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Rhodium(I)-Catalyzed Nucleophilic Ring-Opening Reactions of Oxabicyclo Adducts Derived from the [4 + 2]-Cycloaddition of 2-Imido-Substituted Furans

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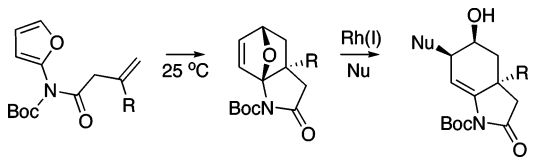

A series of 2-imido-substituted furans containing tethered unsaturation were prepared by the addition of the lithium carbamate of furan-2-ylcarbamic acid *tert*-butyl ester to a solution of the mixed anhydride of an appropriately substituted 3-butenoic acid. The initially formed imido furans undergo a rapid intramolecular [4 + 2]-cycloaddition at room temperature to deliver the Diels−Alder cycloadducts in good to excellent yield. Isolation of the highly labile oxabicyclic adduct is believed to be a consequence of the lower reaction temperatures employed as well as the presence of the extra carbonyl group, which diminishes the basicity of the nitrogen atom, thereby retarding the ring cleavage/rearrangement reaction generally encountered with related systems. By using a Rh(I)-catalyzed ring opening of the oxabicyclic adduct with various nucleophilic reagents, it was possible to prepare highly functionalized hexahydro-1*H*-indol-2(3*H*)-one derivatives in good yield. The major stereoisomer obtained possesses a *cis*-relationship between the nucleophile and hydroxyl group in the ring-opened product. The stereochemistry was unequivocally established by X-ray crystallographic analysis. Coordination of Rh(I) to the alkenyl π-bond followed by a nitrogen-assisted cleavage of the carbon−oxygen bond occurs to furnish a π-allyl rhodium(III) species. Addition of the nucleophile then occurs from the least hindered terminus of the resulting π-allyl rhodium(III) complex. Proton exchange followed by rhodium(I) decomplexation ultimately leads to the *cis*-diastereomer.

Introduction

7-Oxabicyclo[2.2.1]heptenes are valuable intermediates in organic synthesis.[1,2] The large number of selective transformations possible with the oxabicyclic system endow this nucleus with impressive versatility.[3−9] A crucial synthetic transformation employing these intermediates involves the cleavage of the oxygen bridge to produce functionalized cyclohexene derivatives. Many groups have developed different approaches including β-elimination of suitable derivatives,[10] treatment with strong acids,[11] reductive elimination of *endo* functionalities,[12] frag-

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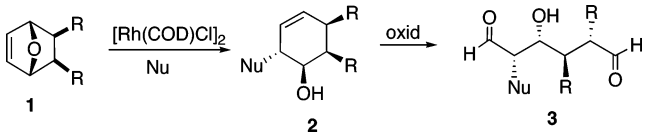
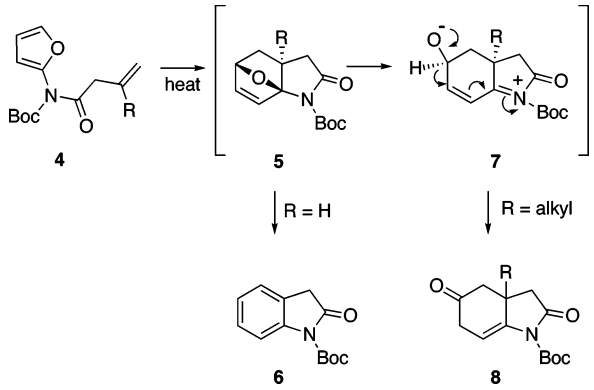
SCHEME 1. Lauten's Oxabicyclic Ring-Opening Protocol



mentation,[13] hydrolytic ring openings,[14] and alkylative bridge cleavage reactions.[15] A significant advancement in the ring-opening chemistry of oxabicyclic compounds occurred in the early 1990s as a result of the elegant work of Lautens and co-workers.[16] This research team demonstrated that the ring opening of unsymmetrical oxabicycloheptenes **1** is a highly regioselective process giving rise to products **2** derived from attack of the nucleophile distal to the bridgehead substituent.[16] These reactions were carried out with a range of nucleophiles including hydride, stabilized and nonstabilized carbanions, alcohols, amines, and carboxylates.[1] Highly stereoselective reactions were also observed to occur with organocuprates, silylcuprates, organolithium reagents, and organomagnesium compounds,[1c] and these processes were used for the synthesis of acyclic (and cyclic compounds) **3** with multiple stereocenters (Scheme 1).[1]

The most general method for the synthesis of 7-oxabicyclo-[2.2.1]heptenes relies on the Diels−Alder reaction of a furan derivative with various dienophiles.[17] Furan itself is not very reactive as a diene due to the loss of aromaticity which accompanies the cycloaddition.[18] Among the solutions investigated to improve the [4 + 2]-cycloaddition reaction are catalysis using Lewis acids,[2c] use of metal salts,[19] silica gel,[20] zeolites,[21] centrifugation,[22] ultrasound,[23] and high-pressure techniques.[24] The placement of an electron-donor substituent on the furan ring also significantly enhances its reactivity toward dienophiles by raising its HOMO level. The intramolecular version of the Diels−Alder reaction of furans (IMDAF) has been described in several reviews,[17,25] including an excellent treatise by Keay and Hunt.[26] For the IMDAF reaction to proceed

SCHEME 2. IMDAF Reaction of Furanyl Carbamates



favorably, the aromatic character of the furan ring and the strain associated with the oxabicyclic adduct must be overcome. Steric factors, rather than electronic or solvent effects, appear to have the greatest influence on the outcome of the [4 + 2]-cycloaddition.[27] Electronically disfavored furan cycloadditions can be brought about by creative functional group modifications.

Several years ago, we began a synthetic program to provide general access to a variety of alkaloids by [4 + 2]-cycloaddition chemistry of substituted 2-amidofurans.[28] Our synthetic strategy was to take advantage of an intramolecular Diels−Alder reaction of an alkenyl-substituted furanyl carbamate derivative (IMDAF).[29,30] Not only does this IMDAF reaction allow for the preparation of aza-polycyclic ring compounds, but they proceed at lower temperatures than their intermolecular counterparts. Even more significantly, unactivated π-bonds are reactive toward the internal cycloaddition reaction. We discovered that the IMDAF reaction of a series of furanyl carbamates (i.e., **4**) occurred smoothly to furnish the cyclized indoline **6** as the only isolable product in high yield when a monosubstituted alkenyl tether (R = H) was used (Scheme 2).[28] When the alkenyl group possesses a substituent other than hydrogen at the 2-position of the π-bond, the thermal reaction furnished a rearranged hexahydroindolinone (i.e., **8**). With this system, the initially formed cycloadduct **5** cannot aromatize. Instead, ring opening of the oxabicyclic intermediate occurs to generate zwitterion **7**, which undergoes a subsequent proton elimination by tautomerization to give the rearranged ketone **8**.[30]

When furanyl carbamates such as **4** were used, the IMDAF reaction required heating at 165 °C for several hours in order to produce the rearranged product (i.e., **6** or **8**). The Diels−Alder adduct **5** that was first formed underwent reorganization under the reaction conditions and could not be isolated or detected in the crude reaction mixture. During the course of investigating the general nature of this reaction, significant rate differences were noticed when the alkenyl tether was incorporated onto the amido side chain. With these systems, the IMDAF cycloaddition occurred at room temperature, and in some cases,[31] it was possible to isolate the initially formed aza-oxabicyclo

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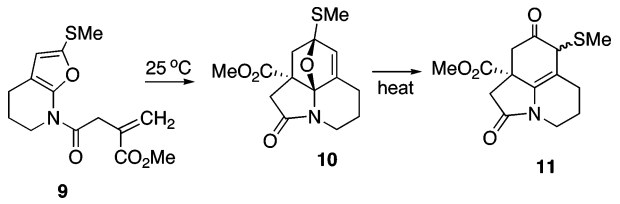
SCHEME 3. Isolation of the Aza-oxabicyclic Cycloadduct



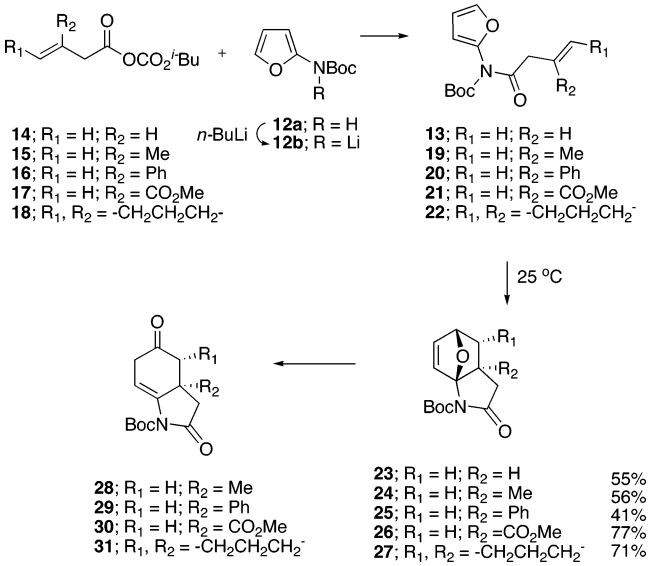
adduct. For example, the intramolecular [4 + 2]-cycloaddition of amidofuran **9** afforded cycloadduct **10** in 77% yield when the reaction was carried out at 25 °C (Scheme 3). Further heating of a benzene solution of this cycloadduct at reflux provided the rearranged tricyclic lactam **11** in 75% yield. The notion of further functionalizing an aza-oxabicyclo adduct by a transition-metal-catalyzed ring-opening reaction with various nucleophilic reagents was most attractive to us since the resulting product(s) can be envisaged as precursors to a wide assortment of alkaloids. In this paper, we detail our recent findings using a series of alkenyl-substituted imidofurans where we address the issues of (a) ease of access to the starting aza-oxabicyclo adducts, (b) the efficiency of the IMDAF reaction, and (c) regio- and stereocontrol in the metal-catalyzed ring-opening reaction.

