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Syntheses of Dimeric Tetrahydroxanthones with Varied Linkages: Investigation of "Shapeshifting" Properties

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Supporting Information Placeholder

ABSTRACT: 2,4'- and 4,4'-Linked variants of the cytotoxic agent secalonic acid A and their analogues have been synthesized. Kinetic resolution of an unprotected tetrahydroxanthone scaffold followed by copper-mediated biaryl coupling allowed for efficient access to these compounds. Evaluation of the "shapeshifting" properties of 2,2'-, 2,4'- and 4,4'-linked secalonic acids A in a polar solvent in conjunction with assays of the compounds against select cancer cell lines was conducted in order to study possible correlations between linkage variation and cytotoxicity.

INTRODUCTION

Dimeric tetrahydroxanthone natural products belong to a family of secondary metabolite mycotoxins.[1] Their interesting biological properties and varied structures have attracted significant attention from both the biological and chemical communities. Among these natural products, the secalonic acids, 2,2'-linked dimeric tetrahydroxanthones,[2] were found to exhibit interesting bioactivities. For instance, secalonic acid A (**1**)[3] has antitumor activity and also reduces colchicine toxicity in rat cortical neurons.[4] In addition to the 2,2'-linked dimeric natural products, 2,4'- and 4,4'-linked secalonic acids are also found in nature. For example, the 2,4'-linked isomer penicillixanthone A, (**2**)[5] and the 4,4'-linked secalonic acid E (talaroxanthone, **4**)[6] have recently been isolated and characterized (**Figure 1**). In addition to the secalonic acids, biaryl linkage variation has been observed in related natural products. Recently, a related subclass of tetrahydroxanthones, phomoxanthones (**5**), have been isolated and characterized.[7] The presence of a 4,4' linkage was established by X-ray crystallography. The corresponding 2,2'-linked dimer dicerandrol C (**6**)[8] and 2,4'-linked dimer phomoxanthone B (**7**) have also been isolated from natural sources.

Due to the presence of varied biaryl linkages, the shape of molecules may change dramatically which may have a substantial influence on their biological properties. For example, the 4,4'-linked compound phomoxanthone A exhibits a strong cytotoxicity to L5178Y cancer cells (IC_{50} = 0.3 μM),[7c] whereas the 2,2'-linked congener dicerandrol C was found to be somewhat less potent (IC_{50} = 2.8 μM).[8c] For the secalonic acids, previous studies indicated that the linkage may undergo facile isomerization in polar solvents.[9] A similar transformation was observed for the monomeric tetrahydroxanthone parnafungins to generate a mixture of isomers A1 (**8**)/A2 (**9**)/B1 (**10**)/B2 (**11**) from each pure isomer at room temperature (**Figure 2**).[10] The authors propose that *retro-oxa*-Michael reaction of the tetrahydroxanthone to acetophenone intermediates **12**/**13** was responsible for linkage isomerization. Interestingly, it was determined by affinity-selection/mass spectrometry (AS-MS) that parnafungin A1 (**8**) was the active inhibitor of the fungal enzyme polyadenosine polymerase (PAP).[11] The fluxional properties of the tetrahydroxanthone scaffold can be compared to other natural products such as coleophomones[12] and the "shapeshifting" bullvallene system reported by Bode and coworkers.[13]

Due to their interesting chemical and biological properties, tetrahydroxanthones have drawn attention from synthetic organic chemists. Recently, our laboratory[14] as well as the laboratories of Bräse,[15] Nicolaou,[16] Tietze[17], and other groups[18] have accomplished syntheses of monomeric chromone lactones, tetrahydroxanthones, and 2,2'-linked dimeric tetrahydroxanthone natural products. We considered that chemical syntheses of 2,4'-linked and 4,4'-linked secalonic acids would be not only be synthetically challenging but may provide access to dimeric linkage variations to study their "shapeshifting"[13] properties of this class of compounds. Moreover, along with the previously synthesized 2,2'-linked compounds,[14] these compounds may be used to ultimately construct a tetrahydroxanthone library with potentially interesting biological activities. In this paper, we describe syntheses of 2,4'- and 4,4'-linked variants of the cytotoxic agent secalonic acid A and its analogues. Evaluation of the "shapeshifting" properties of 2,2'-, 2,4'- and 4,4'-linked secalonic acids A in conjunction with assays of the compounds against select cancer cell lines was conducted in order to study preliminary correlations between linkage variation and cytotoxicity.

