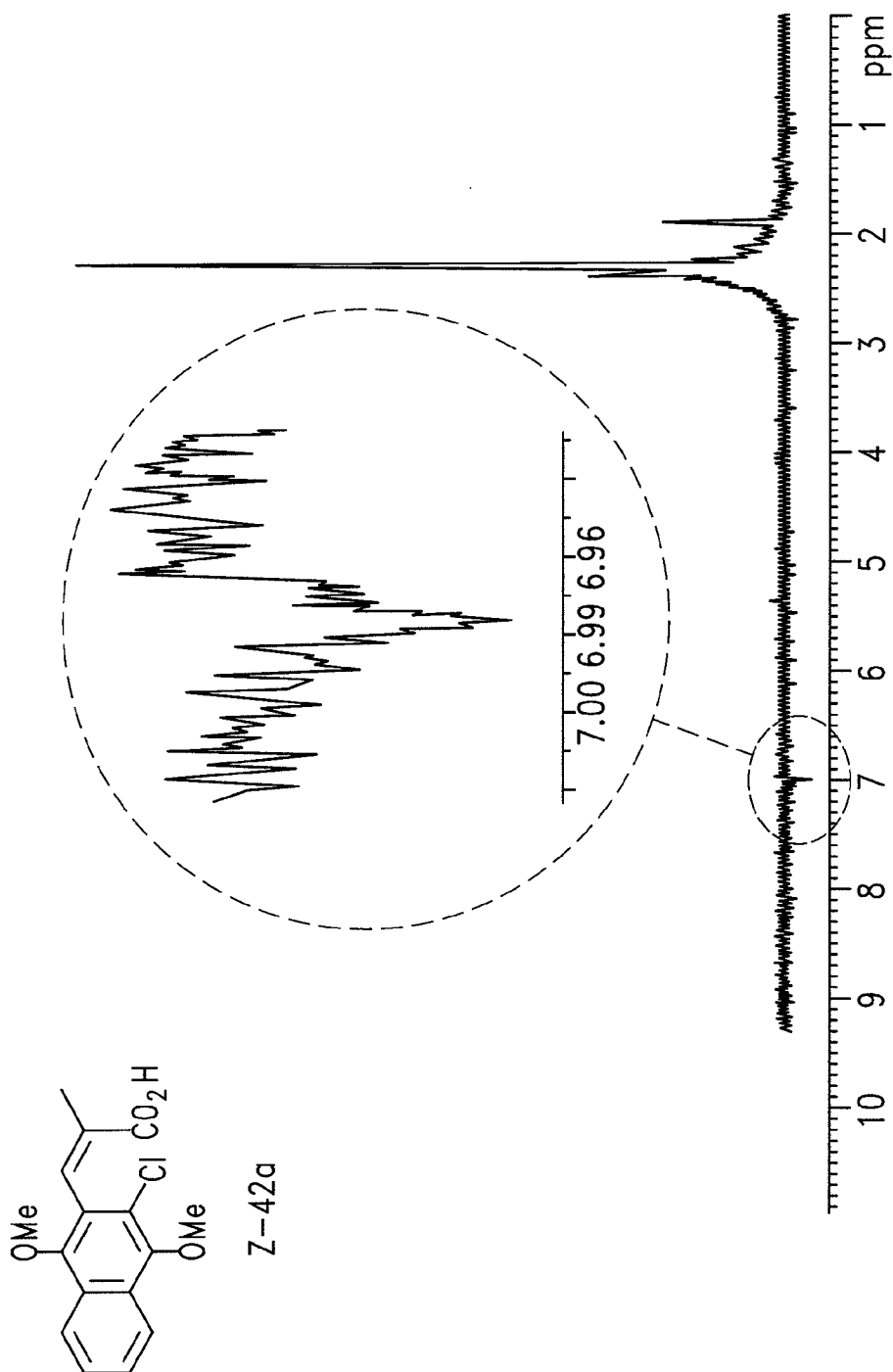


Fig. 15B

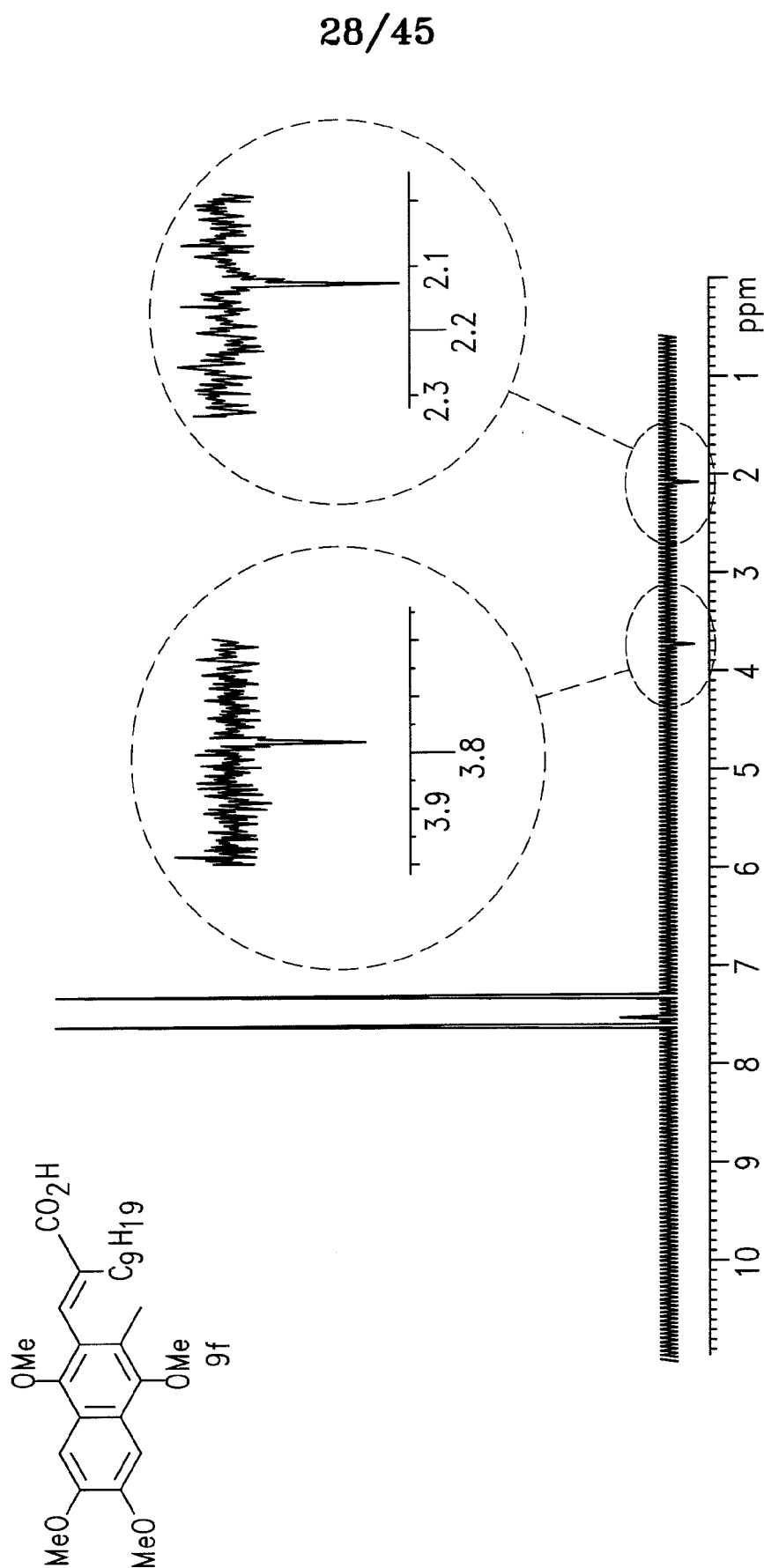


Fig. 15C

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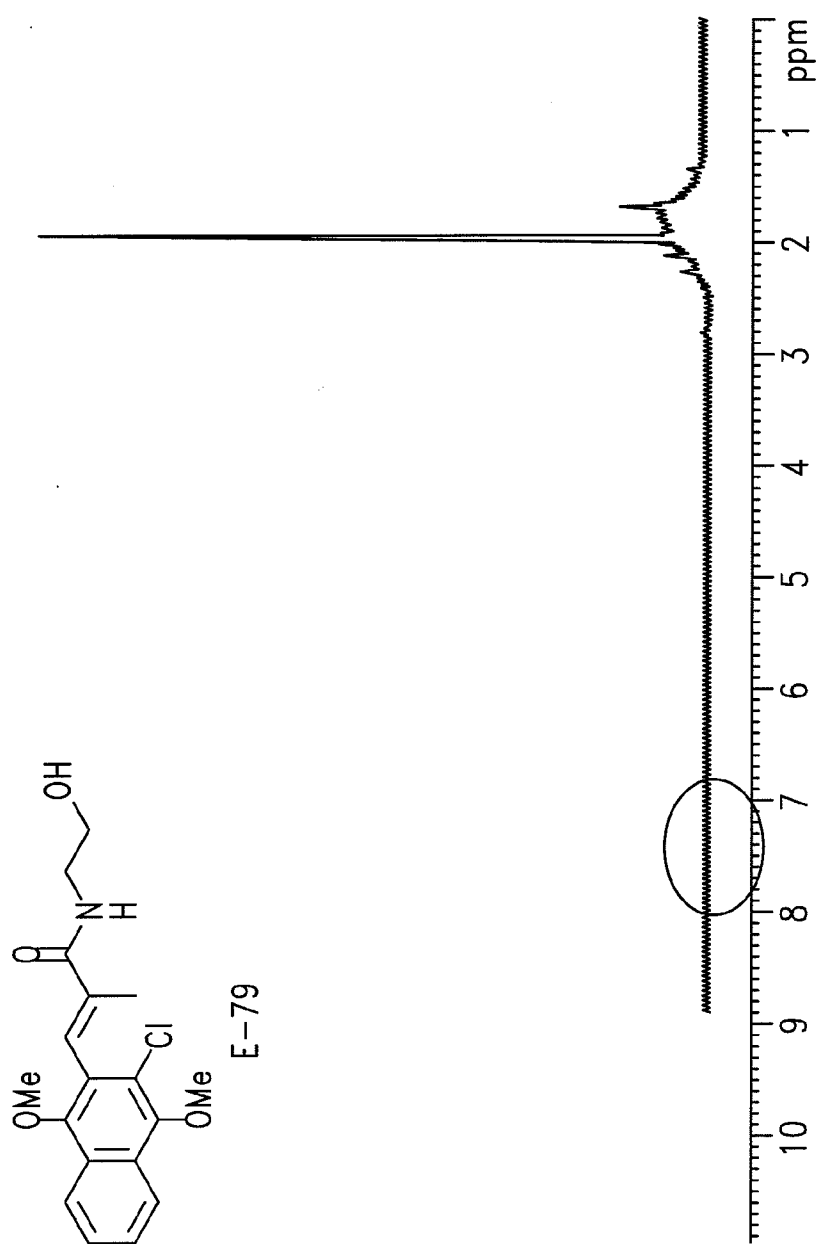