Results and Discussion

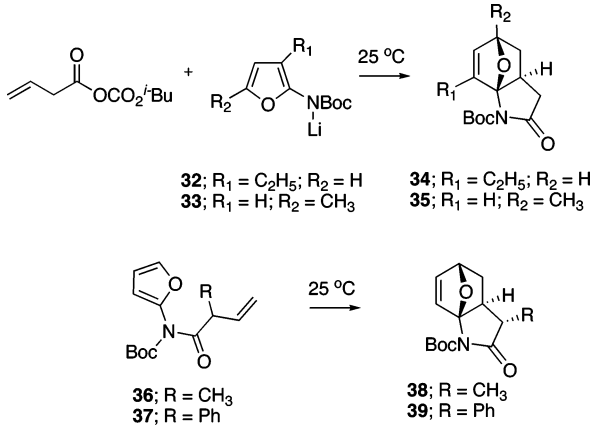
The aza-oxabicyclo[2.2.1] substrates employed in this study were readily prepared from the corresponding imidofurans. Initially, we had envisioned imidofuran **13** arising from the simple acylation of furanyl carbamate **12a** with the acid chloride derived from 3-butenoic acid. However, under a variety of conditions, **12a** proved to be remarkably resistant toward acylation. After some experimentation, we found that the addition of lithiated carbamate **12b**, formed by the action of *n*-BuLi on **12a**, to a solution of the mixed anhydride **14** provided the expected imidofuran **13**, which rapidly reacted at room temperature to deliver the Diels−Alder cycloadduct **23** in 55% isolated yield. Intrigued by the ease with which imidofuran **13** underwent the IMDAF cycloaddition, we investigated several other systems containing related tethers as illustrated in Scheme 4. The mixed anhydrides **15** and **16** were subjected to the acylation protocol and provided the desired imidofurans **19** and **20**, which also underwent cycloaddition at 25 °C (12 h) to furnish the aza-oxabridged cycloadducts **24** and **25**. When the more highly activated anhydride **17** was used, imidofuran **21** could not be observed because the [4 + 2]-cycloaddition occurred too rapidly to preclude its detection, even at 0 °C. In contrast, the more sterically congested anhydride **18** furnished imidofuran **22**, which required heating at 90 °C to give cycloadduct **27**.

Several more heavily substituted imidofuran substrates were also found to rapidly undergo the intramolecular [4 + 2]-cycloaddition at room temperature and gave aza-oxabicyclo adducts in good yield. Thus, the reaction of the mixed anhydride of vinylacetic acid with lithiated carbamates **32** and **33** provided the expected imidofurans as transient species which underwent a subsequent IMDAF reaction at 25 °C to deliver cycloadducts **34** and **35** in 60% yield, respectively (Scheme 5). Interestingly, the IMDAF cycloaddition of the somewhat labile imidofurans **36** and **37** (prepared in a similar manner) occurred with very high diastereoselectivity (>20:1) producing the *cis*-substituted cycloadducts **38** and **39** in 96% and 98% yield, respectively.

SCHEME 4. IMDAF Cycloaddition of the 2-Imidofuran System



SCHEME 5. More Heavily Substituted Systems



The increase in reactivity of these 2-imido-substituted furans (0−90 °C) when compared to the related furanyl carbamates[32] (>150 °C) is clearly related to the placement of the carbonyl center within the dienophilic tether. Dramatic effects on the rate of the Diels−Alder reaction were previously noted to occur when an amido group was used to anchor the diene and dienophile.[33] The effect of amide-linked tethers on both the rate and diastereoselectivity of intramolecular Diels−Alder reactions were previously attributed to relative transition-state stabilities.[33] The rate enhancement observed with the imidofuranyl system probably originates from restricted rotation about the C−N bond, producing a lower energy ground-state conformer that is more energetically similar to the reactive conformer.[34] Our ability to isolate the highly labile aza-oxabicyclic adducts is presumably

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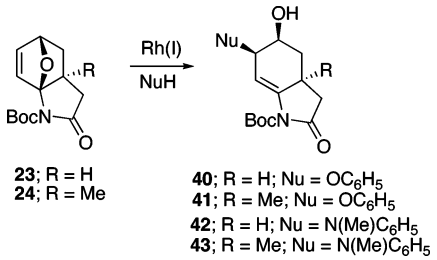
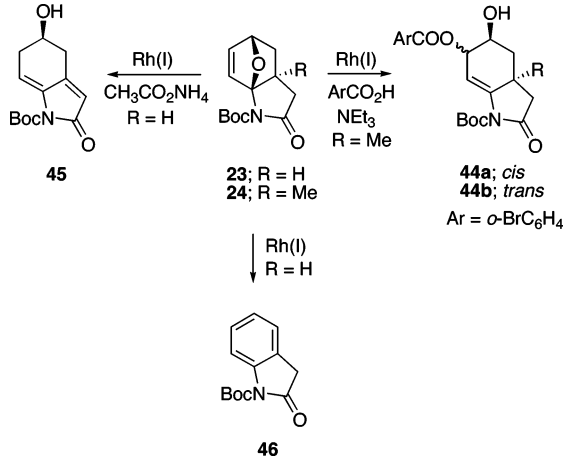
a result of the lower reaction temperatures employed as well as the presence of the extra carbonyl group, which diminishes the basicity of the nitrogen atom thereby retarding the ring cleavage/rearrangement reaction generally encountered with these systems.[32] When exposed to more forcing conditions (i.e., >100 °C), the oxabridged cycloadducts **24**−**27** were smoothly transformed (>90%) into the corresponding hexahydroindolinone systems **28**−**31**. It should also be noted that the IMDAF reaction of these systems proceeds by a transition state where the sidearm of the tethered alkenyl group is oriented *exo* with respect to the oxygen bridge. Products resulting from an *endo* sidearm transition state were neither detected nor isolated. This result is quite reasonable since, in these mobile cycloaddition equilibria, the *exo* adducts are thermodynamically more stable. In fact, the stereochemical results that we have encountered with the IMDAF cycloaddition of these 2-imidofurans is consistent with those reported by others for related systems possessing short tethers.[35] As a consequence of this preferred *exo* orientation, the oxido bridge is located *anti* to the substituent on the bridgehead carbon. The *cis*-diastereoselectivity observed in the cycloaddition of imidofurans **36** and **37** can be rationalized as being the result of approach of the furan ring from the less hindered π-face of the double bond.

Regioselective cleavage of the oxygen bridge of the 7-oxabicyclo-[2.2.1]hept-2-ene skeleton to give functionalized cyclohexene derivatives is central to many synthetic strategies.[36] Remote electronic effects mediated by an aromatic π-system have been thoroughly investigated for the transformation of substituted oxabenzonorbornadienes to the corresponding naphthols under protic conditions.[37] The ring-opening reaction of 7-oxanorbornenes with organometallic reagents has also been investigated in some detail by several research groups.[38] Lautens and co-workers demonstrated that a variety of oxabicyclo[2.2.1]-heptene derivatives readily undergo Rh(I)-catalyzed nucleophilic ring-opening,[1] and this key reaction was employed for the synthesis of highly functionalized acyclic polypropionate and polyacetate chains using the related oxabicyclo[3.2.1] system.[39] Our research plan was to explore the reactivity of the IMDAF-derived aza-oxabicyclo adducts toward several nucleophilic partners with the thought of eventually applying the resulting methodology toward the synthesis of several alkaloid skeletons.

SCHEME 6. Rh(I)-Catalyzed Ring Opening of the 10-Oxa-2-azatricyclodecene System



SCHEME 7. Rh(I)-Catalyzed Ring-Opening Reactions Using Carboxylates as the Nucleophile



With a representative selection of 10-oxa-2-azatricyclo-[5.2.1.$0^{1,5}$]decenes on hand, a standard set of ring-opening conditions was employed. Our first set of experiments was carried out with cycloadducts **23** and **24** using Lauten's conditions[16] ([Rh(COD)Cl]$_2$, DPPF). Phenol and *N*-methylaniline were employed as the nucleophilic reagents. This led to the ring-opened alcohols **40**−**43** in good yield (Scheme 6) and with *cis*/*trans* ratios (Nu to OH) of 5:1 for **40** and **41** and 20:1 for **42** and **43**. An X-ray crystal structure of the major diastereomer of **41** unequivocally established the *cis* relationship between the nucleophile and hydroxyl groups in the ring-opened product. Interestingly, the stereochemical outcome of this reaction was exactly opposite to that reported by Lautens for the Rh(I)-catalyzed alcoholysis and aminolysis of oxabenzonorbornadiene.[16] When oxabicyclo **24** was subjected to the Rh(I)-catalyzed conditions using 2-bromobenzoic acid and NEt_3, a 3:1 mixture of the ring-opened product **44** was obtained in 72% yield (Scheme 7). The *cis*-stereochemical assignment of the major diastereomer **44a** was made on the basis of analogy with substrate **41** where X-ray data had been obtained. Subsequent experiments revealed that the reaction of the related oxabicyclo adduct **23** with the Rh(I) catalyst in the presence of various ammonium carboxylates[16c] generated the dienyl alcohol **45** in 80% isolated yield as the exclusive product. In the absence of the Rh(I) catalyst, only starting material was recovered. On the other hand, when the Rh(I)-catalyzed reaction was carried out in the absence of ammonium carboxylate, oxindole **46** was formed in 90% yield.

A reasonable mechanism to account for the Rh(I)-catalyzed reaction of the oxabicyclic adduct is outlined in Scheme 8.

(34) Jung and Gervay, however, reported data for intramolecular Diels−Alder reactions which suggest that substitution on the tether results in an increase in the population of reactive rotamers. The rate enhancement was suggested to originate from a restricted rotation, producing a lowest energy ground state conformer that is more energetically similar to the reactive conformer, see: (a) Jung, M. E.; Gervay, J. *J. Am. Chem. Soc.* **1991**, *113*, 224. See also: (b) Sternbach, D. D.; Rossana, D. M.; Onan, K. D. *Tetrahedron Lett.* **1985**, *26*, 591. (c) Giessner-Prettre, C.; Hükel, S.; Maddaluno, J.; Jung, M. E. *J. Org. Chem.* **1997**, *62*, 1439.

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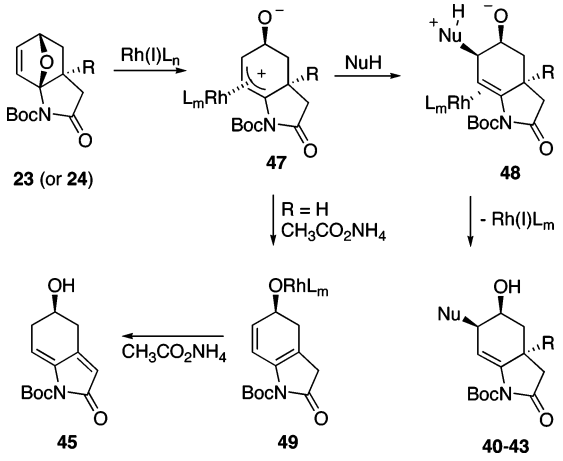
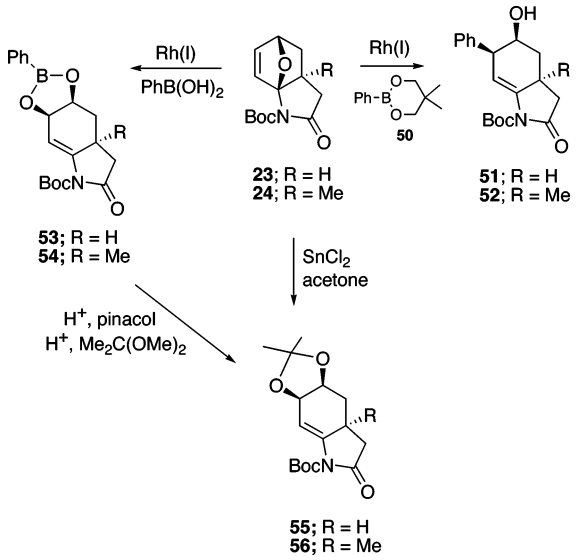
SCHEME 8. Proposed Mechanism for the Ru(I)-Catalyzed Ring-Opening Reactions



Coordination of Rh(I) to the alkenyl π-bond followed by nitrogen-assisted cleavage of the carbon−oxygen bond occurs to furnish the π-allyl rhodium(III) species **47**. Nucleophilic addition then occurs from the least hindered terminus of **47** and on the side opposite the rhodium complex.[40] Proton exchange of intermediate **48** followed by rhodium decomplexation ultimately leads to the *cis* diastereromers **40**−**43**. In the presence of the basic ammonium carboxylate, intermediate **47** (R = H) undergoes preferential deprotonation and subsequent loss of Rh(I) to generate a transient diene **49** which then isomerizes to give **45**. Without a base to induce double-bond isomerization, intermediate **49** undergoes an aromatization reaction to furnish oxindole **46**.