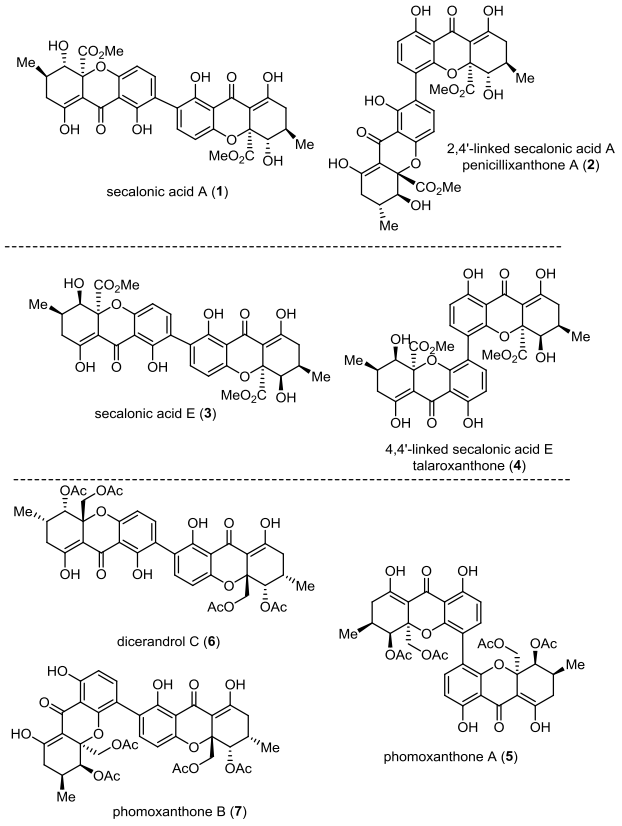


Figure 1. 2,2'-Linked and Related 2,4'- and 4,4'-Linked Secalonic Acids

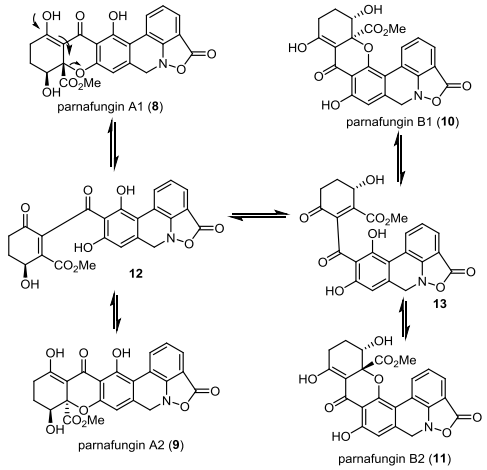


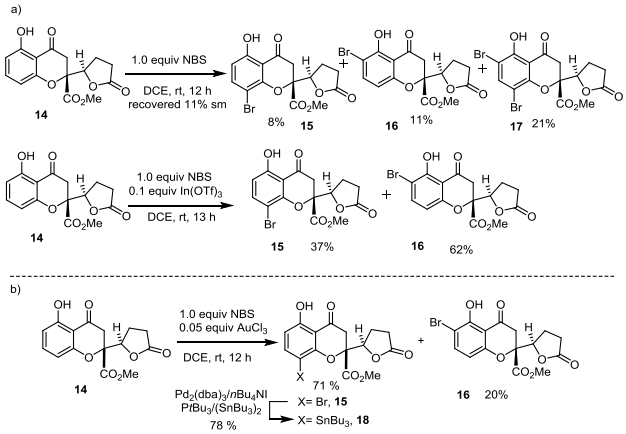
Figure 2. Shapeshifting, Dynamic Equilibration of the Parnafungins

RESULTS AND DISCUSSION

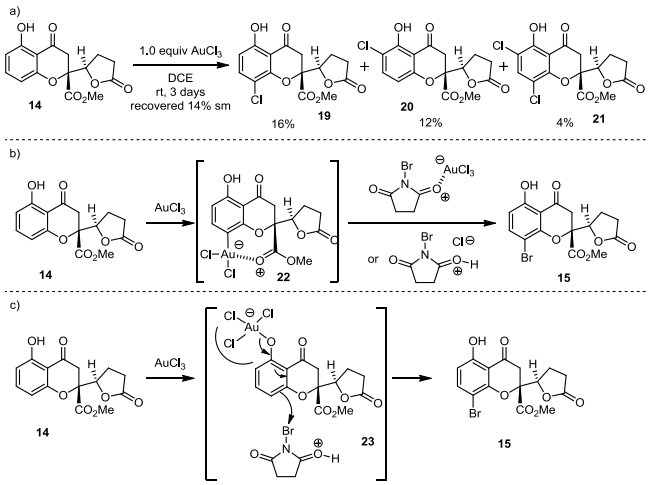
Synthesis of 4,4'-Linked Chromone Lactone Dimers.