Fig. 15D

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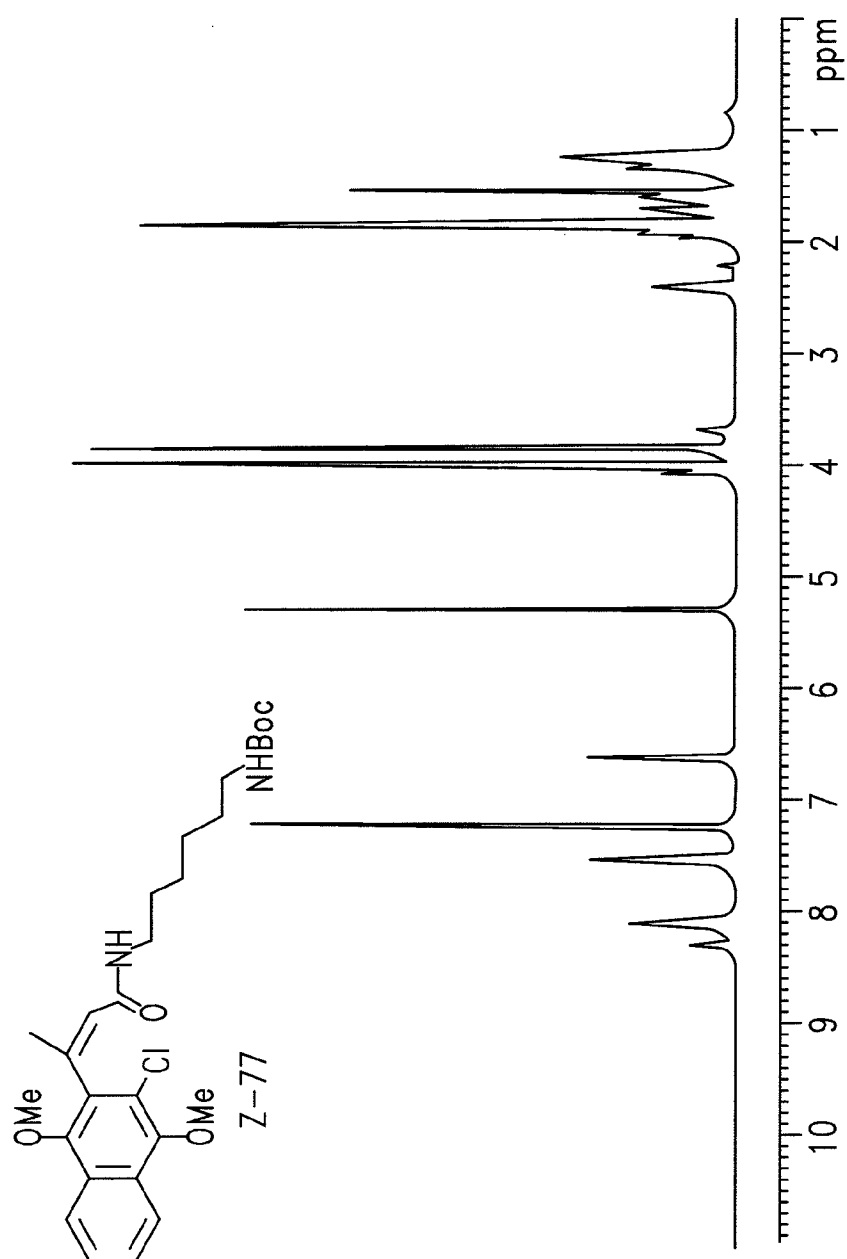


Fig. 16A

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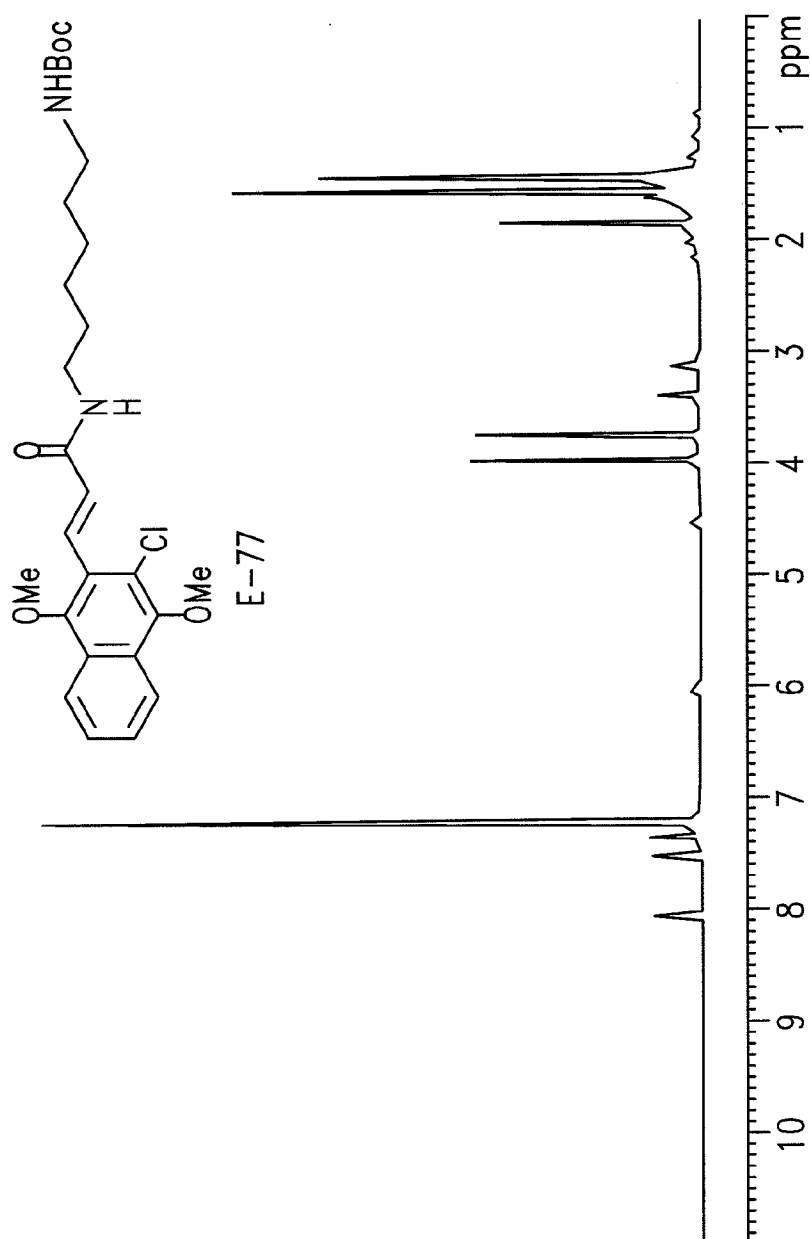