In recent years, the Rh(I)-catalyzed addition of arylboronic acids to olefins has become an active research area in organic synthesis.[41] Conjugate addition generally occurs with electron-deficient olefins such as enone,[42] alkenylphosphonates,[43] and nitroalkenes.[44] The facile addition of boronic acids to oxabenzonorbornenes has also been achieved using a catalytic amount of a rhodium(I) complex.[45] A common step in these reactions is the carborhodation of the carbon−carbon double bond followed by hydrolysis of the organorhodium intermediate. These earlier findings prompted us to examine whether a related transformation might occur upon treating the IMDAF-derived cycloadducts **23**/**24** with organoboronic acids in the presence of a Rh(I) catalyst. With this in mind, the reaction of 5,5-dimethyl-2-phenyl-1,3,2-dioxaborinane (**50**) with oxabicyclics **23** and **24**, using 5 mol % of the Rh(I) catalyst and 2.0 equiv of Cs_2CO_3 (5 M in H_2O) in THF at 65 °C, led to the ring-opened alcohols **51** and **52** in 70−80% yield (Scheme 9). The *cis* isomer was formed exclusively (X-ray structure of **51** was obtained) and parallels the results observed with the alcoholysis

SCHEME 9. Rh(I)-Catalyzed Addition of Arylboronic Acids to the IMDAF Cycloadducts



and aminolysis experiments. When the Rh(I)-catalyzed reaction was carried out with phenylboronic acid and without added base, the ring-opened boronates **53** and **54** were obtained in excellent yield (>95%). The *cis*-stereochemistry of **53** was unequivocally established by an X-ray crystal structure. Both boronates were cleaved to the corresponding diols,[46] which were subsequently transformed into dioxolanes **55** and **56** by reaction with 2,2-dimethoxypropane. It was also possible to prepare the same 1,3-dioxolanes (>90%) by treating oxabicyclic adducts **23** and **24** with catalytic anhydrous $SnCl_2$ in acetone.[47]

The following mechanistic scheme is suggested to account for the formation of the ring-opened alcohol **51** (or **52**). Initially, phenylrhodium(I) **57** is generated by transmetalation of a rhodium(I) chloride or hydroxide with dioxaborinane **50**. This process might well be promoted by the presence of a base. The resulting rhodium species **57** then undergoes *exo*-selective carborhodation at the oxabicycle olefin to generate intermediate **58**. Chelation of the rhodium metal with the olefin and oxygen atom of the oxabicycle probably contributes to the high *exo*-selectivity. β-Oxygen elimination, perhaps assisted by the nitrogen lone pair, furnishes the ring-opened intermediate **59**, which undergoes eventual protonolysis with water to produce the final product (i.e., **51**) (Scheme 10). The rhodium(I) species that is regenerated in this step is available to promote the next catalytic cycle.

When phenylboronic acid is used without added base, the oxabicyclic adduct **23** seemingly prefers to undergo a Rh(I)-catalyzed oxygen elimination reaction as the first step, perhaps as a consequence of the higher Lewis acidity of $PhB(OH)_2$ vs dioxaborinane **50**, and gives the ring-opened intermediate **60**.

This intermediate then undergoes reaction with the boronic acid from the side opposite the rhodium metal to produce **61**, which eventually affords **53** (or **54**) by cyclization and liberation of rhodium(I) hydroxide (Scheme 11).

In summary, a highly convergent synthesis of hexahydro-1*H*-indol-2-(3*H*)-one derivatives has been devised using an IMDAF cycloaddition reaction of 2-imido-substituted furans.

(40) With the oxabenzonorbornene system studied by the Lautens' group,[16] the rhodium metal undergoes initial *exo*-coordination with the π-bond and this is followed by C−O insertion and then a subsequent displacement of the allyl rhodium species via *endo* attack of the nucleophile.

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(42) Takaya, Y.; Ogasawara, M.; Hayashi, T.; Sakai, M.; Miyaura, N. *J. Am. Chem. Soc.* **1998**, *120*, 5579.

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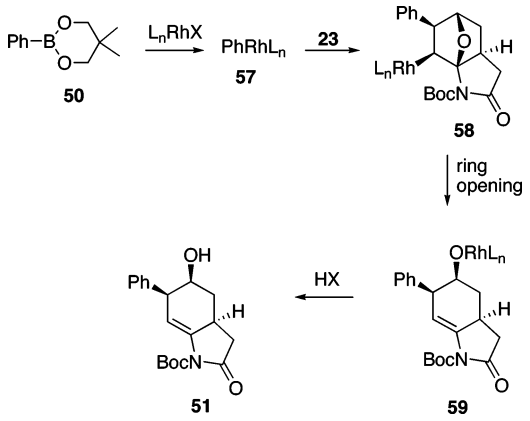
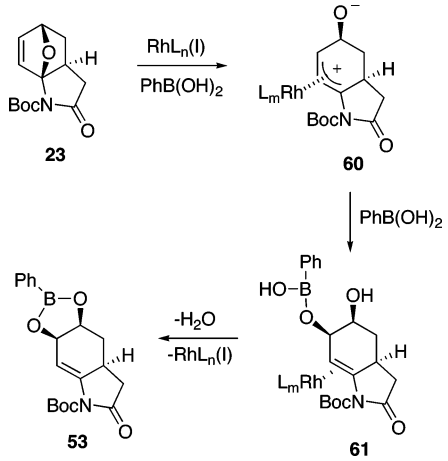
SCHEME 10. Rh(I)-Catalyzed Reaction of the Oxabicyclic System Using 5,5-Dimethyl-2-phenyl-1,3,2-dioxaborinane (50)



SCHEME 11. Rh(I)-Catalyzed Reaction Using PhB(OH)$_2$



The increase in reactivity of these imidofurans when compared to the related furanyl carbamates is related to the placement of the carbonyl center within the dienophilic tether. Isolation of the highly labile aza-oxabicyclo adducts is a result of the lower reaction temperatures used (ca. 25 °C) as well as the presence of the extra carbonyl group, which diminishes the basicity of the nitrogen atom, thereby retarding the thermal cleavage/rearrangement reaction generally encountered with these systems. The Rh(I)-catalyzed ring-opening reactions of the IMDAF cycloadducts were investigated using a variety of nucleophiles. The catalyzed reactions proceed in high yield under very mild conditions and occur with excellent diasteroselectivity. Application of this methodology to various alkaloid skeletons is currently under investigation, the results of which will be disclosed in due course.

Experimental Section

***tert*-Butyl 3-Oxo-10-oxa-2-azatricyclo[5.2.1.01,5]dec-8-ene-2-carboxylate (23).** To a solution of 0.2 g (1.2 mmol) of *tert*-butyl furan-2-ylcarbamate (**12a**) in 4 mL of THF at 0 °C was added dropwise 0.8 mL (1.3 mmol) of *n*-BuLi (1.5 M in hexane). The reaction mixture was stirred at 0 °C for 20 min. In a separate flask, 0.1 mL (1.2 mmol) of 3-butenoic acid was dissolved in 5 mL of THF at 0 °C, and 0.13 mL (1.2 mmol) of 4-methylmorpholine and 0.15 mL (1.2 mmol) of isobutyl chloroformate were added dropwise. After the mixture was stirred for 5 min, the white precipitate was removed via filtration and washed with 2 mL of THF. The filtrate was cooled to 0 °C, and the preformed lithiate was added dropwise via syringe to the above solution. After being stirred at 0 °C for an additional 5 min, the reaction mixture was quenched with H_2O and extracted with EtOAc. The organic layer was washed with a saturated aqueous $NaHCO_3$ solution, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to afford a colorless oil which underwent spontaneous cycloaddition while standing at room temperature for 12 h. The crude yellow solid was subjected to flash silica gel chromatography to provide 0.09 g (55%) of **23** as a white solid: mp 126−127 °C; IR (neat) 1792, 1767, 1726, 1357, 1296, and 1157 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.52 (s, 9H), 1.65 (dd, 1H, J = 11.6 and 7.6 Hz), 1.80 (dt, 1H, J = 11.6 and 4.4 Hz), 2.05−2.13 (m, 1H), 2.41 (dd, 1H, J = 17.2 and 10.0 Hz), 2.75 (dd, 1H, J = 17.2 and 8.8 Hz), 5.02 (dd, 1H, J = 4.4 and 2.0 Hz), 6.30 (dd, 1H, J = 6.0 and 2.0 Hz), and 6.52 (d, 1H, J = 6.0 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 28.2, 32.6, 35.9, 38.4, 77.6, 84.1, 102.0, 133.6, 134.7, 149.4, and 174.6. Anal. Calcd for $C_{13}H_{17}NO_4$: C, 62.14; H, 6.82; N, 5.57. Found: C, 62.01; H, 6.80; N, 5.52.