In addition to the dimeric tetrahydroxanthones, there have been a number of related 4,4'-linked chromone lactone dimers isolated from nature, including gonytolide A[19] and paecilin A.[20] Based on our strategy for the synthesis of 2,2'-linked chromone lactones,[14b] we anticipated that the corresponding 4,4'-linked dimers may be accessed using our previously developed copper-mediated stannane coupling approach if prefunctionalization of the *para*-position of the chromone lactone monomer could be accomplished. However, after investigating various iodination and bromination conditions on monomer **14**, we found that the *para*-halogenated chromone lactone was generally the minor product. For example, treatment of substrate **14** with 1 equiv. of NBS led to a mixture of brominated products **15**, **16**, and **17** (**Scheme 1**). Interestingly, use of $In(OTf)_3$ as catalyst[21] for the bromination led to the production of *ortho*-bromide **16** in 62 % yield along with *para* isomer **15** (37%). After further evaluation of additives, we found that a catalytic amount of $AuCl_3$[22] significantly changed the outcome of the bromination (**Scheme 1**, **b**)). Treatment of **14** with NBS in the presence of 5 mol% of $AuCl_3$ favored production of the *para*-brominated chromone lactone **15**. This phenomenon was also observed in other related chromone lactone substrates.[23] To understand possible operative mechanisms, chromone lactone **14** was treated with $AuCl_3$ (72 h) (**Scheme 2, a**)) in which case several chlorinated products **19-21** were obtained.[24] We considered that the Au(III) catalyst may chelate with the lactone and/or methyl ester moieties of substrate **14** to direct the bromination, potentially *via* a direct auration process[25] to generate the chelated gold (III) aryl intermediate **22** (**Scheme 2, b**)). This hypothesis is also supported by the fact that $AuCl_3$ failed to enhance the yield of the *para* product on tetrahydroxanthone substrates. However, an auration pathway cannot completely explain the unselective chlorination observed using $AuCl_3$. As an alternative mechanism, $AuCl_3$ may also chelate to the phenol[26] of substrate **14** to afford a putative aurate complex **23** which may effectively block the *ortho*-position to bromination with NBS (**Scheme 2, c**)). The latter mechanism is also supported by ^{1}H NMR experiments involving complexation of substrate **14** with $AuCl_3$ in which case loss of the phenol resonance of **14** was observed.[23] Our current results highlight the importance of the chromone lactone ring system in the gold (III)-catalyzed bromination process.

Scheme 1. Bromination of a Chromone Lactone Substrate

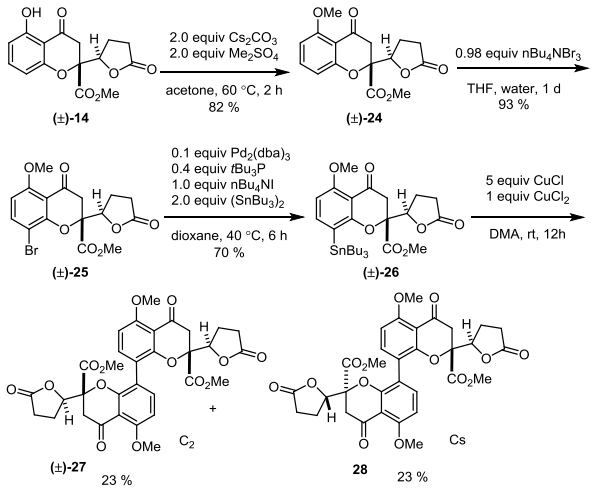


Scheme 2. Possible Mechanisms for *para*-Bromination



With the *para*-bromide **15** in hand, it was smoothly converted to the corresponding *para*-stannane **18** in 79 % yield (**Scheme 1**). We next investigated stannane dimerization with different metals (*e.g.* CuCl) and oxidants (*e.g.* air, O_2, $CuCl_2$).[14b] Surprisingly, phenolic stannane **18** did not generate the desired 4,4'-linked dimers under these conditions; the main side reaction generally observed was protodestannylation likely due to the low pKa of the proximal phenol. Accordingly, we altered our strategy and compound **14** was *O*-methylated with Me_2SO_4 (**Scheme 3**). Treatment of **24** with nBu_4NBr_3 led to the production of bromide **25** in 93% yield.[27] Subsequent stannylation provided compound **26** in 70 % yield. When we applied the previously developed CuCl/air mediated coupling conditions,[14b] stannane **26** was only converted to dimeric products in trace amounts with a large amount of the starting material remained intact. We thought that use of air as oxidant was difficult to accurately control and that this could lead to the variable conversions observed in the reaction. Fortunately, use of $CuCl_2$ as oxidant afforded the C_2 and C_s dimers **27** and **28** in reproducible yields (23 %).

Scheme 3. Synthesis of a Chiral, Racemic 4,4'-Linked Chromone Lactone



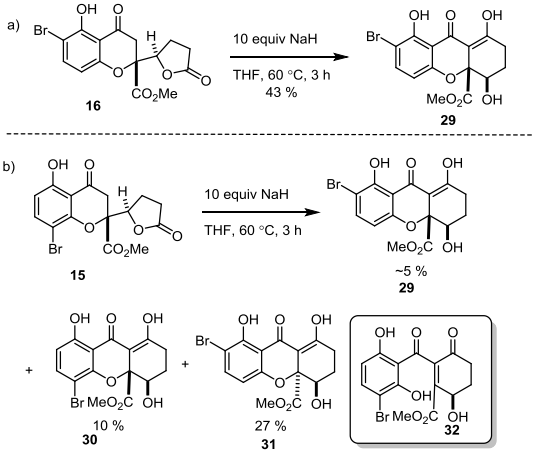
Synthesis of 4,4'-Linked Tetrahydroxanthone Dimers.