Fig. 16B

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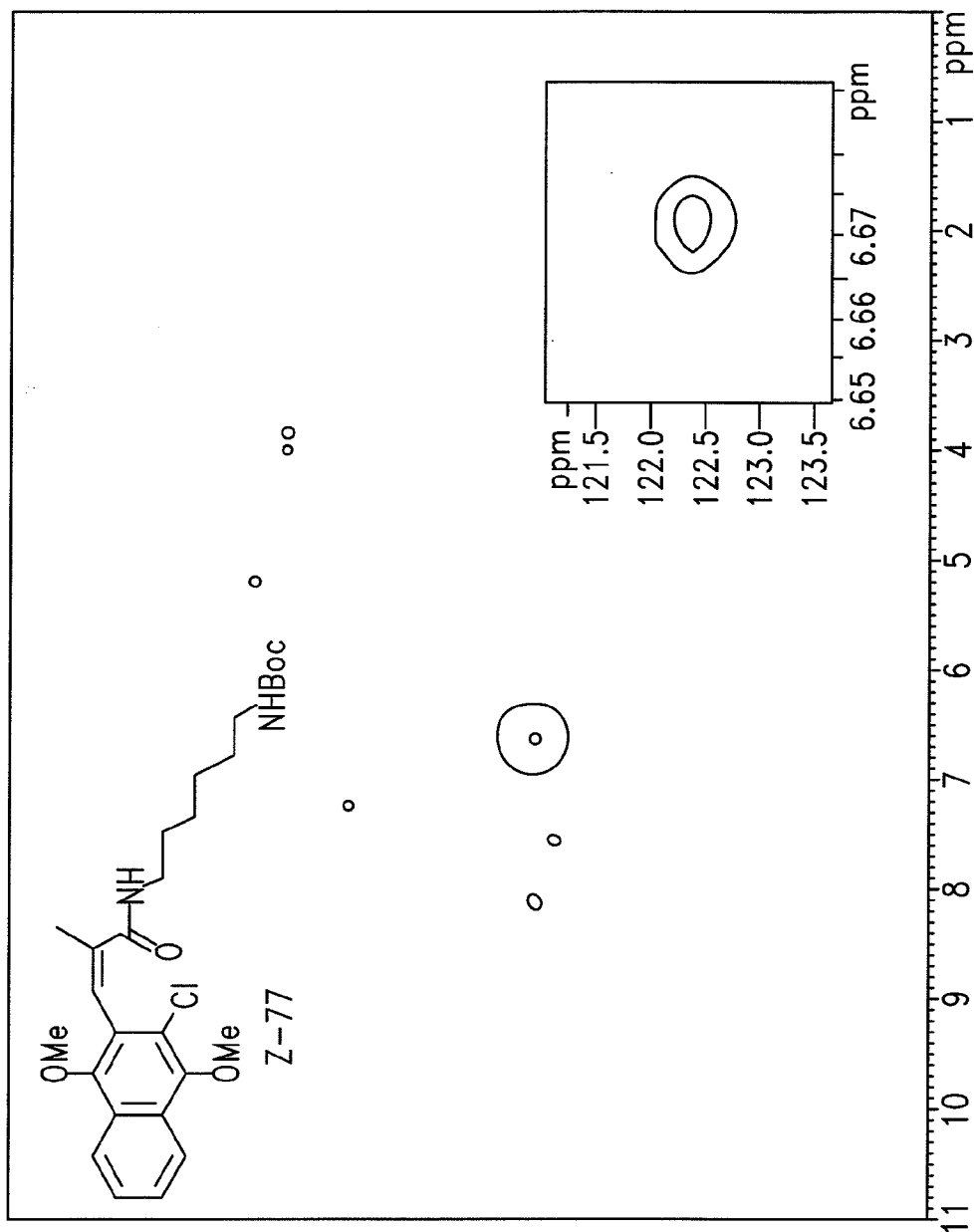


Fig. 16C

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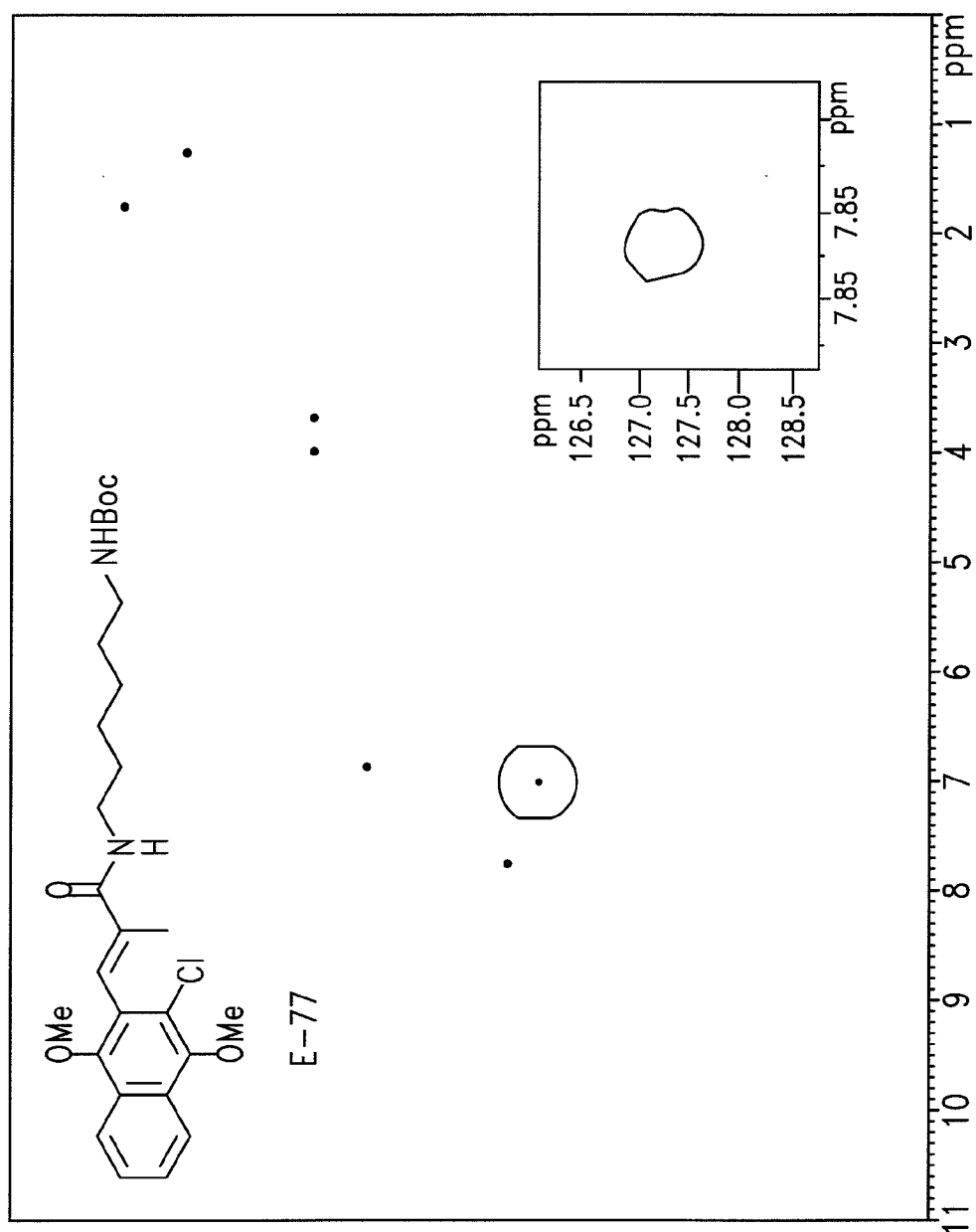


Fig. 16D.

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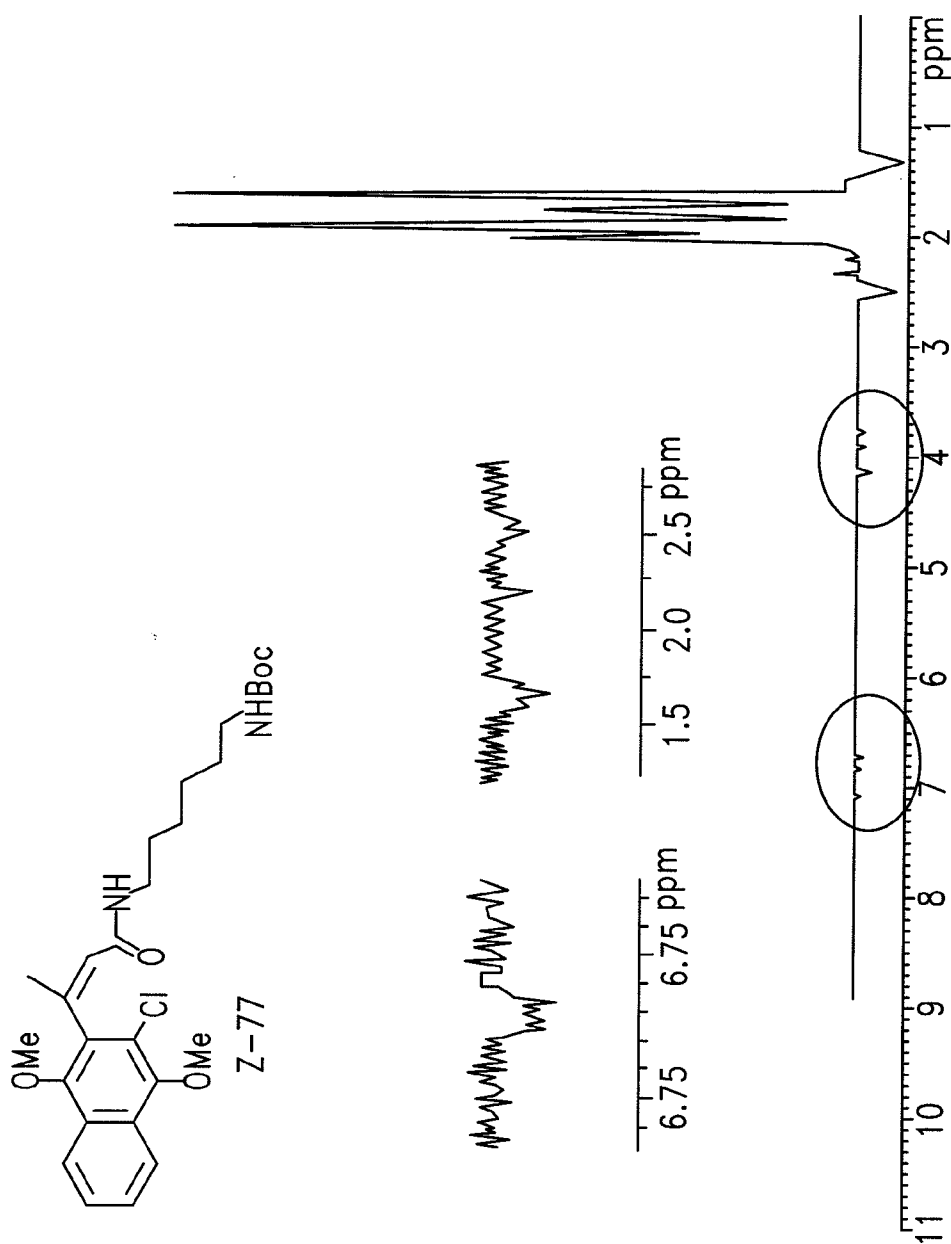