***tert*-Butyl 5-Methyl-3-oxo-10-oxa-2-azatricyclo[5.2.1.01,5]dec-8-ene-2-carboxylate (24).** To a solution of 0.6 g (3.2 mmol) of carbamate **12a** in 10 mL of THF at 0 °C was added dropwise 1.6 mL (3.4 mmol) of *n*-BuLi (2.1 M in hexane). The reaction mixture was stirred at 0 °C for 20 min. In a separate flask, 0.35 g (3.5 mmol) of 3-methylbut-3-enoic acid[48] was dissolved in 10 mL of THF at 0 °C, and 0.38 mL (3.5 mmol) of 4-methylmorpholine and 0.45 mL (3.5 mmol) of isobutyl chloroformate were added dropwise to the above solution. After the mixture was stirred for 5 min, the white precipitate was removed via filtration and washed with 4 mL of THF. The filtrate was cooled to 0 °C, and the preformed lithiate was added dropwise via syringe. After being stirred at 0 °C for an additional 5 min, the reaction was quenched with H_2O and extracted with EtOAc. The organic layer was washed with a saturated aqueous $NaHCO_3$ solution, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to afford a clear oil which underwent spontaneous cycloaddition while standing at room temperature for 12 h. The crude yellow oil was subjected to flash silica gel chromatography to provide 0.5 g (56%) of **24** as a white solid: mp 96−98 °C; IR (neat) 1793, 1767, 1730, 1353, 1306, and 1157 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.97 (s, 3H), 1.25 (d, 1H, J = 11.6 Hz), 1.50 (s, 9H), 2.13 (dd, 1H, J = 11.6 and 4.4 Hz), 2.39 (d, 1H, J = 16.8 Hz), 2.67 (d, 1H, J = 16.8 Hz), 4.93 (dd, 1H, J = 4.4 and 2.0 Hz), 6.32 (dd, 1H, J = 6.0 and 2.0 Hz), and 6.48 (d, 1H, J = 6.0 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 24.3, 28.1, 39.9, 41.8, 46.5, 77.1, 84.0, 104.0, 132.8, 133.3, 149.7, and 174.5. Anal. Calcd for $C_{14}H_{19}NO_4$: C, 63.38; H, 7.22; N, 5.28. Found: C, 63.33; H, 7.13; N, 5.24.

***tert*-Butyl 3-Oxo-5-phenyl-10-oxa-2-azatricyclo[5.2.1.01,5]dec-8-ene-2-carboxylate (25).** To a solution of 0.41 g (2.2 mmol) of carbamate **12a** in 8 mL of THF at 0 °C was added dropwise 1.7 mL (2.5 mmol) of *n*-BuLi (1.5 M in hexane). The reaction mixture was stirred at 0 °C for 20 min. In a separate flask, 0.40 g (2.5 mmol) of 3-phenylbut-3-enoic acid[49] was dissolved in 10 mL of THF at 0 °C, and 0.27 mL (2.5 mmol) of 4-methylmorpholine and 0.32 mL (2.5 mmol) of isobutyl chloroformate were added dropwise. After the mixture was stirred for 5 min, the white precipitate was removed via filtration and washed with 4 mL of THF. The filtrate was cooled to 0 °C, and the preformed lithiate was added dropwise via syringe to the above solution. After being stirred at 0 °C for an additional 5 min, the reaction was quenched with H_2O and extracted with EtOAc. The organic layer was washed with saturated aqueous $NaHCO_3$, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was subjected to flash

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(49) Itoh, K.; Harada, T.; Nagashima, H. *Bull. Chem. Soc. Jpn.* **1991**, *64*, 3746.

silica gel chromatography to afford a pale yellow oil which underwent spontaneous cycloaddition while standing at room temperature for 12 h. The crude yellow oil was subjected to flash silica gel chromatography to provide 0.3 g (41%) of **25** as a clear oil: IR (neat) 1798, 1762, 1726, 1357, and 1296 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.53 (s, 9H), 2.17 (d, 1H, J = 12.0 Hz), 2.52 (dd, 1H, J = 12.0 and 4.8 Hz), 2.84 (d, 1H, J = 16.8 Hz), 3.02 (d, 1H, J = 16.8 Hz), 5.10 (dd, 1H, J = 4.8 and 2.0 Hz), 6.31 (dd, 1H, J = 6.0 and 2.0 Hz), 6.36 (d, 1H, J = 6.0 Hz), 7.11−7.14 (m, 2H), and 7.17−7.28 (m, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 28.2, 40.4, 48.4, 49.9, 77.0, 84.2, 104.5, 126.9, 127.1, 128.8, 133.0, 134.4, 143.2, 149.3, and 174.4. Anal. Calcd for $C_{19}H_{21}NO_4$: C, 69.71; H, 6.47; N, 4.28. Found: C, 69.52; H, 6.37; N, 4.38.

***tert*-Butyl 3-Oxo-5-carbomethoxy-10-oxa-2-azatricyclo-[5.2.1.01,5]dec-8-ene-2-carboxylate (26).** To a solution of 0.36 g (2.0 mmol) of *tert*-butyl furan-2-yl-carbamate (**12a**) in 8 mL of THF at 0 °C was added dropwise 1.3 mL (2.2 mmol) of *n*-BuLi (1.6 M in hexane). The reaction mixture was stirred at 0 °C for 20 min. In a separate flask, 0.37 g (2.6 mmol) of 3-carbomethoxybut-3-enoic acid was dissolved in 10 mL of THF at 0 °C, and 0.28 mL (2.6 mmol) of 4-methylmorpholine and 0.33 mL (2.6 mmol) of isobutyl chloroformate were added dropwise. After the mixture was stirred for 5 min, the white precipitate was removed via filtration and washed with 4 mL of THF. The filtrate was cooled to 0 °C, and the preformed lithiate was added dropwise via syringe to the above soltuion. After being stirred at 0 °C for an additional 10 min, the reaction was quenched with H_2O and extracted with EtOAc. The organic layer was washed with saturated aqueous $NaHCO_3$, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to afford 0.47 g (77%) of **26** as a yellow oil: IR (neat) 2971, 2955, 1801, and 1728 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.50 (s, 9H), 2.08 (dd, 1H, J = 12.0 and 4.4 Hz), 2.28 (d, 1H, J = 12.0 Hz), 2.67 (d, 1H, J = 17.0 Hz), 2.89 (d, 1H, J = 17.0 Hz), 3.63 (s, 3H), 5.03 (dd, 1H, J = 4.4 and 2.0 Hz), 6.38 (dd, 1H, J = 6.0 and 2.0 Hz), and 6.41 (d, 1H, J = 6.0 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 28.1, 36.7, 42.4, 51.7, 52.9, 77.4, 84.2, 103.2, 132.7, 134.8, 149.0, 172.3, and 172.9; FAB HRMS calcd for $[(C_{15}H_{19}NO_6) + Li]^+$ 316.1372, found 316.1372.

***tert*-Butyl 2-(Cyclopent-1-enylacetyl)furan-2-yl)carbamate (22).** To a solution of 0.5 g (2.6 mmol) of furanyl carbamate **12a** in 8 mL of THF at 0 °C was added dropwise 1.9 mL (2.8 mmol) of *n*-BuLi (1.5 M in hexane). The reaction mixture was stirred at 0 °C for 20 min. In a separate flask, 0.36 g (2.8 mmol) of 2-cyclopent-1-enylacetic acid[50] was dissolved in 10 mL of THF at 0 °C, and 0.3 mL (2.8 mmol) of 4-methylmorpholine and 0.36 mL (2.8 mmol) of isobutyl chloroformate were added dropwise. After the mixture was stirred for 5 min, the white precipitate was removed via filtration and washed with 4 mL of THF. The filtrate was cooled to 0 °C, and the preformed lithiate was added dropwise via syringe to the above solution. After the mixture was stirred at 0 °C for an additional 5 min, the reaction was quenched with H_2O and extracted with EtOAc. The organic layer was washed with saturated aqueous $NaHCO_3$ solution, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to afford 0.43 g (58%) of **22** as a white solid: mp 55−56 °C; IR (neat) 1792, 1746, 1608, 1265, and 1147 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.42 (s, 9H), 1.85−1.92 (m, 4H), 2.33 (t, 2H, J = 7.4 Hz), 3.57 (s, 2H), 5.52 (s, 1H), 6.14 (dd, 1H, J = 3.2 and 0.8 Hz), 6.41 (dd, 1H, J = 3.2 and 2.4 Hz), and 7.32 (dd, 1H, J = 2.4 and 0.8 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 23.7, 27.9, 32.8, 35.4, 39.8, 84.0, 106.1, 111.4, 128.4, 137.1, 140.7, 144.1, 151.6, and 173.0. Anal. Calcd for $C_{16}H_{21}NO_4$: C, 65.96; H, 7.27; N, 4.81. Found: C, 65.83; H, 7.14; N, 4.88.

***tert*-Butyl 5,6-Cyclopentyl-3-oxo-10-oxa-2-azatricyclo[5.2.1.0^{1,5}]-dec-8-ene-2-carboxylate (27).** A solution of 0.2 g (0.7 mmol) of imidofuran **22** in 4 mL of toluene was heated at 90 °C for 4 h. The solution was cooled to room temperature, and the solvent was removed under reduced pressure. The residue was subjected to flash silica gel chromatography to afford 0.15 g (71%) of **27** as a white solid: mp 154−155 °C; IR (neat) 1792, 1357, 1255, and 1157 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.20−1.26 (m, 1H), 1.32−1.40 (m, 1H), 1.53 (s, 9H), 1.55−1.79 (m, 4H), 2.51 (d, 1H, J = 17.0 Hz), 2.76−2.81 (m, 1H), 2.96 (d, 1H, J = 17.0 Hz), 4.88 (dd, 1H, J = 5.2 and 2.0 Hz), 6.41 (dd, 1H, J = 6.0 and 2.0 Hz), and 6.59 (d, 1H, J = 6.0 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 27.2, 28.2, 29.2, 35.1, 46.9, 55.2, 56.7, 80.1, 84.1, 104.4, 133.9, 134.8, 149.6, and 174.8. Anal. Calcd for $C_{16}H_{21}NO_4$: C, 65.96; H, 7.27; N, 4.81. Found: C, 65.68; H, 7.20; N, 4.90.

***tert*-Butyl 2,3,3a,4,5,6-hexahydro-3a-methyl-2,5-dioxoindole-1-carboxylate (28).** A solution containing 0.05 g (0.19 mmol) of oxabicycle **24** in 2 mL of toluene in a sealed tube was heated at 140 °C for 4 h. Concentration under reduced pressure and purification by silica gel chromatography provided 0.046 g (92%) of **28** as a yellow oil: IR (neat) 1763, 1724, 1681, 1301, 1150 and 845 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.18 (s, 3H), 1.57 (s, 9H), 2.43 (d, 1H, J = 17.2 Hz), 2.56 (d, 1H, J = 14.6 Hz), 2.57 (d, 1H, J = 17.2 Hz), 2.63 (d, 1H, J = 14.6 Hz), 3.03 (d, 2H, J = 3.8 Hz), and 6.00 (t, 1H, J = 3.8 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 25.8, 28.2, 37.8, 37.9, 46.0, 51.4, 84.7, 102.6, 142.0, 149.5, 171.8, and 207.6; HRMS calcd for $C_{14}H_{19}NO_4$ 265.1314, found 265.1312.