The successful synthesis of 4,4'-linked chromone lactones encouraged us to further investigate syntheses of the corresponding 4,4'-linked dimeric tetrahydroxanthones. We envisioned that an enantiopure, *para*-functionalized tetrahydroxanthone could serve as a key intermediate. Our initial thought was that a *para*-brominated tetrahydroxanthone could be obtained from a brominated chromone lactone through Dieckmann cyclization (**Scheme 4**). However, potential linkage isomerization of tetrahydroxanthones could create difficulties in this transformation. Accordingly, we treated the *ortho*-brominated chromone lactone **16** with 10 equivalents of NaH in THF for 3 h. In this case, the corresponding tetrahydroxanthone **29** was isolated in 43 % yield as a single diastereomer. Surprisingly, when we treated the bromide **15** with 10 equivalents of NaH, we obtained three different tetrahydroxanthone products. The desired *para*-brominated tetrahydroxanthone **30** was obtained in only 10 % yield. The main byproduct observed was the *ortho*-bromide **31** with an *anti*-configuration between the hydroxyl and ester groups. Even when we shortened the reaction time or lowered the reaction temperature, the undesired tetrahydroxanthones **29**/**31** were still observed. Thus, we considered that under Dieckmann cyclization conditions, *para*-bromide **15** may generate intermediate **32** *in situ.* Subsequent *oxa*-Michael reaction could convert **32** to the corresponding tetrahydroxanthone products.

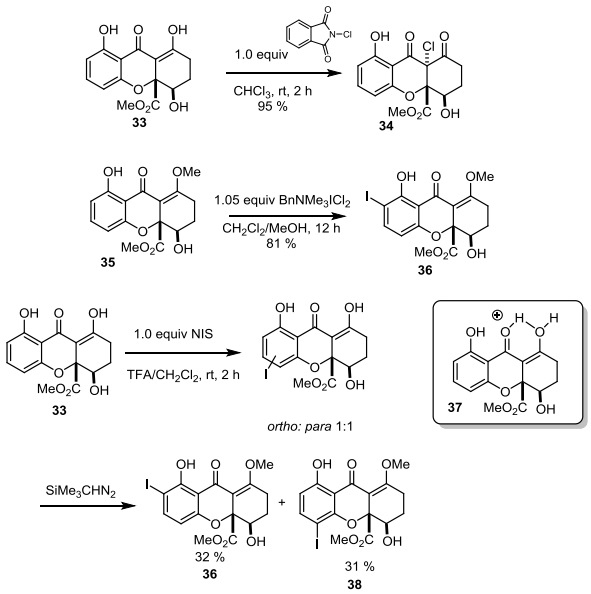
From these results, we hypothesized that production of the desired *para*-bromo-tetrahydroxanthone (*cf.* **30**) was not favored under Dieckmann cyclization conditions. Therefore, we changed our strategy to prefunctionalize the tetrahydroxanthone moiety. However, when tetrahydroxanthone **33** was treated with chlorinating reagents such as *N*-chlorophthalimide, the chloro-diketone **34** was isolated in near quantitative yield as a single diastereomer (**Scheme 5**). The *anti*-configuration between the chlorine and the methyl ester moieties was confirmed by X-ray crystal structure analysis (**Figure 3**).[23] The high diastereoselectivity observed is likely due to steric repulsion between the electrophile and the methyl ester.

As the vinylogous acid should be the most nucleophilic moiety in the tetrahydroxanthone substrate, we thought that use of the enol-protected compound **35** could avoid this problem. After evaluating different iodination and bromination conditions, the *ortho*-halogenated product (*cf.* **36**) was found to be dominant. We reasoned that the vinylogous acid moiety in the tetrahydroxanthone could be deactivated under acidic conditions. After forming the presumed protonated tetrahydroxanthone **37**, the phenol may become the more nucleophilic site. As an alternative, the added TFA could protonate NIS which may generate a more active iodination reagent with different selectivity. Indeed,

Scheme 4. Dieckmann Cyclization of Brominated Tetrahydroxanthones



Scheme 5. Synthesis of a *para*-Iodo Tetrahydroxanthone



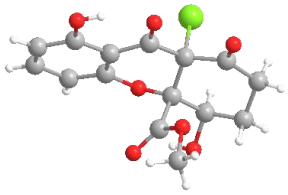


Figure 3. X-ray Crystal Structure of Chlorinated Tetrahydroxanthone **34**

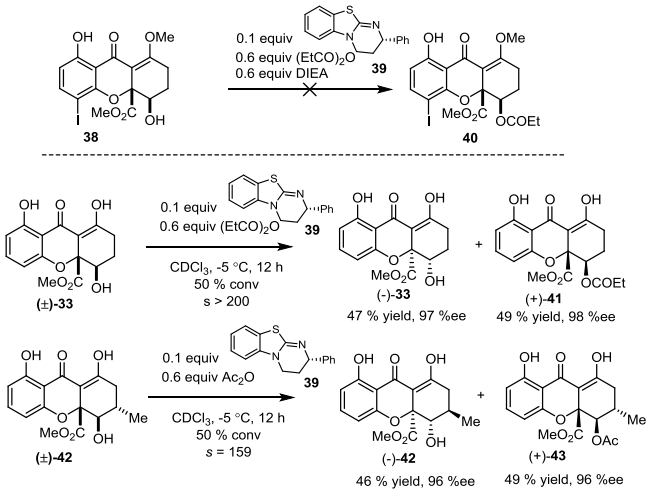
when substrate **33** was treated with NIS in TFA/CH_2Cl_2 (**Scheme 5**), both *para*-iodo and *ortho*-iodo-tetrahydroxanthones were generated in a 1:1 ratio by crude ^{1}H NMR analysis. The mixture was further methylated using trimethylsilyldiazomethane to afford *para*-iodide **38** and *ortho*-iodide **36** in 31 % and 32 % isolated yields, respectively (two steps).