Fig. 16E

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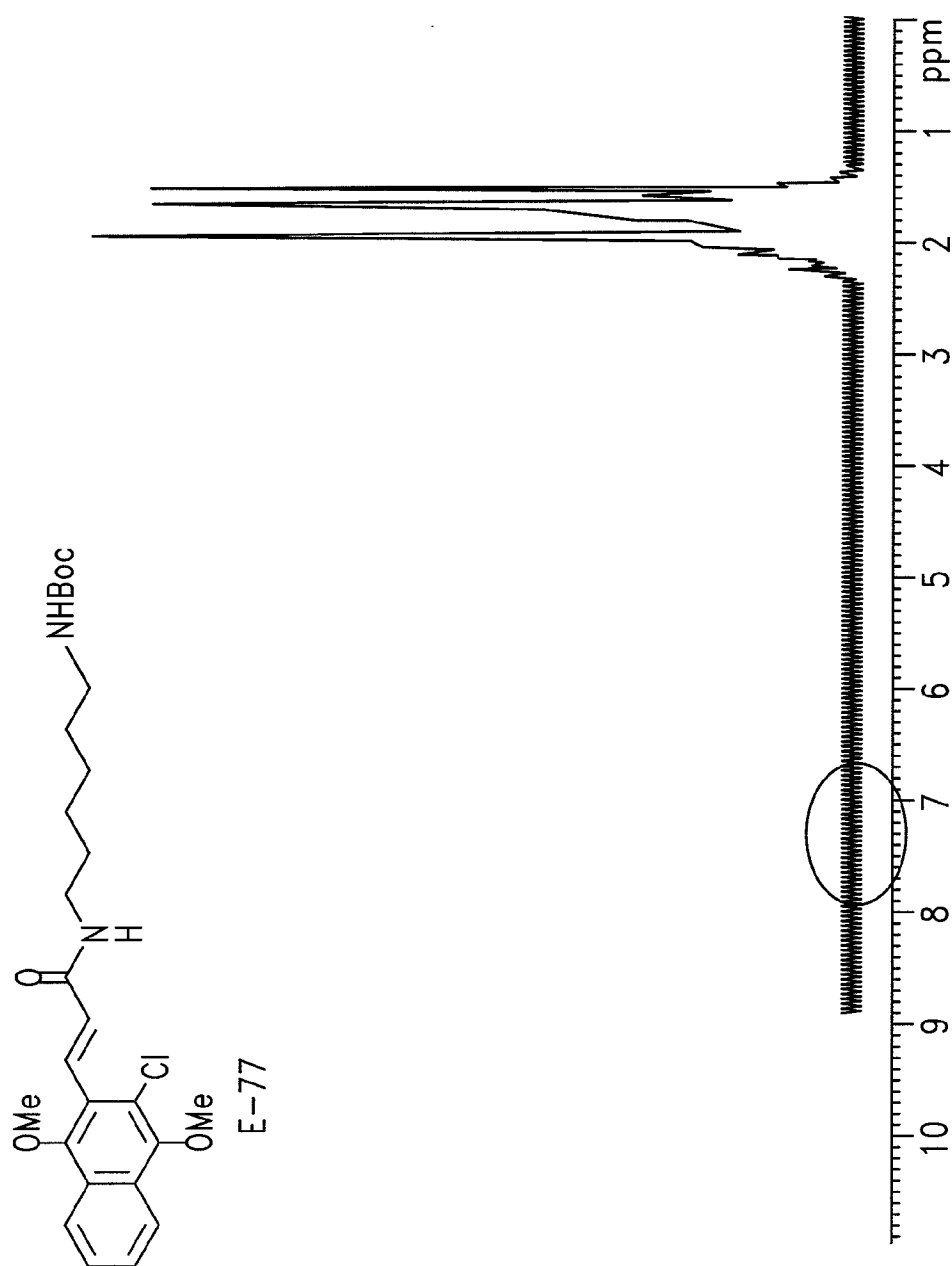


Fig. 16F

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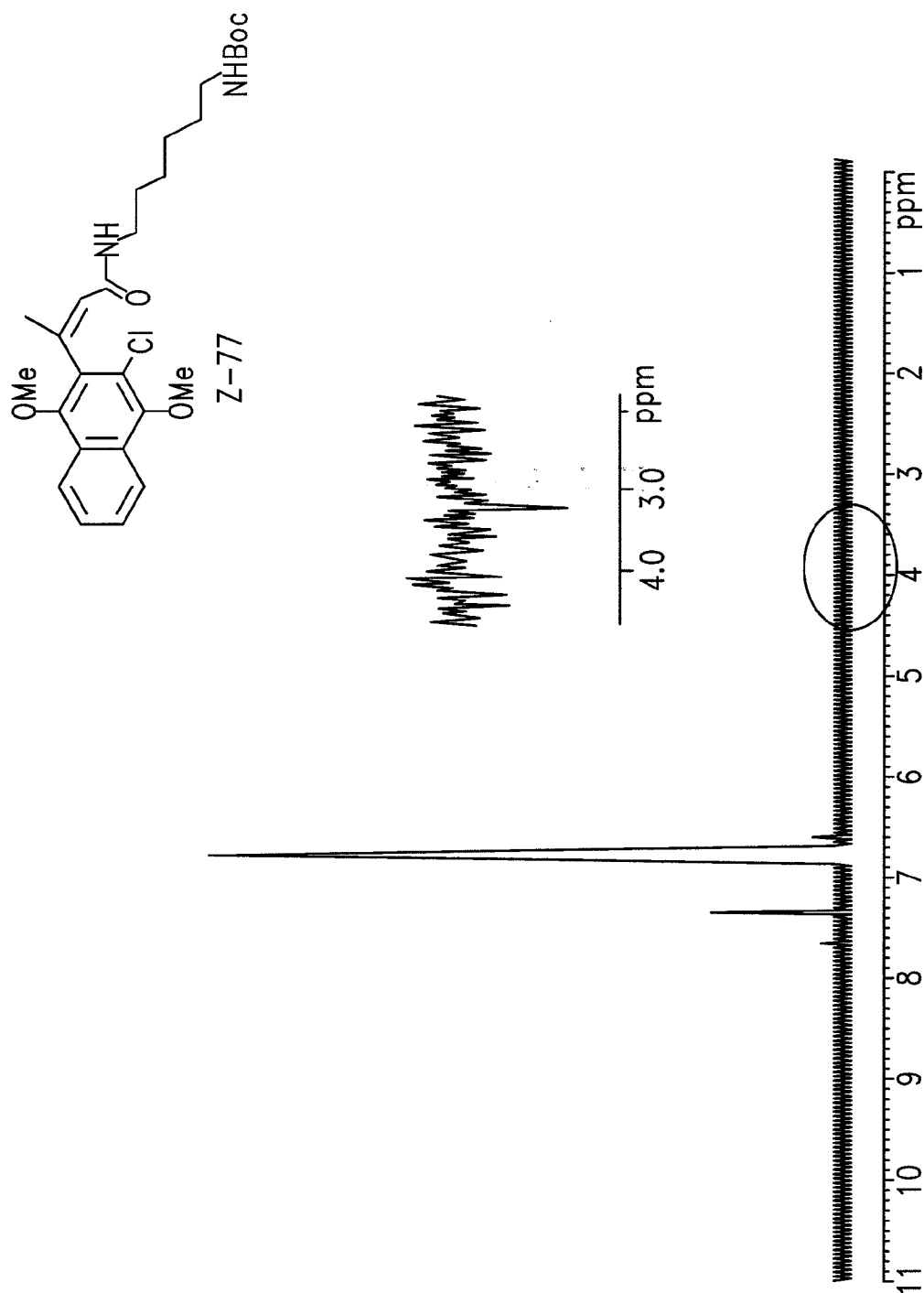