***tert*-Butyl 2,5-Dioxo-3a-phenyl-2,3,3a,4,5,6-hexahydroindole-1-carboxylate (29).** A solution containing 0.02 g (0.06 mmol) of hexahydroindolinone **25** in 1 mL of toluene was heated at 135 °C for 14 h and then cooled to rt. Concentration of the solution under reduced pressure followed by purification using silica gel chromatography afforded 0.018 g (91%) of **29** as clear oil: IR (neat) 2986, 1766, 1725, 1298, 1149, and 707 cm^{-1}; ^1H NMR ($CDCl_3$, 600 MHz) δ 1.59 (s, 9H), 2.82 (dd, 1H, J = 23.4 and 2.4 Hz), 2.84 (d, 1H, J = 14.4 Hz), 2.94 (s, 2H), 3.01 (dd, 1H, J = 23.4 and 5.4 Hz), 3.17 (d, 1H, J = 14.4 Hz), 6.35 (dd, 1H, J = 5.4 and 2.4 Hz), 7.23−7.26 (m, 3H), and 7.32 (t, 2H, J = 7.8 Hz); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 28.2, 38.2, 46.1, 47.8, 53.0, 84.9, 106.0, 126.0, 128.2, 129.6, 140.1, 141.0, 149.4, 171.2, and 206.6; HRMS calcd for $C_{19}H_{21}NO_4$ 327.1471, found 327.1470.

1-*tert*-Butyl 3a-Methyl-2,5-dioxo-2,3,3*a*,4,5,6-tetrahydro-1*H*-indole-1,3a*(4H)*-dicarboxylate (30). A solution containing 0.04 g of oxabicycle **26** in 2 mL of toluene in a sealed tube was heated at 140 °C for 14 h. Concentration under reduced pressure and purification by silica gel chromatography provided 0.035 g (90%) of **30** as a yellow solid: mp 101−103 °C; IR (neat) 2980, 1774, 1736, 1302, 1153, and 842 cm^{-1}; ^1H NMR ($CDCl_3$, 600 MHz) δ 1.58 (s, 9H), 2.42 (d, 1H, J = 16.2 Hz), 2.54 (d, 1H, J = 17.4 Hz), 3.01 (d, 1H, J = 16.2 Hz), 3.02 (dd, 1H, J = 22.8 and 6.0 Hz), 3.11 (d, 1H, J = 17.4 Hz), 3.15 (dd, 1H, J = 22.8 and 2.4 Hz), 3.73 (s, 3H), and 6.27 (dd, 1H, J = 6.0 and 2.4 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 28.2, 37.2, 41.0, 46.7, 47.0, 53.7, 85.0, 106.4, 135.5, 149.2, 170.7, 171.3, and 204.7; HRMS calcd for $C_{15}H_{19}NO_6$ 309.1212, found 309.1214.

***tert*-Butyl 2,6-Dioxo-1,2,5,6,6a,7,8,9-octahydro-3-azacyclopenta[*d*]indene-3-carboxylate (31).** A solution containing 0.03 g (0.1 mmol) of oxabicycle **27** in 2 mL of toluene in a sealed tube was heated at 140 °C for 3 h. Concentration under reduced pressure and purification by silica gel chromatography provided 0.027 g (90%) of **31** as a yellow oil: IR (neat) 1767, 1728, 1683, 1295, and 1151 cm^{-1}; ^1H NMR ($CDCl_3$, 600 MHz) δ 1.47−1.57 (m, 1H), 1.58 (s, 9H), 1.65−1.73 (m,1H), 1.84−2.75 (m, 2H), 2.40−3.45 (m, 1H), 2.45 (d, 1H, J = 16.8 Hz), 2.49 (dd, 1H, J = 16.8 and 1.6 Hz), 2.54 (d, 1H, J = 7.2 Hz), 3.05 (dd, 1H, J = 21.6 and 4.8 Hz), 3.10 (dd, 1H, J = 21.6 and 3.6 Hz), and 5.99 (dd, 1H, J = 4.8 and 3.6 Hz); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 21.6, 24.8, 28.2, 37.5, 37.7, 45.0, 49.0, 56.7, 84.6, 102.6, 139.7, 149.5, 171.9, and 208.6; HRMS calcd for $C_{16}H_{21}NO_4$ 291.1471, found 291.1470.

***tert*-Butyl (3-Ethylfuran-2-yl)carbamate (32).** A modification of the procedure of Burness[51] was used to prepare methyl

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3-ethylfuran-2-carboxylate. To a mixture containing 23 g (156 mmol) of 1,1-dimethoxy-3-pentanone,[52] 22 mL (250 mmol) of methyl chloroacetate, and 125 mL of dry Et_2O at −10 °C was added 13.5 g (250 mmol) of freshly prepared powdered NaOMe in small portions over 30 min maintaining an internal temperature below −5 °C. The reaction mixture was stirred for an additional 2 h at −10 °C and then warmed to room temperature overnight. The slurry was cooled to 0 °C and quenched by the slow addition of a solution of 3 mL of AcOH in 50 mL of H_2O, and then the aqueous layer was extracted with Et_2O. The combined organic layers were washed with a dilute $NaHCO_3$ solution and brine, dried over anhydrous $MgSO_4$, and concentrated under reduced pressure. The crude residue was transferred to a flask equipped with a 5 in. Vigreux column and distillation head and was heated at 170 °C until MeOH distillation ceased. The mixture was cooled to room temperature and distilled under reduced pressure to afford 11.7 g (49%) of 3-ethyl-furan-2-carboxylic acid methyl ester as a colorless oil: bp 80−95 °C (15 mm); IR (neat) 1716, 1598, 1490, 1434, 1301, and 1198 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.18 (t, 3H, J = 7.6 Hz), 2.81 (q, 2H, J = 7.6 Hz), 3.87 (s, 3H), 6.40 (d, 1H, J = 1.6 Hz) ,and 7.43 (d, 1H, J = 1.6 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 14.3, 19.1, 51.7, 113.5, 137.8, 139.5, 145.2, and 160.1; HRMS calcd for $C_8H_{10}O_3$ 154.0630, found 154.0631.

A suspension of 4.0 g (26 mmol) of the above 3-ethylfuran-2-carboxylic acid methyl ester in 30 mL of a 10% aqueous NaOH solution was heated at reflux for 2 h. The homogeneous reaction mixture was cooled to 0 °C and was slowly acidified with concd HCl. The resultant white precipitate was collected by filtration, washed with several portions of cold H_2O, and dried under high vacuum to afford 3.4 g (94%) of 3-ethylfuran-2-carboxylic acid as a white solid: mp 106−107 °C; IR (neat) 3139, 1675, 1593, 1490, and 1285 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.22 (t, 3H, J = 7.6 Hz), 2.85 (q, 2H, J = 7.6 Hz), 6.46 (d, 1H, J = 1.6 Hz), 7.52 (d, 1H, J = 1.6 Hz), and 12.31 (brs, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 14.2, 19.4, 113.9, 138.9, 140.3, 146.5, and 165.0. Anal. Calcd for $C_7H_8O_3$: C, 59.99; H, 5.75. Found: C, 59.82; H, 5.74.

To a solution of 2.0 g (14.3 mmol) of the above acid in 60 mL of CH_2Cl_2 were added 1.5 mL (17 mmol) of oxalyl chloride and 1 drop of DMF. The reaction mixture was stirred at rt for 1 h and then concentrated under reduced pressure. The crude residue was dissolved in 40 mL of Et_2O, and a solution of 1.1 g (17 mmol) of NaN_3 in 20 mL of H_2O was added. The biphasic reaction mixture was stirred vigorously for 3 h, and then the organic layer was separated, dried over $MgSO_4$, and concentrated under reduced pressure. The crude residue was dissolved in 40 mL of *t*-BuOH and heated at reflux for 12 h. The reaction mixture was cooled to rt and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to afford 1.6 g (52%) of *tert*-butyl (3-ethyl-furan-2-yl)carbamate (**32**) as a pale yellow oil: IR (neat) 3313, 1716, 1644, 1511, 1244, and 1157 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.13 (t, 3H, J = 7.6 Hz), 1.46 (s, 9H), 2.34 (q, 2H, J = 7.6 Hz), 6.09 (brs, 1H), 6.25 (d, 1H, J = 2.0 Hz), and 7.13 (d, 1H, J = 2.0 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 14.2, 17.7, 28.3, 81.2, 111.8, 119.2, 138.9, 139.3, and 154.0; HRMS calcd for $C_{11}H_{17}NO_3$ 211.1208, found 211.1215.

***tert*-Butyl 9-Ethyl-3-oxo-10-oxa-2-azatricyclo[5.2.1.0^{1,5}]dec-8-ene-2-carboxylate (34).** To a solution of 0.27 g (1.2 mmol) of the above furan in 4 mL of THF at 0 °C was added dropwise 1.0 mL (1.4 mmol) of *n*-BuLi (1.4 M in hexane). The reaction mixture was stirred at 0 °C for 20 min so as to generate the lithiated carbamate **32**. In a separate flask, 0.12 mL (1.4 mmol) of vinylacetic acid was dissolved in 5 mL of THF at 0 °C, and 0.15 mL (1.4 mmol) of 4-methylmorpholine and 0.18 mL (1.4 mmol) of isobutyl chloroformate were added dropwise. After being stirred for 5 min, the white precipitate was removed by filtration and was washed with 2 mL of THF. The filtrate was cooled to 0 °C, and the preformed lithiate was added dropwise via syringe. After the mixture was stirred at 0 °C for an additional 5 min, the reaction was quenched with H_2O and extracted with EtOAc. The organic layer was washed with a saturated aqueous $NaHCO_3$ solution, dried over $MgSO_4$. and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to afford the expected imidofuran as a labile oil which underwent spontaneous cycloaddition while standing at room temperature for 12 h. The crude colorless oil was subjected to flash silica gel chromatography to afford 0.21 g (60%) of **34** as a colorless oil: IR (neat) 1798, 1762, 1731, 1296, and 1157 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.09 (t, 3H, J = 7.2 Hz), 1.53 (s, 9H), 1.68 (dd, 1H, J = 11.6 and 8.0 Hz), 1.79 (dt, 1H, J = 11.6 and 4.0 Hz), 1.92−2.06 (m, 2H), 2.29−2.37 (m, 1H), 2.40 (dd, 1H, J = 17.2 and 10.4 Hz), 2.74 (dd, 1H, J = 17.2 and 8.8 Hz), 4.99 (d, 1H, J = 4.0 Hz), and 5.89 (q, 1H, J = 2.0 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 11.4, 18.8, 28.0, 35.0, 35.4, 38.3, 77.5, 84.0, 103.3, 126.5, 149.6, 150.0, and 175.1. Anal. Calcd for $C_{15}H_{21}NO_4$: C, 64.48; H, 7.58; N, 5.02. Found: C, 64.36; H, 7.35; N, 5.37.