In order to access chiral, non-racemic 4,4'-linked secalonic acid A, synthesis of an enantiopure, monomeric tetrahydroxanthone was required. Relying on our recently developed kinetic resolution of the tetrahydroxanthone moiety using homobenzotetramisole (HBTM) catalyst **39**, [28] we anticipated that an enantiopure *para*-iodide could be obtained in a similar fashion. However, contrary to the excellent kinetic resolution observed for *ortho*-iodide **36**, HBTM catalyst **39** did not successfully catalyze acetylation of *para*-iodide **38** or only yielded moderate levels of enantioselectivity (**Scheme 6**). This unexpected result indicated that substitution on the *para*-position of the tetrahydroxanthone jeopardized its reactivity with the HBTM catalyst system.

After the unsuccessful kinetic resolution attempts with the *para*-iodo tetrahydroxanthone, we considered that the kinetic resolution could be performed on unprotected tetrahydroxanthone scaffolds. Indeed, HBTM catalyst **39**[14b] could convert **33** to the acylated product. However, even with a substoichiometric amount of the base (*N*,*N*-diisopropylethylamine, DIEA), the tetrahydroxanthone still underwent *syn/anti* and retro-Dieckmann rearrangement (*not shown*). As tetrahydroxanthone substrates were found to be stable under acidic conditions, we wondered whether base was necessary for acylation. Gratifyingly, without any base, kinetic resolution proceeded smoothly on tetrahydroxanthone **33** to generate (-)-**33** and (+)-**41** in excellent yield and in excellent enantiomeric excess (**Scheme 6**). The *s* factor for the latter reaction was above 200. For blennolide B (**42**) as substrate, we were concerned that the additional methyl group on *C* ring could dramatically decrease the acylation reactivity of the secondary alcohol. For this case, enantioselectivities using propionic anhydride never exceeded 40 % conversion after screening various conditions. Fortunately, after switching to the less hindered acylating reagent acetic anhydride, (-)-**42** and the acylated tetrahydroxanthone (+)-**43** were obtained in high yield and ee. Notably, the *s* factor observed for the unprotected blennolide B (*s*=159) was even higher than for the enol-protected blennolide B shown previously (*s*=93).[14b]

Using the enantioenriched tetrahydroxanthones, the *para*-iodo tetrahydroxanthones were prepared in a similar manner. With compound (-)-**38** in hand (**Scheme 7**), we followed our previous sequence to protect the free phenol. However, in this case MOM protection was found to be low yielding and

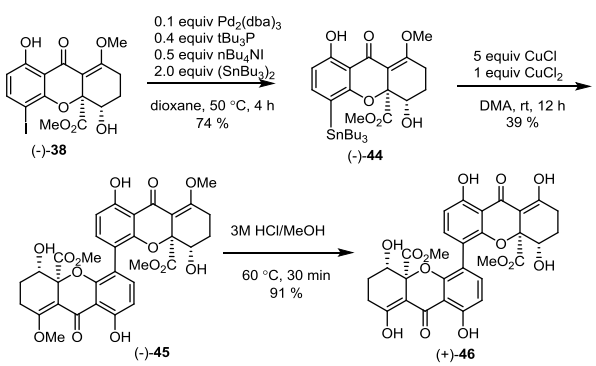
Scheme 6. Kinetic Resolution of an Unprotected Tetrahydroxanthone Substrate



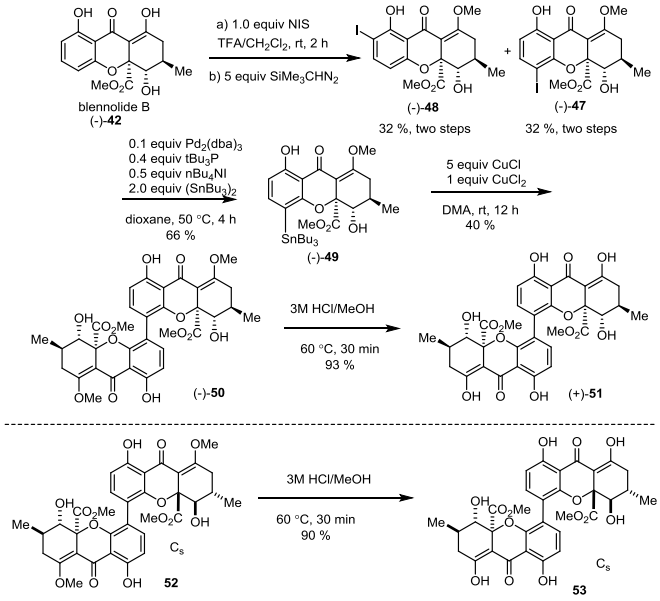
irreproducible. Fortunately, stannylation could be cleanly performed on the unprotected substrate (-)-**44**. Remarkably, the *para*-iodide (-)-**38** was not transformed to a dimeric product under our previous one-pot Suzuki dimerization conditions[14c] (Pd-SPhos-II, $BPin_2$, K_3PO_4).