Fig. 16G

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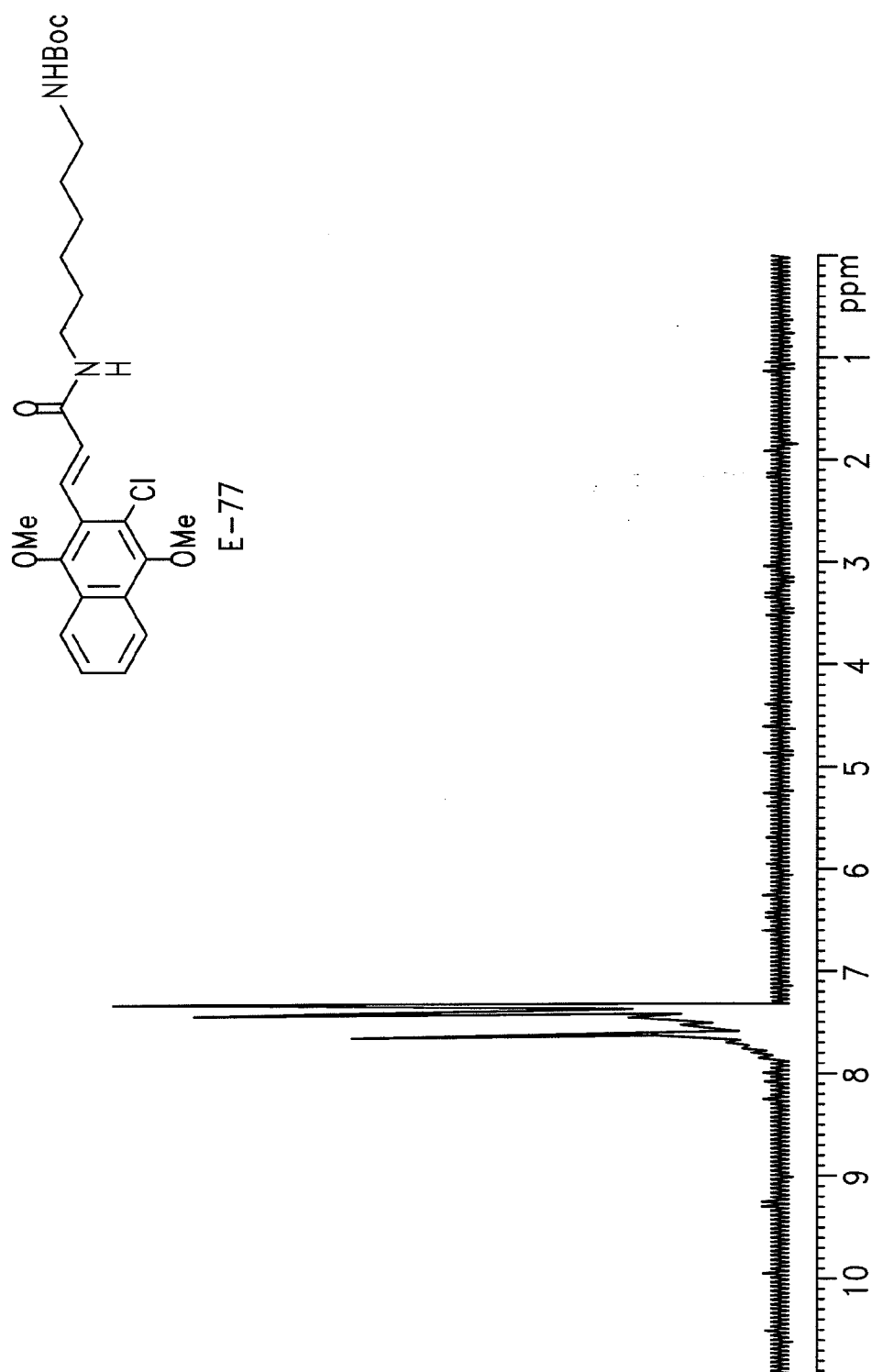


Fig. 16H.

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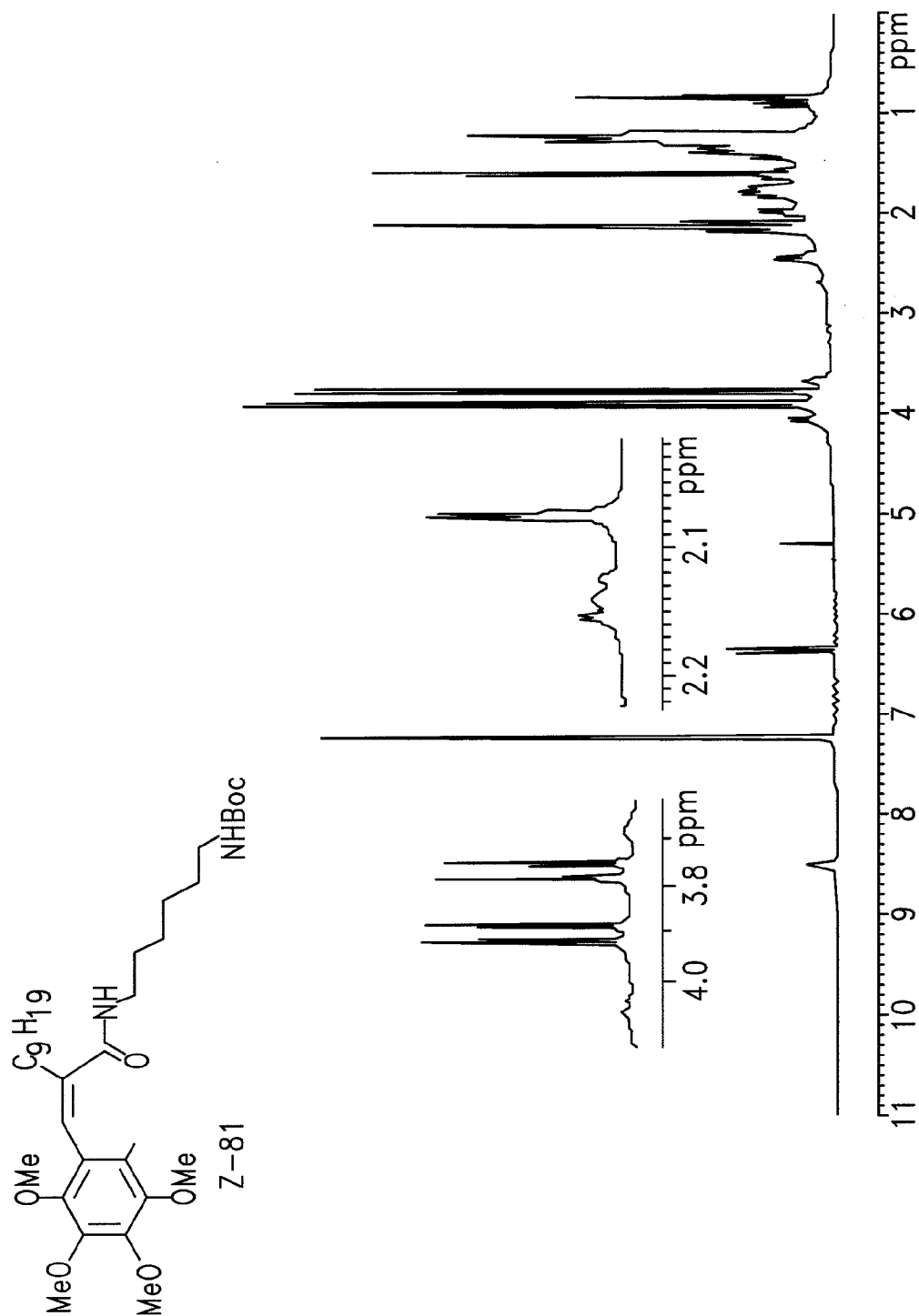