***tert*-Butyl 7-Methyl-3-oxo-10-oxa-2-azatricyclo[5.2.1.0^{1,5}]dec-8-ene-2-carboxylate (35).** To a solution of 0.3 g (1.5 mmol) of the known *tert*-butyl (5-methylfuran-2-yl)carbamate[53] in 5 mL of THF at 0 °C was added dropwise 1.2 mL (1.7 mmol) of *n*-BuLi (1.4 M in hexane). The reaction mixture was stirred at 0 °C for 20 min so as to generate the lithiated carbamate **33**. In a separate flask, 0.14 mL (1.7 mmol) of vinylacetic acid was dissolved in 5 mL of THF at 0 °C, and 0.18 mL (1.7 mmol) of 4-methylmorpholine and 0.22 mL (1.7 mmol) of isobutyl chloroformate were added dropwise. After the mixture was stirred for 5 min, the white precipitate that formed was removed by filtration and washed with 2 mL of THF. The filtrate was cooled to 0 °C, and the preformed lithiate was added dropwise via syringe. After the mixture was stirred at 0 °C for an additional 5 min, the reaction was quenched with H_2O and extracted with EtOAc. The organic layer was washed with a saturated aqueous $NaHCO_3$ solution, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to afford the expected imidofuran as a labile oil which underwent spontaneous cycloaddition while standing at room temperature for 12 h. The crude yellow solid was subjected to flash silica gel chromatography to give 0.3 g (68%) of **35** as a white solid: mp 86−87 °C; IR (neat) 1796, 1763, 1731, 1295, and 1160 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.46 (dd, 1H, J = 7.6 and 4.4 Hz), 1.49 (s, 9H), 1.60 (s, 3H), 1.71 (dd, 1H, J = 11.6 and 7.6 Hz), 2.12−2.19 (m, 1H), 2.40 (dd, 1H, J = 17.0 and 10.2 Hz), 2.70 (dd, 1H, J = 17.0 and 8.6 Hz), 6.10 (d, 1H, J = 5.8 Hz), and 6.49 (d, 1H, J = 5.8 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 19.5, 28.1, 38.5, 38.9, 39.0, 83.8, 85.2, 101.2, 135.2, 136.6, 149.4, and 174.6. Anal. Calcd for $C_{14}H_{19}NO_4$: C, 63.38; H, 7.22; N, 5.28. Found: C, 63.45; H, 7.32; N, 5.33.

***tert*-Butyl 4-Methyl-3-oxo-10-oxa-2-azatricyclo[5.2.1.0^{1,5}]dec-8-ene-2-carboxylate (38).** To a solution of 0.7 g (4.1 mmol) of *tert*-butyl furan-2-ylcarbamate (**12a**) in 12 mL of THF at 0 °C was added dropwise 2.1 mL (4.3 mmol) of *n*-BuLi (2.1 M in hexane). The reaction mixture was stirred at 0 °C for 20 min. In a separate flask, 0.47 mL (4.5 mmol) of 2-methylbut-3-enoic acid was dissolved in 15 mL of THF at 0 °C, and 0.5 mL (4.5 mmol) of 4-methylmorpholine and 0.58 mL (4.5 mmol) of isobutyl chloroformate were added dropwise. After the mixture was stirred for 5 min, the white precipitate that formed was removed by filtration and washed with 2 mL of THF. The filtrate was cooled to 0 °C, and the preformed lithiate was added dropwise via syringe to the above solution. After being stirred at 0 °C for an additional 10 min, the reaction mixture was quenched with H_2O and extracted with EtOAc. The organic layer was washed with a saturated aqueous

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$NaHCO_3$ solution, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to afford 0.69 g (65%) of furan **36** as a colorless oil which underwent spontaneous cycloaddition while standing at room temperature for 12 h. The ^1H NMR spectra revealed the presence of a 20:1 mixture of two diastereomers. The crude residue was subjected to flash silica gel chromatography to provide 0.66 g (96%) of the major *cis* diastereomer **38** as a white solid: mp 102−104 °C; IR (neat) 2979, 1794, 1766, 1731, and 1159 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.24 (d, 3H, J = 6.8 Hz), 1.52 (s, 9H), 1.64 (dd, 1H, J = 11.2 and 7.2 Hz), 1.73 (ddd, 1H, J = 10.0, 7.2 and 3.2 Hz), 1.81 (ddd, 1H, J = 11.2, 4.4 and 3.2 Hz), 2.43 (dq, 1H, J = 10.0 and 6.8 Hz), 5.03 (dd, 1H, J = 4.4 and 2.0 Hz), 6.31 (dd, 1H, J = 6.0 and 2.0 Hz), and 6.50 (d, 1H, J = 6.0 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 14.3, 28.2, 31.7, 44.0, 44.5, 77.7, 83.9, 100.0, 133.8, 134.6, 149.6, and 177.0. Anal. Calcd for $C_{14}H_{19}NO_4$: C, 63.38; H, 7.22; N, 5.28. Found: C, 63.44; H, 7.32; N, 5.30.

***tert*-Butyl 3-Oxo-4-phenyl-10-oxa-2-azatricyclo[5.2.1.0^{1,5}]dec-8-ene-2-carboxylate (39).** To a solution of 0.35 g (1.9 mmol) of carbamate **12a** in 10 mL of THF at 0 °C was added dropwise 1.1 mL (2.2 mmol) of *n*-BuLi (2.1 M in hexane). The reaction mixture was stirred at 0 °C for 20 min. In a separate flask, 0.37 g (2.3 mmol) of 2-phenylbut-3-enoic acid[54] was dissolved in 15 mL of THF at 0 °C, and 0.25 mL (2.3 mmol) of 4-methyl-morpholine and 0.3 mL (2.3 mmol) of isobutyl chloroformate were added dropwise. After the mixture was stirred for 5 min, the white precipitate that formed was removed by filtration and washed with 2 mL of THF. The filtrate was cooled to 0 °C, and the preformed lithiate was added dropwise via syringe to the above solution. After being at 0 °C for an additional 10 min, the reaction mixture was quenched with H_2O and extracted with EtOAc. The organic layer was washed with a saturated aqueous $NaHCO_3$ solution, dried over $MgSO_4$, and concentrated under reduced pressure. The residue was subjected to flash silica gel chromatography to afford 0.34 g (55%) of furan **37** as a colorless oil, which underwent spontaneous cycloaddition while standing at room temperature for 12 h. The ^1H NMR spectrum of the solid showed a 30:1 mixture of two diastereomers. The crude residue was subjected to flash silica gel chromatography to provide 0.34 g (98%) of the major *cis* isomer **39** as a white solid: mp 124−125 °C; IR (neat) 1793, 1732, 1296, and 1157 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.54 (s, 9H), 1.63 (dd, 1H, J = 12.0 and 8.0 Hz), 1.94 (dt, 1H, J = 12.0 and 3.6 Hz), 2.27 (ddd, 1H, J = 10.8, 8.0 and 3.6 Hz), 3.63 (d, 1H, J = 10.8 Hz), 5.09 (dd, 1H, J = 3.6 and 2.0 Hz), 6.36 (dd, 1H, J = 6.0 and 2.0 Hz), 6.59 (d, 1H, J = 6.0 Hz), and 7.22−7.36 (m, 5H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 28.1, 31.9, 44.9, 55.6, 77.8, 84.2, 99.7, 127.7, 128.6, 128.9, 134.1, 134.4, 136.5, 149.5, and 174.4. Anal. Calcd for $C_{19}H_{21}NO_4$: C, 69.71; H, 6.47; N, 4.28. Found: C, 69.76; H, 6.42; N, 4.22.

***tert*-Butyl 2,3,3a,4,5,6-Hexahydro-5-hydroxy-2-oxo-6-phenoxyindole-1-carboxylate (40).** To a solution containing 0.05 g (0.2 mmol) of oxabicycle **23** in 0.5 mL of THF was added 3 mg (0.006 mmol) of $[Rh(COD)Cl]_2$, 6 mg (0.012 mmol) of 1,1′-bis(diphenylphosphino)ferrocene (DPPF), and 0.19 g (2.0 mmol) of phenol. The mixture was heated at 80 °C for 12 h, cooled to rt, and diluted with ether. The organic layer was washed with a 4% aqueous NaOH solution and dried over $MgSO_4$. The solvent was removed under reduced pressure, and a ^1H NMR spectrum of the crude mixture showed the presence of a 5:1 mixture of isomeric products. Purification by flash silica gel chromatography afforded 0.02 g (62%) of the major isomer **40** as a clear oil: IR (neat) 3448, 1771, 1732, 1300, and 1152 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.50 (s, 9H), 1.82 (d, 1H, J = 11.6 Hz), 2.18 (dt, 1H, J = 11.6 and 4.4 Hz), 2.43 (dd, 1H, J = 16.8 and 11.6 Hz), 2.57 (d, 1H, J = 11.6 Hz), 2.66 (dd, 1H, J = 16.8 and 8.4 Hz), 2.76−2.88 (m,1H), 3.96 (tt, 1 H, J = 11.6 and 4.4 Hz), 4.94 (t, 1H, J = 4.4 Hz), 6.21 (dd, 1H, J = 4.4 and 2.4 Hz), 6.97−7.00 (m, 3H), and 7.29 (t, 2H, J = 8.0 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 28.1, 32.5, 34.9, 37.7, 68.7, 72.6, 84.7, 104.4, 116.2, 122.0, 130.0, 143.6, 149.2, 157.8, and 172.3; HRMS calcd for $C_{19}H_{23}NO_5$ 345.1576, found 345.1574.

***tert*-Butyl 5-Hydroxy-3a-methyl-2-oxo-6-phenoxy-2,3,3a,4,5,6-hexahydroindole-1-carboxylate (41).** To a solution containing 0.06 g (0.22 mmol) of oxabicycle **24** in 0.5 mL of THF were added 3 mg (0.007 mmol) of $[Rh(COD)Cl]_2$, 7 mg (0.014 mmol) of DPPF, and 0.22 g (2.3 mmol) of phenol. The mixture was heated at 80 °C for 2 h, cooled to rt, and diluted with ether. The organic layer was washed with a 4% aqueous NaOH solution and dried over $MgSO_4$. The solvent was removed under reduced pressure, and a NMR spectrum of the crude reaction mixture showed the presence of a 5:1 mixture of isomeric products. Purification by flash silica gel chromatography afforded 0.06 g (75%) of the major isomer **41** as a white solid: mp 126−128 °C; IR (neat) 3508, 1774, 1732, 1302, and 1153 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.29 (s, 3H), 1.52 (s, 9H), 1.95 (t, 1H, J = 12.1 Hz), 2.02 (dd, 1H, J = 12.1 and 4.1 Hz), 2.36 (d, 1H, J = 16.2 Hz), 2.47 (d, 1H, J = 16.2 Hz), 2.57 (d, 1H, J = 10.5 Hz), 4.14−4.23 (m, 1H), 4.94 (t, 1H, J = 4.7 Hz), 6.15 (d, 1H, J = 4.7 Hz), 6.97−7.01 (m, 3H), and 7.28−7.32 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 25.9, 28.1, 38.8, 38.9, 47.4, 66.1, 72.3, 84.5, 104.6, 116.2, 122.0, 129.9, 147.2, 149.5, 157.8, and 171.8; HRMS calcd for $C_{20}H_{25}NO_5$ 359.1733, found 359.1733.