As there are no literature reports of stannane dimerizations with substrates containing a free phenol, we were concerned that a free phenol could jeopardize the dimerization step. Nevertheless, the resulting stannane (-)-**44** was subjected to dimerization conditions. Applying our previously developed CuCl/air conditions to stannane (-)-**44** cleanly produced a protodestannylated product. After further evaluation of oxidants (*e.g.* Cu(ethylhexanoate)$_2$, Cu(OAc)$_2$, $FeCl_3$, Mn(acac)$_3$), we found that $CuCl_2$ and ferrocenium tetrafluoroborate could provide the corresponding 4,4'-linked dimer (-)-**45** in 40-50 % conversion (**Scheme 7**). However, the yield/conversion remained inconsistent over several experimental trials. After further screening of additives (*e.g.* Na_2SO_4, $CaCO_3$, $NaHCO_3$), we found that trace amounts of water decreased the yield dramatically. Use of freshly-dried stannane (-)-**44** afforded the corresponding C_2 symmetric dimer (-)-**45** in 39 % yield. Treatment of (-)-**45** with 3M HCl led to the formation of the deprotected 4,4'-linked tetrahydroxanthone dimer (+)-**46** in 91 % yield.

Scheme 7. Asymmetric Synthesis of a Model 4,4'-Linked Tetrahydroxanthone Dimer

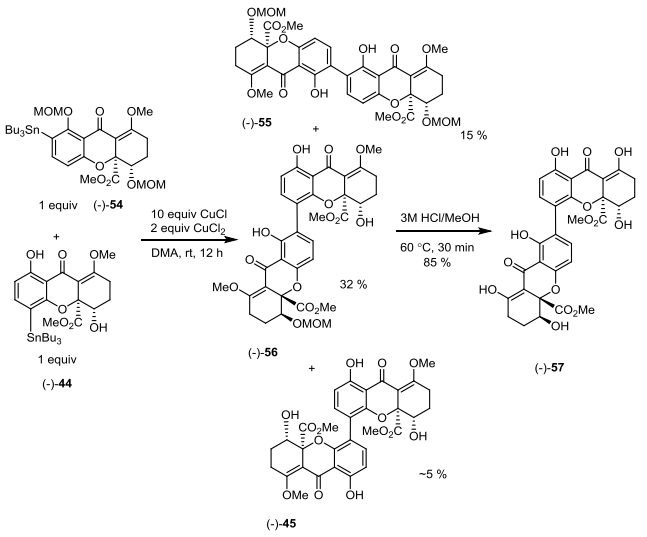


Scheme 8. Asymmetric Synthesis of a 4,4'-Linked Secalonic Acid A

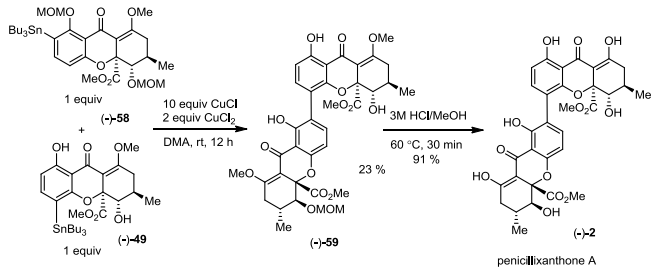


After successfully establishing access to a model 4,4'-linked dimeric tetrahydroxanthone, we considered that 4,4'-secalonic acid A could be synthesized in a similar manner (**Scheme 8**). Blennolide B (-)-**42** was iodinated with NIS in TFA/CH_2Cl_2. The resulting *para*- and *ortho*-iodides were *O*-methylated to afford (-)-**47** and (-)-**48** (32% yield for both compounds). Stannylation proceeded smoothly following the previously described protocol to generate (-)-**49**. The C_2 dimer (-)-**50** was successfully synthesized by treating freshly-dried stannane (-)-**49** with CuCl/$CuCl_2$. The presence of a 4,4'-linkage was further verified through a key HMBC correlation between *C*-2 and 1-*OH*.[23] Finally, 4,4'-linked secalonic acid A (+)-**51** was obtained after acidic deprotection. In a similar manner, the C_s symmetric tetrahydroxanthone dimer **53** was synthesized from dimer **52**, the latter obtained from the chiral, racemic monomer **42**.[23]

Scheme 9. Asymmetric Synthesis of Model 2,4'-Linked Tetrahydroxanthone Dimer



Scheme 10. Asymmetric Synthesis of a 2,4'-Linked Secalonic Acid A (Penicillixanthone A)



Synthesis of 2,4'-Linked Tetrahydroxanthone Dimers.