Fig. 17A

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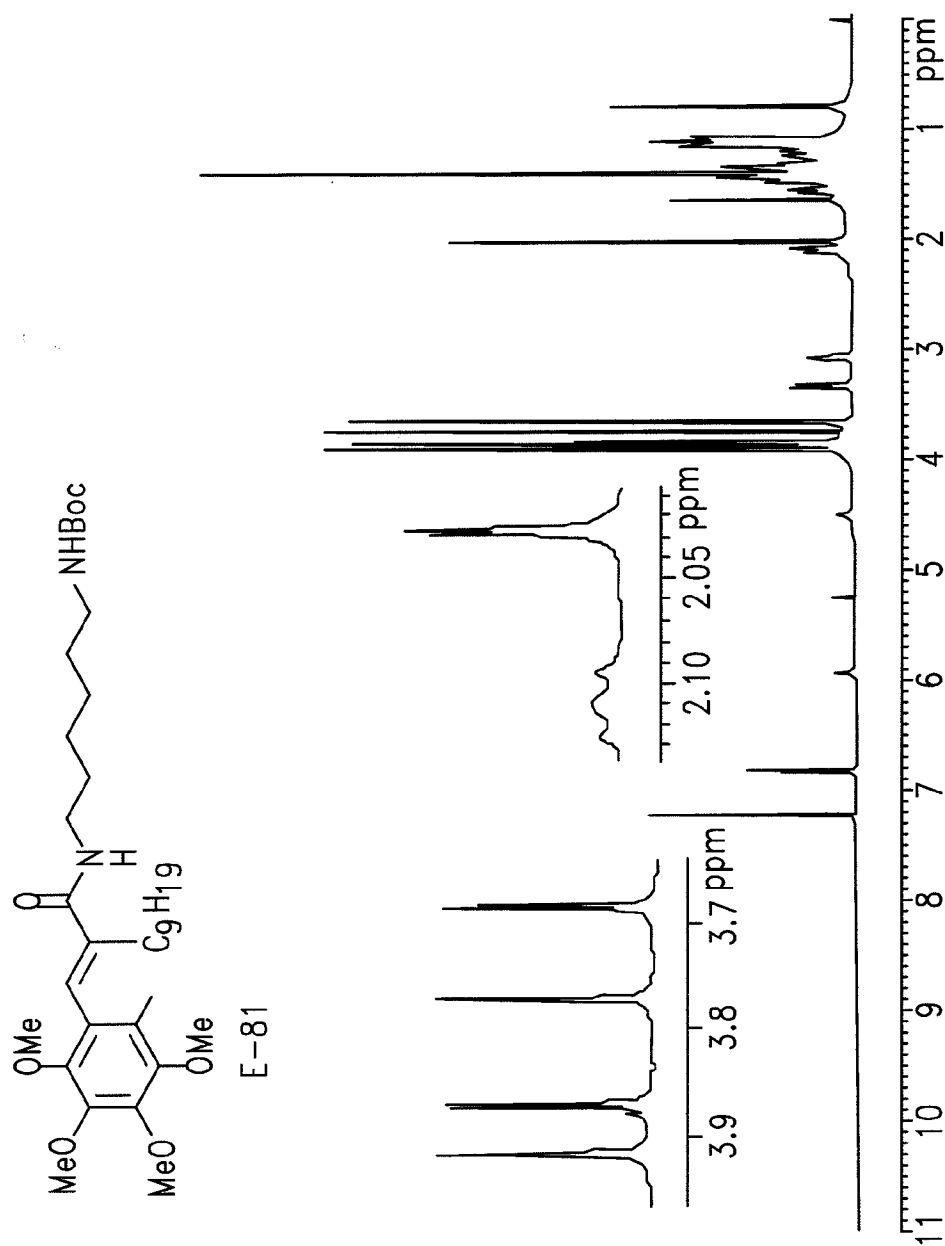


Fig. 17B

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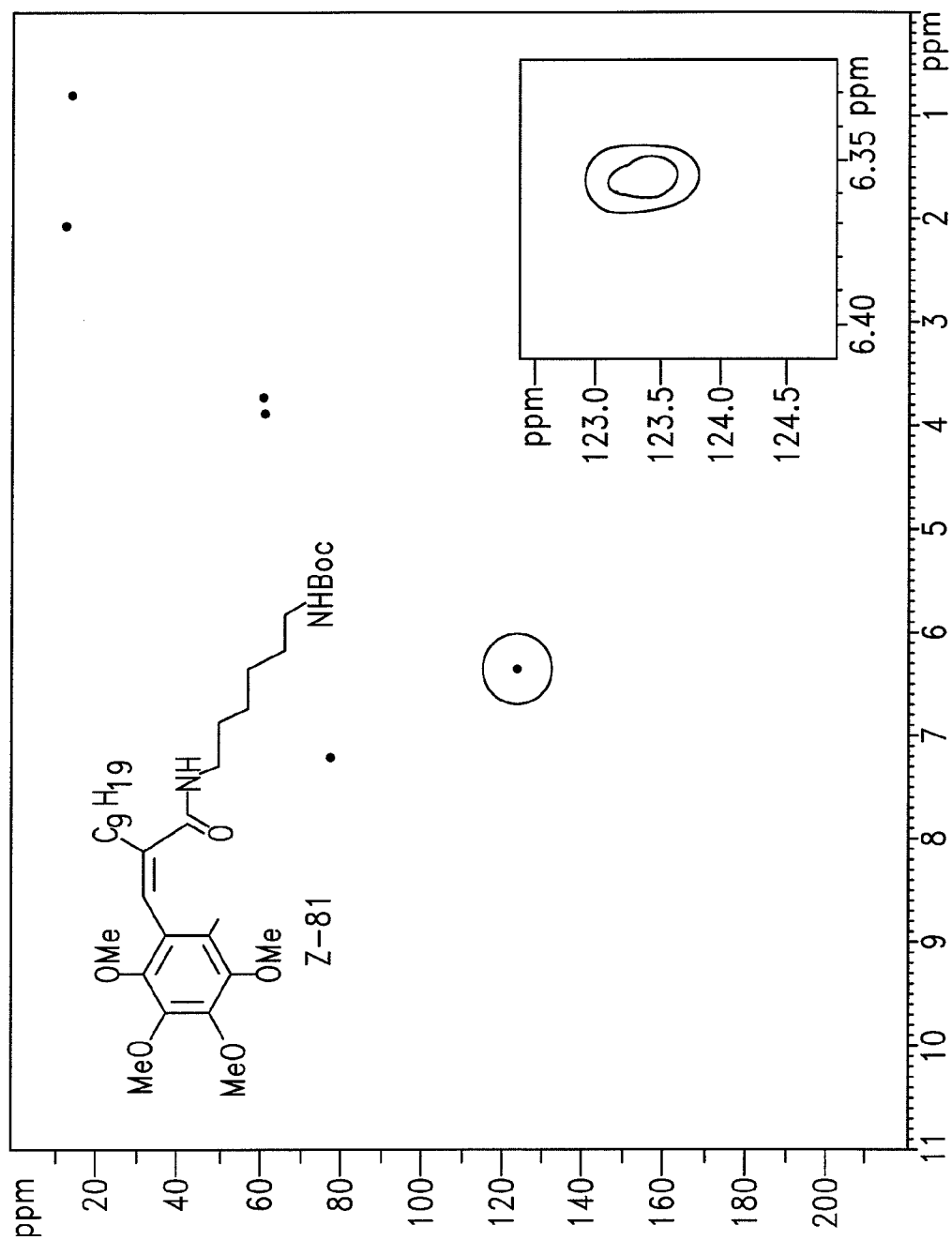


Fig. 17C

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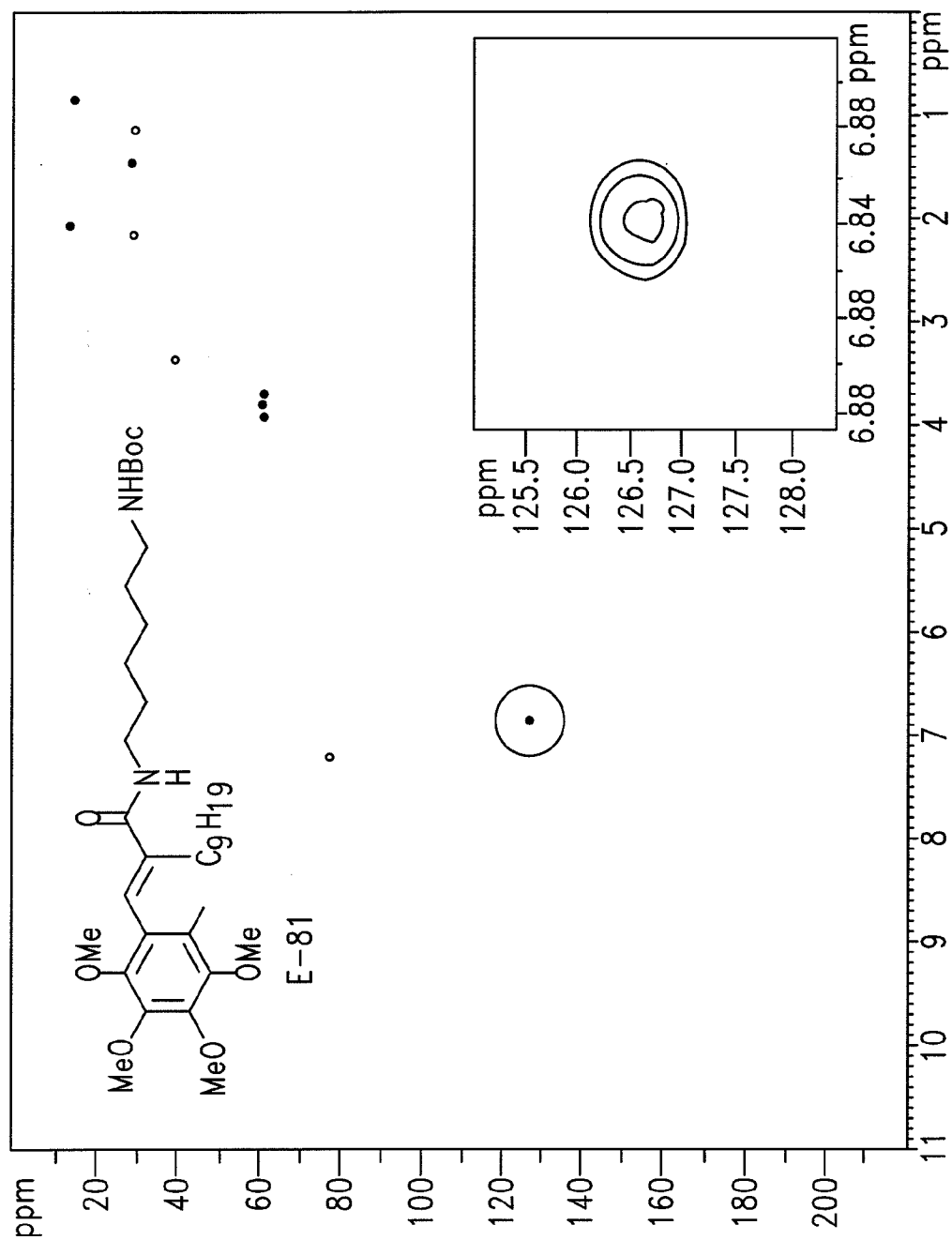