The minor isomer (0.01 g (15%)) was obtained as a clear oil: IR (neat) 1786, 1733, 1301, and 1148 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.37 (s, 3H), 1.44(s, 9H), 1.86 (t, 1H, J = 16.8 Hz), 2.15 (dd, 1H, J = 16.8 and 5.2 Hz), 2.35−2.46 (m, 3H), 4.28−4.38 (m, 1H), 4.91 (dd, 1H, J = 9.6 and 4.0 Hz), 5.98 (d, 1H, J = 4.0 Hz), 6.96−7.00 (m, 3H), and 7.26−7.32 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 26.5, 28.1, 28.2, 38.3, 40.8, 47.6, 68.8, 81.0, 84.5, 105.1, 116.6, 121.8, 129.9, 145.1, 157.8, and 173.4; HRMS calcd for $C_{20}H_{25}NO_5$ 359.1733, found 359.1730.

***tert*-Butyl 6-(*N*-Methyl-*N*-phenylamino)-5-hydroxy-2-oxo-2,3,-3a,4,5,6-hexahydroindole-1-carboxylate (42).** To a solution containing of 0.06 g (0.24 mmol) of oxabicycle **23** in 1 mL of THF were added 3 mg (0.007 mmol) of $[Rh(COD)Cl]_2$, 8 mg (0.014 mmol) of DPPF, 0.13 mL (1.2 mmol) of *N*-methylaniline, and 0.44 g (1.2 mmol) of tetrabutylammonium iodide. The mixture was heated at reflux for 12 h, cooled to rt, diluted with water, and extracted with $CHCl_3$. The organic layer was dried over $MgSO_4$ and concentrated under reduced pressure. A ^1H NMR spectrum of the crude reaction mixture indicated a 20:1 mixture of two isomeric products. Purification by silica gel chromatography afforded 0.03 g (33%) of the major isomer **42** as a clear oil: IR (neat) 3451, 1786, 1732, 1306, and 1150 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.51 (s, 9H), 1.67 (q, 1H, J = 12.0 Hz), 2.29 (dd, 1H, J = 16.8 and 12.0 Hz), 2.36 (dt, 1H, J = 10.0 and 4.0 Hz), 2.51 (brs, 1H), 2.64 (dd, 1H, J = 16.8 and 8.8 Hz), 2.78 (s, 3H), 2.88−2.97 (m, 1H), 4.01 (ddd, 1H, J = 12.0, 8.8 and 4.0 Hz), 4.49 (dt, 1H, J = 8.8 and 2.8 Hz), 5.64 (t, 1H, J = 2.8 Hz), 6.80 (t, 1H, J = 7.6 Hz), 6.95 (d, 2H, J = 7.6 Hz), and 7.25 (t, 2H, J = 7.6 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 28.2, 32.8, 34.1, 38.3, 66.1, 68.4, 84.73, 107.5, 115.2, 118.8, 129.5, 140.1, 148.9, 151.1, and 172.8; HRMS calcd for $C_{20}H_{26}N_2O_4$ 358.1892, found 358.1892.

***tert*-Butyl 6-(*N*-Methyl-*N*-phenylamino)-5-hydroxy-3a-methyl-2-oxo 2,3,3a,4,5,6-hexahydroindole-1-carboxylate (43).** To a solution containing 0.05 g (0.19 mmol) of oxabicycle **24** in 1 mL of THF were added 3 mg (0.006 mmol) of $[Rh(COD)Cl_2]_2$, 6 mg (0.012 mmol) of DPPF, 0.13 g (0.94 mmol) of *N*-methylaniline, and 0.13 g (0.94 mmol) of Et_3NHCl. The mixture was heated at 80 °C for 10 h, cooled to rt, diluted with water, and extracted with $CHCl_3$. The organic layer was dried over $MgSO_4$ and concentrated under reduced pressure. A ^1H NMR spectrum of the crude mixture showed the presence of two isomeric products in a ratio of 10:1. Purification by silica gel chromatography afforded 0.04 g (58%) of the major isomer **43** as a clear oil: IR (neat) 3462, 1786, 1733, 1301, and 1149 cm^{-1}; ^1H NMR ($CDCl_3$, 400 MHz) δ 1.34 (s, 3H), 1.51 (s, 9H), 1.82 (t, 1H, J = 12.4 Hz), 2.17 (dd, 1H, J = 12.4 and 4.0 Hz), 2.36 (d, 1H, J = 16.4 Hz), 2.36 (brs, 1H), 2.43 (d, 1H, J

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= 16.4 Hz), 2.80 (s, 3H), 4.19 (ddd, 1H, J = 12.0, 8.8 and 4.0 Hz), 4.47 (dd,1H, J = 8.8 and 2.8 Hz), 5.60 (d, 1H, J = 2.8 Hz), 6.80 (t, 1H, J = 7.6 Hz), 6.95 (d, 2H, J = 7.6 Hz), and 7.25 (t, 2H, J = 7.6 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 26.5, 28.2, 32.9, 38.2, 41.1, 47.9, 66.0, 66.4, 84.2, 107.9, 115.1, 118.7, 129.5, 143.7, 149.2, 151.0, and 172.4; HRMS calcd for $C_{21}H_{28}N_2O_4$ 372.2049, found 372.2048.

***tert*-Butyl 6-(2-Bromobenzoyloxy)-5-hydroxy-3a-methyl-2-oxo-2,3,3a,4,5,6-hexahydroindole-1-carboxylate (44a).** To a solution containing 0.05 g (0.19 mmol) of oxabicycle **24** in 1 mL of THF was added 3 mg (0.006 mmol) of $[Rh(COD)Cl]_2$, 6 mg (0.012 mmol) of DPPF, 0.38 g (1.9 mmol) of 2-bromobenzoic acid, and 0.26 mL (1.9 mmol) of Et_3N. The mixture was heated at 80 °C for 10 h, cooled to room temperature, diluted with water, and extracted with ether. The organic layer was dried over $MgSO_4$ and concentrated under reduced pressure. A NMR spectrum of the crude mixture showed the presence of two isomeric products in a ratio of 10:3. Purification by silica gel chromatography afforded 0.06 g (72%) of the major *cis*-isomer **44a** as a clear oil: IR (neat) 3487, 1786, 1732, and 1148 cm^{-1}; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 1.33 (s, 3H), 1.54 (s, 9H), 1.85 (t, 1H, J = 12.0 Hz), 2.19 (dd, 1H, J = 12.0 and 4.8 Hz), 2.37 (d, 1H, J = 16.2 Hz), 2.45 (d, 1H, J = 16.2 Hz), 3.26 (brs, 1H), 4.32 (ddd, 1H, J = 12.0, 7.2 and 4.8 Hz), 5.58 (dd, 1H, J = 7.2 and 3.6 Hz), 5.96 (d, 1H, J = 3.6 Hz), 7.34 (td, 1H, J = 7.8 and 1.8 Hz), 7.37 (td, 1H, J = 7.8 and 1.8 Hz), 7.66 (dd, 1H, J = 7.8 and 1.8 Hz) and 7.80 (dd, 1H, J = 7.8 and 1.8 Hz); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 26.1, 28.2, 37.6, 41.6, 47.2, 68.8, 80.6, 84.7, 104.4, 121.9, 127.5, 131.7, 132.2, 133.1, 134.6, 146.8, 149.2, 167.9, and 172.0; HRMS calcd for $C_{21}H_{24}NO_6Br$ 465.0787, found 465.0784.

***tert*-Butyl 5-Hydroxy-2-oxo-2,4,5,6-tetrahydroindole-1-carboxylate (45).** To the mixture of 0.18 g (0.72 mmol) of oxabicycle **23**, 7 mg (0.014 mmol) of $[Rh(COD)Cl]_2$, and 4.9 μL (0.029 mmol) $P(OEt)_3$ in 2 mL of THF was added 0.28 g (3.6 mmol) of ammonium acetate. The reaction mixture was heated at reflux for 12 h and cooled to rt. The mixture was poured into a saturated $NaHCO_3$ aqueous solution and was extracted with EtOAc. The combined organic layer was washed with brine and dried over $MgSO_4$. The solvent was removed under reduced pressure, and the residue was subjected to flash column chromatography to give 0.14 g (80%) of **45** as a white solid: mp 167−168 °C; IR (neat) 3452, 1733, 1326, and 818 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.56 (s, 9H), 2.34 (brs, 1H), 2.44 (ddd, 1H, J = 17.6, 8.4 and 4.0 Hz), 265−2.71 (m, 2H), 2.92 (dd, 1H, J = 16.8 and 4.0 Hz), 4.15 (m, 1H), 5.77 (s, 1H), and 6.54 (ddd, 1H, J = 5.6, 4.0 and 1.6 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 28.3, 33.7, 33.8, 66.2, 83.9, 115.2, 117.1, 136.0, 149.4, 149.7, and 168.2. Anal. Calcd for $C_{13}H_{17}NO_4$: C, 62.14; H, 6.82; N, 5.57. Found: C, 61.73; H, 6.79; N, 5.41.

***tert*-Butyl 2-Oxo-2,3-dihydroindole-1-carboxylate (46).** To a solution of 0.18 g (0.72 mmol) of oxabicycle **23** in 2 mL of THF was added 7 mg (0.014 mmol) of $[Rh(COD)Cl]_2$ and 4.9 μL (0.029 mmol) of $P(OEt)_3$. The reaction mixture was heated at reflux for 2 h and cooled to room temperature. The solvent was removed under reduced pressure. The residue was subjected to flash silica gel chromatography to give 0.16 g (90%) of **46** as a colorless oil: ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.59 (s, 9H), 3.61 (s, 2H), 7.12 (t, 1H, J = 7.6 Hz), 7.23 (d, 1H, J = 7.6 Hz), 7.28 (t, 1H, J = 7.6 Hz), and 7.77 (d, 1H, J = 7.6 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 28.3, 33.7, 84.6, 115.3, 123.4, 124.4, 128.3, 141.2, 149.4, and 173.3; HRMS calcd for $C_{13}H_{15}NO_3$ 233.1052, found 233.1050.