With our success in synthesizing of 2,2'- and 4,4'- secalonic acids, we anticipated that we could also obtain the 2,4'-linked tetrahydroxanthones from heterodimerization of 2- and 4-stannyl tetrahydroxanthone monomers. Equimolar amounts of (-)-**54** and (-)-**44** were treated with CuCl/$CuCl_2$ in DMA. The desired 2,4'-linked dimer (-)-**56** was obtained in 32 % yield (**Scheme 9**), along with 15 % of the 2,2' dimer (-)-**55** and less than 5 % of the 4,4' dimer (-)-**45**. After acidic deprotection, the 2,4'-linked model tetrahydroxanthone dimer (-)-**57** was obtained in 85 % yield. In a similar manner, protected 2,4'-linked secalonic acid A (-)-**59** was constructed from (-)-**58** and (-)-**49** (**Scheme 10**). The corresponding 2,2'-linked dimer (-)-**62** and 4,4'-linked dimer (-)-**50** (*not shown*) were also produced in this reaction in around 20 and <5% yields, respectively. The 2,4'-linked dimer secalonic acid A (penicillixanthone A) (-)-**2** was obtained smoothly after deprotection with 3M HCl. NMR spectra and α_D values for (-)-**2** were found to be identical to those reported for the natural sample.[5a, d]

Shapeshifting Properties of 2,2'-, 2,4'- and 4,4'-Secalonic Acids A.

Burobane and coworkers[9] reported that 2,2'- secalonic acids could isomerize to the corresponding 2,4'- and 4,4'-linked congeners in polar solvents (*e.g.* pyridine and CH_3CN). Intrigued by this phenomenon, and with the synthetic 2,2'-, 2,4'- and 4,4'- linked secalonic acids A in hand, we were interested to monitor this process using UPLC analysis in order to determine the ratio of products obtained based on thermodynamic equilibration. We first considered use of DMSO as solvent for our isomerization study based on use of this solvent in biological assays. [29] We first prepared a solution of the 4,4'-linked secalonic acid (+)-**51** in DMSO (0.5 mg/mL) at room temperature and the solution was monitored by UPLC analysis. As shown in **Figure 4**, we observed that the 4,4'-linked secalonic acid (+)-**51** was converted to 2,2'- (-)-**1** and 2,4'-linked secalonic acids (-)-**2** slowly at room temperature. After 13 h, the secalonic acids reached thermodynamic equilibrium. A similar equilibrium process was observed starting with the pure 2,2'- or 2,4'-linked secalonic acids A.[23] The thermodynamic ratio of 2,2'-, 2,4'- and 4,4'- secalonic acids was determined to be 3.2:2:1 as determined by crude ^{1}H NMR analysis.[23] The isomerization process was also found to be faster with 10% pyridine in DMSO[23] which indicates that base can promote isomerization (*cf.* **Figure 2**). Forming the less sterically hindered biaryl bond may be a driving force for this equilibrium

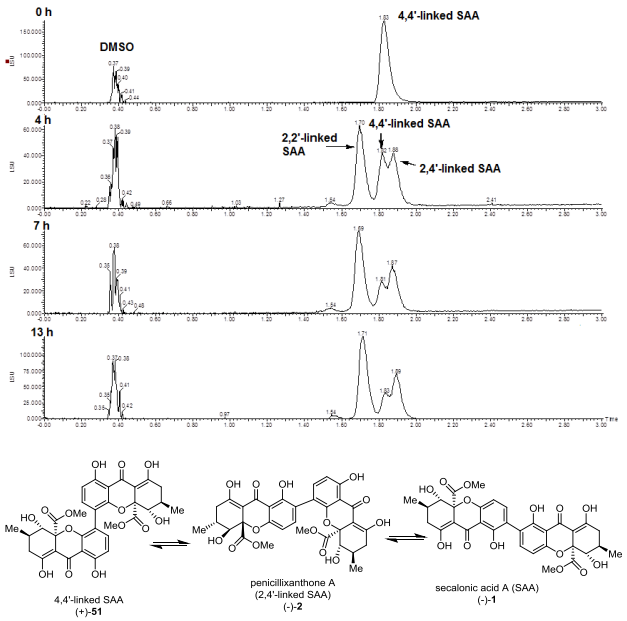


Figure 4. Equilibration of 4,4'-Linked Secalonic Acid A in DMSO

Table 1. Cytotoxicities of secalonic acids and related compounds with varied linkages against four human tumor cell lines, IC_{50} values in μM.

compound	A498	UO31	Colo205	KM12	linkage
(-)-**1**	6.0	0.12	0.044	0.072	2,2
(-)-**60**[14c]	>40	>40	>40	>40	2,2
(-)-**61**[14b]	5.5	4.9	2.8	2.8	2,2
(-)-**62**[14b]	3.9	3.6	2.9	n.d.[a]	2,2
(+)-**1**	3.9	0.40	0.052	0.19	2,2
(+)-**63**[14b]	4.8	6.8	4.0	n.d.[a]	2,2
(-)-**56**	6.3	9.9	8.6	8.2	2,4
(-)-**57**	14	35	>40	31	2,4
(-)-**2**	n.d.[a]	0.10	0.067	0.099	2,4
(+)-**46**	11	33	>40	>40	4,4
(+)-**51**	1.1	0.060	0.010	0.012	4,4
(-)-**50**	>40	18	>40	39	4,4
53	33	6.3	>40	27	4,4
(-)-**45**	28	30	22	16	4,4
27	>40	>40	>40	>40	4,4
28	>40	>40	>40	>40	4,4

[a] Conflicting values observed in two experiments.