Fig. 17D

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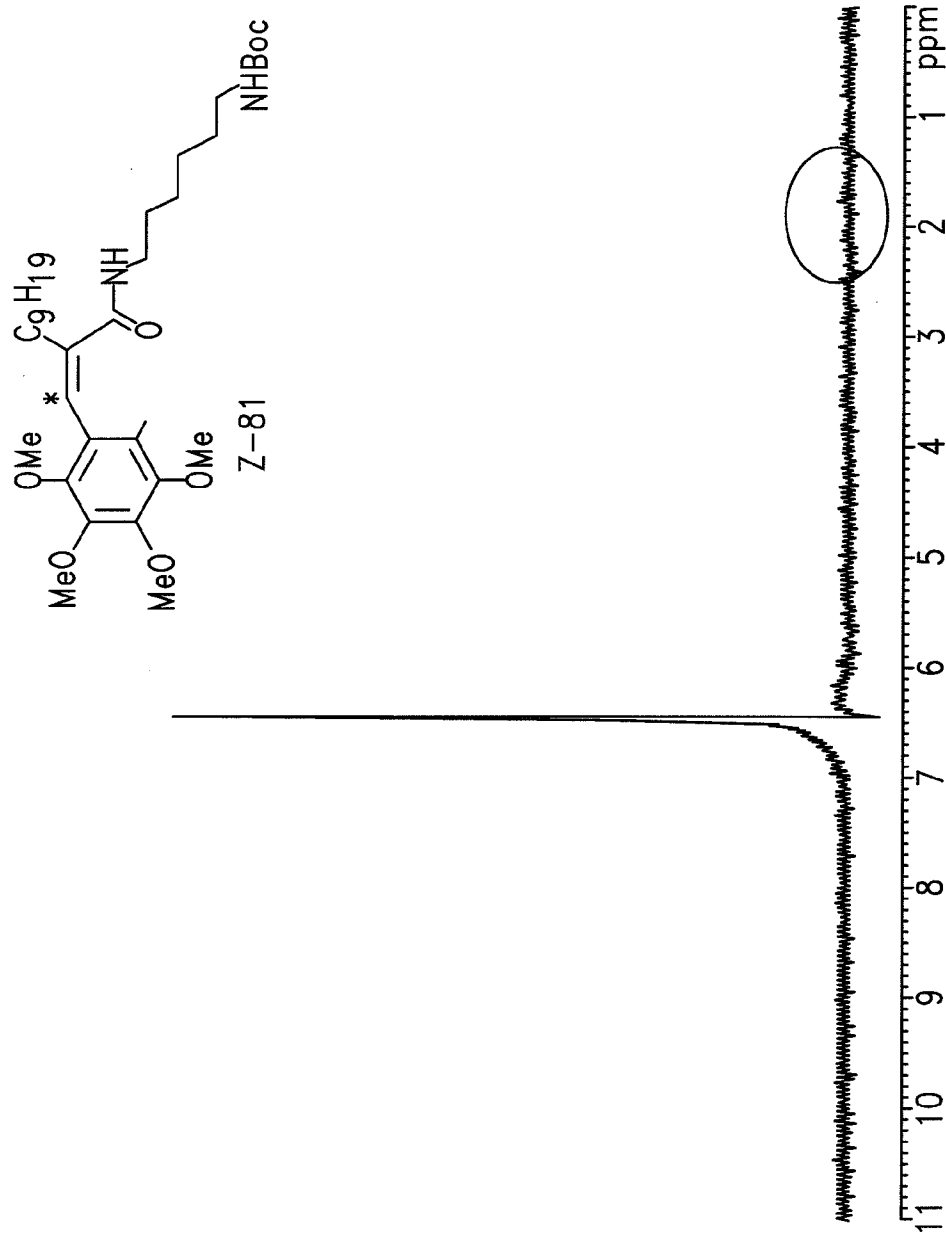


Fig. 17E

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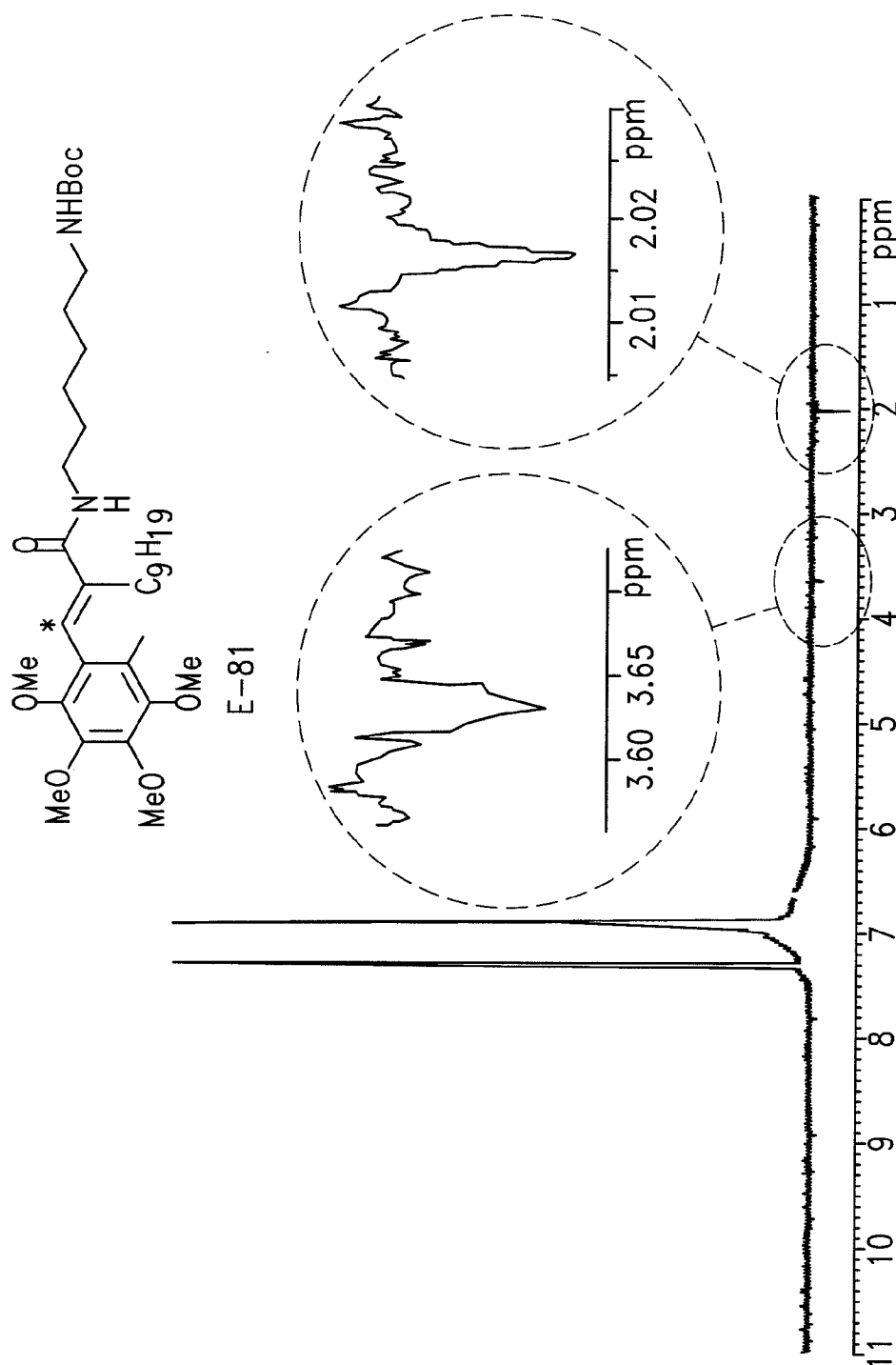