***tert*-Butyl 5-Hydroxy-2-oxo-6-phenyl-2,3,3a,4,5,6-hexahydroindole-1-carboxylate (51).** To a solution containing 0.06 g (0.24 mmol) of oxabicycle **23**, 3 mg (0.007 mmol) of $[Rh(COD)Cl]_2$, and 2.5 μL (0.014 mmol) of $P(OEt)_3$ in 1 mL THF was added 0.09 g (0.48 mmol) of 5,5-dimethyl-2-phenyl-1,3,2-dioxaborinane (**50**) and 0.1 mL (0.48 mmol) of Cs_2CO_3 (5 M in H_2O). The reaction mixture was heated at 65 °C for 2 h, cooled to rt, and quenched with water. The aqueous layer was extracted with EtOAc, and the combined organic layer was dried over $MgSO_4$. The solvent was removed under reduced pressure, and the residue was subjected to the flash silica gel chromatography to afford 0.06 g (72%) of **51** as a white solid: mp 175−176 °C; IR (neat) 3437, 1777, 1724, 1292, and 705 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.05 (d, 1H, J = 10.2 Hz), 1.51−1.55 (m, 1H), 1.55 (s, 9H), 1.99 (ddd, 1H, J = 12.0, 5.2 and 3.2 Hz), 2.37 (d, 1H, J = 17.2 Hz), 2.71 (dd, 1H, J = 17.2 and 8.8 Hz), 2.92−2.95 (m, 1H), 3.91−3.95 (m,1H), 4.12−4.20 (m, 1H), 5.91 (dd, 1H, J = 4.4 and 2.4 Hz), 7.25−7.28 (m, 2H), and 7.30−7.40 (m, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 28.2, 32.6, 38.6, 46.0, 68.7, 84.3, 109.1, 127.9, 128.7, 130.7, 138.2, 138.8, 149.4, and 172.8. Anal. Calcd for $C_{19}H_{23}NO_4$: C, 69.28; H, 7.04; N, 4.25. Found: C, 69.19; H, 7.07; N, 4.21.

***tert*-Butyl 5-Hydroxy-3a-methyl-2-oxo-6-phenyl-2,3,3a,4,5,6-hexahydroindole-1-carboxylate (52).** To a solution containing 0.05 g (0.19 mmol) of oxabicycle **24**, 3.0 mg (0.006 mmol) of $[Rh(COD)Cl]_2$, and 2.0 μL (0.012 mmol) of $P(OEt)_3$ in 1 mL of THF were added 0.07 g (0.4 mmol) of 5,5-dimethyl-2-phenyl-1,3,2-dioxaborinane (**50**) and 0.08 mL (0.38 mmol) of Cs_2CO_3 (5 M in H_2O). The reaction mixture was heated at 65 °C for 2 h, cooled to rt, and quenched with water. The aqueous layer was extracted with EtOAc, and the combined organic layer was dried over $MgSO_4$. The solvent was removed under reduced pressure, and the residue was subjected to flash silica gel chromatography to afford 0.05 g (80%) of **52** as a white solid: mp 170−173 °C; IR (neat) 3491, 1785, 1729, 1302, and 714 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.34 (s, 3H), 1.54 (s, 9H), 1.61 (t, 1H, J = 12.4 Hz), 1.82 (dd, 1H, J = 12.4 and 3.6 Hz), 2.42 (d, 1H, J = 16.0 Hz), 2.49 (d, 1H, J = 16.0 Hz), 3.93 (dd, 1H, J = 6.4 and 4.4 Hz), 4.27−4.37 (m,1H), 5.85 (d, 1H, J = 4.4 Hz), 7.22 (d, 2H, J = 7.2 Hz), 7.31 (t, 1H, J = 7.2 Hz), and 7.36 (t, 2 H, J = 7.2 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 26.4, 28.2, 38.9, 39.0, 46.1, 48.2, 66.2, 84.2, 109.5, 127.9, 128.7, 130.6, 137.9, 142.4, 149.7, and 172.4. Anal. Calcd for $C_{20}H_{25}NO_4$: C, 69.95; H, 7.34; N, 4.08. Found: C, 69.67; H, 7.26; N, 4.01.

***tert*-Butyl 2,3,3a,4,5,6-Hexahydro-2-oxo-5,6-phenylboronate-indole-1-carboxylate (53).** To a solution containing 0.1 g (0.4 mmol) of oxabicycle **23**, 6 mg (0.01 mmol) of $[Rh(COD)Cl]_2$, and 4.0 μL (0.02 mmol) of $P(OEt)_3$ in 2 mL of THF was added 0.07 g (0.6 mmol) of phenylboronic acid. The reaction mixture was heated at 65 °C for 2 h, cooled to rt, and quenched with water. The aqueous layer was extracted with EtOAc, and the combined organic layer was washed with a saturated aqueous $NaHCO_3$ solution and dried over $MgSO_4$. The solvent was removed under reduced pressure, and the residue was subjected to the flash silica gel chromatography to afford 0.14 g (98%) of **53** as a white solid: mp 139−141 °C; IR (neat) 1798, 1736, 1340, 1150, and 702 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.42 (q, 1H, J = 12.0 Hz), 1.58, (s, 9H), 2.28 (dd, 1H, J = 20.0 and 13.6 Hz), 2.45 (ddd, 1H, J = 12.0, 5.6 and 4.0 Hz), 2.61−2.68 (m, 1H), 2.68 (dd, 1H, J = 20.0 and 9.2 Hz), 4.67 (ddd, 1H, J = 12.0, 7.6 and 5.6 Hz), 5.07 (ddd, 1H, J = 7.6, 3.2 and 2.0 Hz), 6.24 (dd, 1H, J = 4.0 and 2.0 Hz), 7.37 (t, 2H, J = 7.2 Hz), 7.47 (tt, 1H, J = 7.2 and 1.6 Hz), and 7.80 (dd, 2H, J = 7.2 and 1.6 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 28.1, 31.1, 33.8, 36.9, 73.7, 74.6, 84.8, 104.9, 128.0, 131.8, 135.0, 142.5, 148.9, and 172.6; HRMS calcd for $C_{19}H_{22}BNO_5$ 355.1591, found 355.1593.

***tert*-Butyl 2,3,3a,4,5,6-Hexahydro-3a-methyl-2-oxo-5,6-phenylboronateindole-1-carboxylate (54).** To a solution containing 0.05 g (0.19 mmol) of oxabicycle **24**, 2 mg (0.003 mmol) of $[Rh(COD)Cl]_2$, and 1.0 μL (0.02 mmol) of $P(OEt)_3$ in 1 mL of THF was added 0.035 g (0.28 mmol) of phenylboronic acid. The reaction mixture was heated at 65 °C for 2 h, cooled to rt, and quenched with water. The aqueous layer was extracted with EtOAc, and the combined organic layer was washed with a saturated aqueous $NaHCO_3$ solution and dried over $MgSO_4$. The solvent was removed under reduced pressure, and the residue was subjected to the flash silica gel chromatography to afford 0.06 g (95%) of **54** as a white solid: mp 136−137 °C; IR (neat) 1771, 1735, 1369, 1153, and 692 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.23 (s, 3H), 1.56 (t,

1H, J = 12.0 Hz), 1.59, (s, 9H), 2.37 (d, 1H, J = 16.4 Hz), 2.39 (dd, 1H, J = 12.0 and 6.0 Hz), 2.45 (d, 1H, J = 16.4 Hz), 4.89 (ddd, 1H, J = 12.0, 7.6 and 6.0 Hz), 5.13 (dd, 1H, J = 7.6 and 3.2 Hz), 6.21 (d, 1H, J = 3.2 Hz), 7.38 (t, 2H, J = 7.6 Hz), 7.48 (tt, 1H, J = 7.6 and 1.6 Hz), and 7.80 (dd, 2H, J = 7.6 and 1.6 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 25.3, 28.2, 36.6, 40.0, 46.3, 73.3, 73.6, 84.8, 104.8, 128.0, 131.9, 135.0, 146.1, 149.3, and 172.0. Anal. Calcd for $C_{20}H_{24}BNO_5$: C, 65.06; H, 6.55; N, 3.79. Found: C, 64.80; H, 6.57; N, 3.73.

***tert*-Butyl 2,3,3a,4,5,6-Hexahydro-5,6-acetonide-2-oxoindole-1-carboxylate (55).** To a solution containing 0.1 g (0.39 mmol) of oxabicycle **23** in acetone was added 5 mg (0.03 mmol) of anhydrous stannous chloride. After the mixture was stirred at rt for 15 min, the solvent was removed under reduced pressure and the residue was subjected to the flash silica gel chromatography to afford 0.11 g (91%) of **55** as a white solid: mp 103−105 °C; IR (neat) 1794, 1731, 1370, and 727 cm^{-1}; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.39 (s, 3H), 1.45 (q, 1H, J = 11.6 Hz), 1.48 (s, 3H), 1.55 (s, 9H), 2.17 (ddd, 1H, J = 11.6, 5.6 and 4.0 Hz), 2.25−2.33 (m, 1H), 2.62−2.69 (m, 2H), 4.22 (dt, 1H, J = 11.6 and 5.6 Hz), 4.68−4.71 (m, 1H), and 6.09 (dd, 1H, J = 4.0 and 2.0 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 25.9, 28.1, 28.5, 32.1, 32.8, 37.1, 71.5, 73.1, 84.6, 103.4, 109.2, 143.1, 148.9, and 172.9. Anal. Calcd for $C_{16}H_{23}NO_5$: C, 62.12; H, 7.49; N, 4.53. Found: C, 61.96; H, 7.46; N, 4.53.

***tert*-Butyl 2,3,3a,4,5,6-Hexahydro-3a-methyl-5,6-acetonide-2-oxoindole-1-carboxylate (56).** To a solution containing 0.1 g (0.38 mmol) of oxabicycle **24** in 2 mL of acetone was added 5 mg (0.03 mmol) of anhydrous stannous chloride. After the mixture was stirred at rt for 15 min, the solvent was removed under reduced pressure and the residue was subjected to flash silica gel chromatography to afford 0.11 g (92%) of **56** as a white solid: mp 118−120 °C; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.18 (s, 3H), 1.40 (s, 3H), 1.48 (s, 3H), 1.56 (s, 9H), 1.51−1.58 (m,1H), 2.11 (dd, 1H, J = 12.4 and 6.0 Hz), 2.32 (d, 1H, J = 16.4 Hz), 2.42 (d, 1H, J = 16.4 Hz), 4.44 (dt, 1H, J = 12.0 and 6.0 Hz), 4.73 (dd, 1H, J = 6.0 and 4.0 Hz), and 6.05 (d, 1H, J = 4.0 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 25.4, 25.6, 28.2, 28.3, 34.5, 38.8, 46.7, 71.1, 71.6, 84.6, 103.4, 109.1, 146.6, 149.3, and 172.4; HRMS calcd for $C_{17}H_{25}NO_5$ 323.1733, found 323.1735.

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Supporting Information Available: ^{1}H and ^{13}C NMR data of various key compounds lacking CHN analyses together with an ORTEP drawing for compounds **41**, **51**, and **53** as well as the corresponding CIFs for these compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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