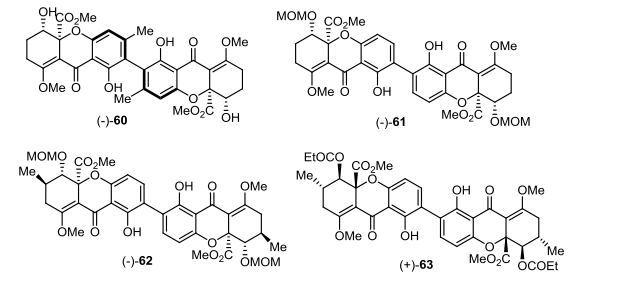


Figure 5. Structure of Additional Dimeric Tetrahydroxanthones Investigated

and the basis for favoring the 2,2'-linkage isomer in the equilibration process.

Biological Studies.

We explored the biological activity of the synthetic xanthones using a 48 h cancer cell growth inhibition assay with two renal cancer cell lines (A498, UO-31) and two colon cancer cell lines (Colo205 and KM12). The results are tabulated in **Table 1** and dose response curves are provided in the Supporting Information.[23] The known compounds secalonic acids A (-)-**1**, D (+)-**1**, and penicillixanthone (-)-**2** all showed potent activity similar to that reported previously in L1210 leukemia cells[30] and MDA-MB-435 melanoma and SW-620 colon cancer cells.[5d] The response for (+)-**1** was also similar in comparison to the NCI 60 screen wherein GI_{50} values of 550, 150, 66 and 55 nM were recorded for the above mentioned cell lines.[30] A major difference between the present biological assay and the NCI 60 screen is the use of a formazan XTT endpoint in contrast to the protein stain SRB in the NCI 60, as well as the use of higher cell densities and a 384 well format in the present assays. It is interesting to observe that both (-)-**1** and (+)-**1** have similar activities, which was also reported for both enantiomers of the anticancer agent simaomicin α.[31]

Chromone lactones **27** and **28** had no activity against any of the four cell lines at 40 μM, showing that the tetrahydroxanthone skeleton is necessary for cell growth inhibition. Comparable patterns of cell growth inhibition were seen for all three dimer linkage types, *e.g.* (-)-**1**, (-)-**2**, and (+)-**51** *via* likely interconversion and equilibration of linkage isomers to a mixture of 2,2'-, 2,4'-, and 4,4'-linked compounds as shown in **Figure 4**. While no specific attempt was made to control this process during bioassays, dry compounds were dissolved in DMSO and immediately frozen at -20°C and then thawed the day of assay. While we are not able to judge the extent of equilibration that has occurred during the 48 h cell growth assays, the similar patterns observed for the three compounds support interconversion of the secalonic acid A linkage isomers in the assay. Interestingly, in our studies we found that the *O*-methyl enol ether appears to prevent dynamic (shapeshifting) behavior. However, methyl enol ethers such as (-)-**56** (2,4'-linked), (-)-**50** (4,4'-linked), were found to have reduced biological activities, while the protected compounds (-)-**62** and (+)-**63** (2,2'-linked) maintained modest bioactivities. Nevertheless, all methyl-protected substrates have reduced bioactivities in comparison to the unprotected dimeric tetrahydroxanthones, which leads us to believe that the tetrahydroxanthone moiety is crucial for their cytotoxicity. It is also noteworthy that compounds such as (-)-**61** and (-)-**62** (**Figure 5**) appear to have different patterns of cell growth inhibition from the others, perhaps indicating a different mode of action. Of the tetrahydroxanthones, only the rugulotrosin derivative (-)-**60**[14c] was found to be inactive against all cell lines tested. Moreover, compound (+)-**46** has a reduced cytotoxicity in comparison to (+)-**51**, which contains an additional methyl group on the tetrahydroxanthone C ring. A similar pattern also was observed for compounds (-)-**57** and (-)-**2**. These results indicate that the methyl group on the C ring may provide a

hydrophobic site which is crucial for cytotoxicity. These conclusions about selectivity and potency are preliminary and a more meaningful analysis will require testing in the full NCI 60 screen.

CONCLUSION

We have developed a copper-mediated aryl stannane coupling protocol to access chromone lactone dimers as well as 4,4'- and 2,4'-linked dimeric tetrahydroxanthones. A highly selective kinetic resolution was performed on an unprotected tetrahydroxanthone scaffold to enable access to chiral, non-racemic monomers. Asymmetric syntheses of 2,4'-linked (penicillixanthone A) and 4,4'-linked secalonic acids A and their analogues have been achieved. Our investigation also led to the discovery of a gold (III)-catalyzed *para*-bromination of a chromone lactone substrate. With a varied linkage series of secalonic acids A, the "shapeshifting" properties were evaluated and monitored by UPLC analysis. Initial biological studies of secalonic acid A analogues revealed that the dimeric tetrahydroxanthone moiety was crucial for cytotoxicity against select cancer cells and that isomerization of the biaryl linkage likely occurs during the cell-based assays. Further biological studies of secalonic acid derivatives, as well as the chemistry of the secalonic acid core structure, are ongoing and will be reported in due course.

ASSOCIATED CONTENT

Supporting Information Available Experimental procedures and characterization data for all new compounds, including X-ray structure analysis of compound **34**, X-ray crystallographic data (CIF), and detailed biological methods and results (PDF). This material is available free of charge *via* the Internet at http://pubs.acs.org.

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