Fig. 17F

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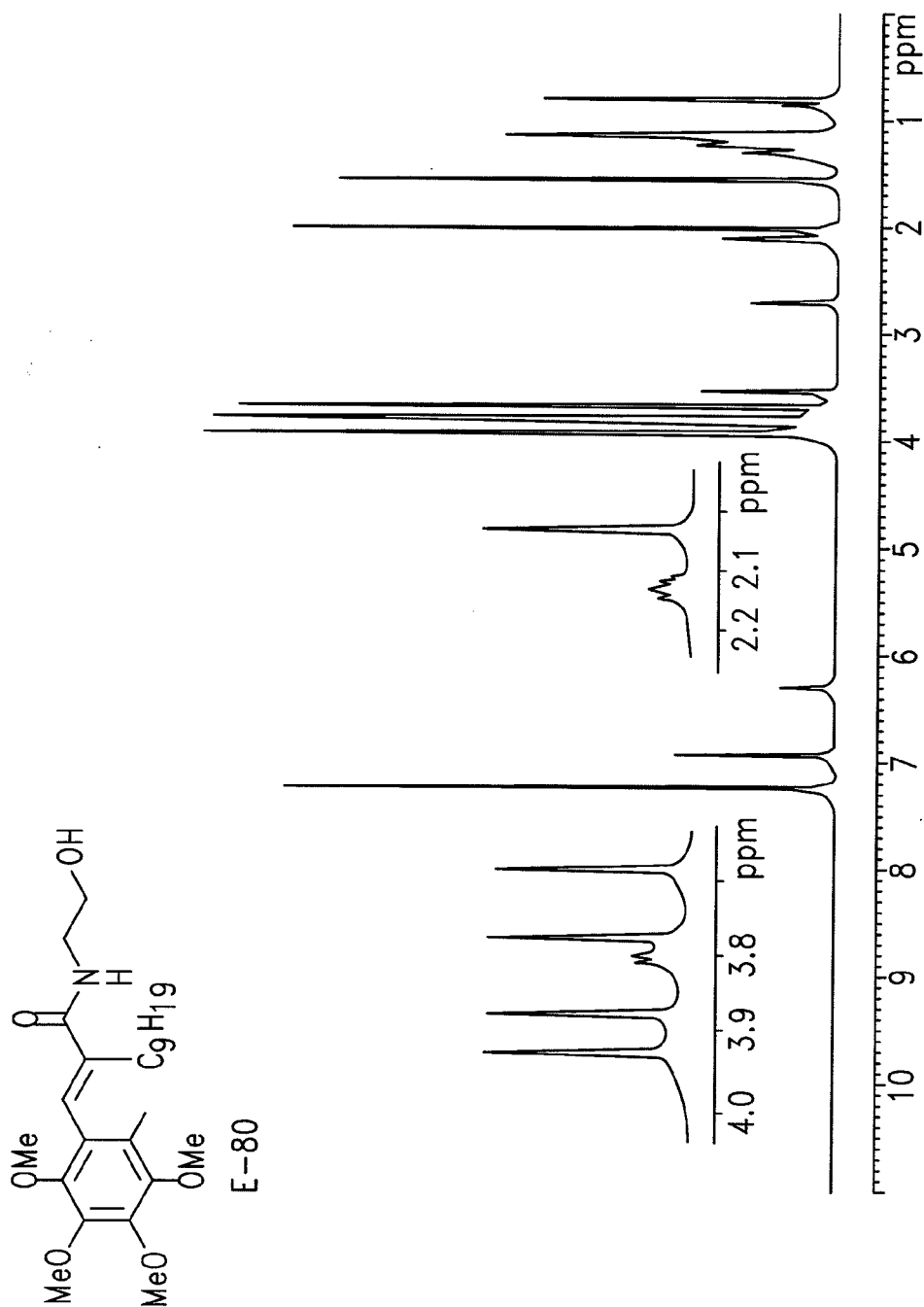


Fig. 17G

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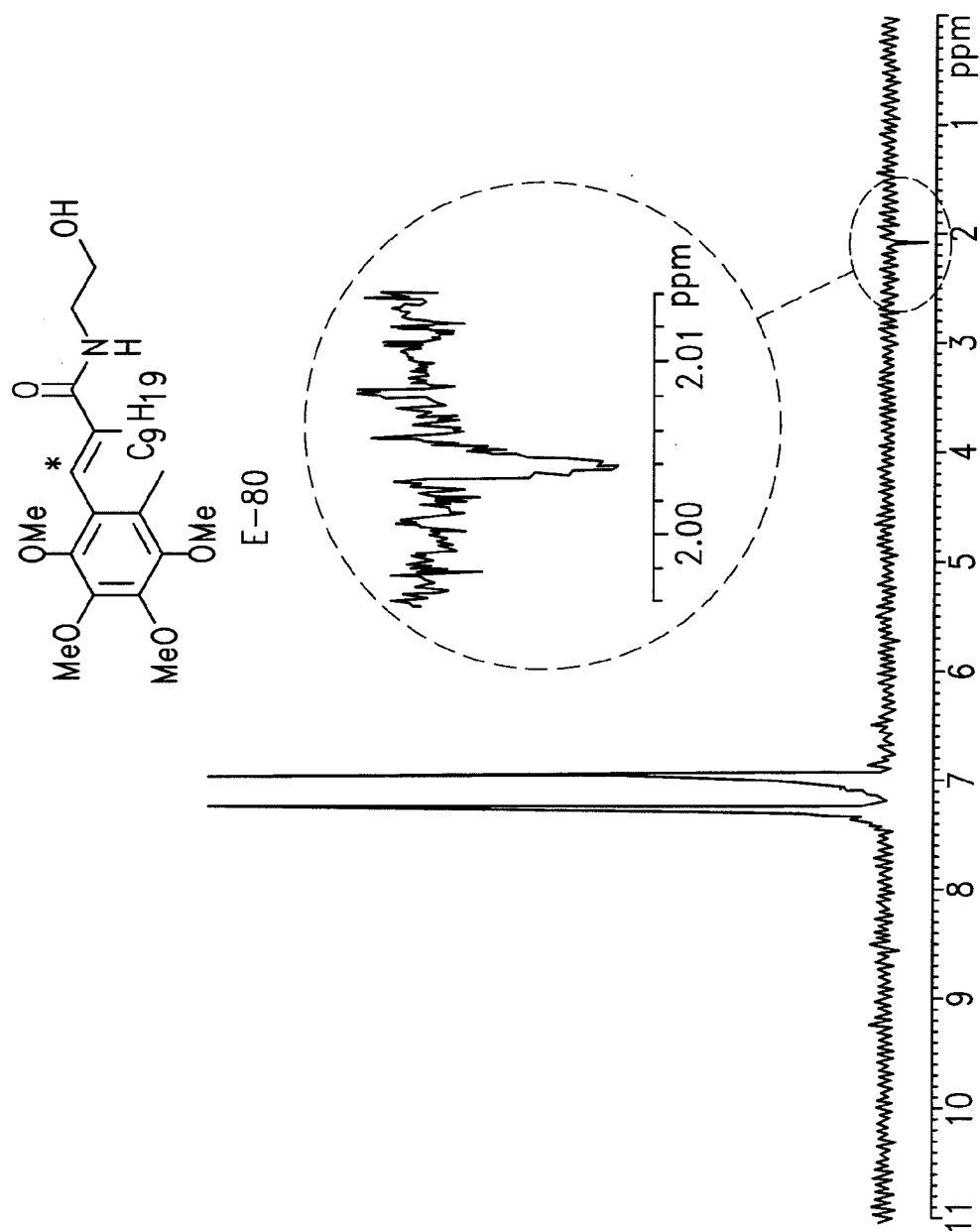


Fig. 17H

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2008/077213

A. CLASSIFICATION OF SUBJECT MATTER

INV. A61K31/122 A61P11/06 A61P11/00 A61P19/02 A61P29/00
A61P17/06 A61P9/00 A61P35/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
A61K A61P

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, CHEM ABS Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	A.MITAL, R.LAD, A.THAKUR, V.S.NEGI, U.RAMACHANDRAN: "Synthesis of novel 2-substituted 1,4-naphthoquinones using Heck reaction in 'green' reaction media" ARKIVOC JOURNAL, vol. 11, no. ISSN:1424-6376, 2006, pages 99-106, XP008101612 Gainesville, FL, US	1,2,5,6
A	page 99 page 101; compounds 8A,8C	3,4,7
X	US 5 849 793 A (PAN SENLIANG [US] ET AL) 15 December 1998 (1998-12-15)	1,2,8
A	column 8; claims 1,2 column 5, lines 52-58	3,4,7
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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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Date of the actual completion of the international search

9 February 2009

Date of mailing of the international search report

16/02/2009

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Opravz, Petra

INTERNATIONAL SEARCH REPORT

International application No

PCT/US2008/077213

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	FISHEL MELISSA L ET AL: "The DNA base excision repair protein Ape1/Ref-1 as a therapeutic and chemopreventive target" MOLECULAR ASPECTS OF MEDICINE 2007 JUN-AUG,, vol. 28, no. 3-4, 1 June 2007 (2007-06-01), pages 375-395, XP002508296	9-13, 15-17
A	page 379 - page 380, lines 1,2 page 386, paragraph 3.3.3. page 389 page 383, paragraph 3.3. page 380	3,4,7
X	----- DATABASE WPI Week 1996 Thomson Scientific, London, GB; AN 1996-017132 XP002508298 GOTO MASAKI ET AL: "NFkB transcription factor inhibitor" -& JP 07 291859 A (EISAI CO LTD) 7 November 1995 (1995-11-07)	9-12,15, 16
A	abstract	3,4,7
X	----- US 2003/229004 A1 (ZARLING DAVID A [US] ET AL) 11 December 2003 (2003-12-11)	9-18
A	page 3, paragraph 27 page 12; claim 26 page 13; claims 82,83 page 14; claims 87,89,95,105	3,4,7
A	----- FAYETTE J ET AL: "Use of angiogenesis inhibitors in tumour treatment" EUROPEAN JOURNAL OF CANCER, PERGAMON PRESS, OXFORD, GB, vol. 41, no. 8, 1 May 2005 (2005-05-01), pages 1109-1116, XP004906861 ISSN: 0959-8049 page 1109 page 1110; table 2 page 1111, paragraph 2.2.1 page 1114, paragraphs 4.6,4.7 -----	13,14, 17,18

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2008/077213

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US 2003229004	A1	11-12-2003	NONE	