Iridium(I)-catalyzed vinylic C–H borylation of 1-cycloalkenecarboxylates with bis(pinacolato)diboron†

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Received (in XXX, XXX) Xth XXXXXXXXX XX0XX, Accepted Xth XXXXXXXXX XX0XX
DOI: 10.1039/b000000x

Ir(I)-catalyzed C–H borylation of 1-cycloalkenecarboxylic derivatives with bis(pinacolato)diboron affords various alkénylboronates with functional groups, in excellent yields. This reaction was also used in a one-pot borylation/Suzuki–Miyaura cross-coupling procedure.

1-Alkenylboronates are an important class of compounds and are versatile intermediates in synthetic organic chemistry. Their utility has been amply demonstrated in the synthesis of natural products and biologically active compounds via C–C bond formations with C–B bonds. Conventional methods for the preparation of alkenylboronates include the reaction of B(OR)3 with alkanyl-lithium or -magnesium reagents, and the Pd-catalyzed cross-coupling reaction of alkyl halides or triflates with bis(pinacolato)diboron (B2pin2) (2) or pinacolborane (HBpin). An alternative process involving the transition-metal-catalyzed C–H borylation of alkényl compounds was recently reported.8a–c Although this method is more economical and environmentally benign than the above conventional methods, the use of such reactions is still limited for cyclic vinyl ethers9 and suffers from the formation of a number of different side products such as allylboronates and alkylboronates.8c,d,e,f,g

Very recently, we reported the regioselective direct ortho borylation of various benzoates or aryl ketones using the complex [Ir(OMe)(COD)]/*P3,5-(CF3)2C6H3] or AsPh3.7 At the same time, several groups, including Sawamura’s,8a Lassaletta’s,8b and Hartwig’s,9 also reported similar borylations of functionalized arenes. The regioselectivity of these reactions is probably driven by interaction between the coordinating O and N atoms in the directing group and the Ir metal center.7a So far, these methods have only been used in the C–H borylation of arenes; to the best of our knowledge, C–H borylation at the vinyl position of α,β-unsaturated esters has not previously been reported. In this communication, we describe a vinylic C–H borylation of 1-cycloalkenecarboxylate 1 with 2, catalyzed using an in-situ-generated Ir complex consisting of readily available [Ir(OMe)(COD)]2 and AsPh3 in octane solvent. The reaction proceeded chemoselectively at 80 °C or 120 °C to give the corresponding alkénylboronic compounds 3 in high yields (Scheme 1). This reaction was used in a one-pot borylation/Suzuki–Miyaura cross-coupling procedure to afford the 2-aryl-substituted 1-cycloalkenecarboxylate in good yield; this carboxylate showed biological activity.

Scheme 1. Vinlylic C–H borylation of 1-cycloalkenecarboxylates.
The reactions of cycloalkenyl substrates with five-membered ring cyclohexene 

\[ \text{Ir(OMe)(cod)} \] 

have a seriously detrimental effect on the reactivity of the substrate. These results showed that the side chain would inhibit directed borylation, the vinyl group in the side chain was completely consumed in the reaction, the product \( 3n \) was obtained in low yield (20%). The reactions of the seven-membered ring \( 1n \) and eight-membered ring \( 1o \) also gave the alkenylboronates \( 3n \) and \( 3o \) in low yields, though the substrates were completely consumed. We speculate that \( 1m-1o \) decomposed under the reaction conditions.

### Table 1. Reaction conditions for methyl 1-cyclohexene carboxylate 1a

<table>
<thead>
<tr>
<th>Entry</th>
<th>( \text{Ir}^+ ) precursor</th>
<th>Ligand</th>
<th>Solvent</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>dipy</td>
<td>Octane</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>P(C_6H_5)_3</td>
<td>Octane</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>P(OCCF_3)_3</td>
<td>Octane</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>( \text{P(4-MOCOC}_3)</td>
<td>Octane</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>( \text{P(4-OCF}_3)</td>
<td>Octane</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>( \text{P(3,5-(CF}_3)_2)</td>
<td>Octane</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>( \text{P(CF}_3)</td>
<td>Octane</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>AsPh_3</td>
<td>Octane</td>
<td>10 (84)</td>
</tr>
<tr>
<td>9</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>AsPh_3</td>
<td>Mesitylene</td>
<td>51</td>
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<tr>
<td>10</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>AsPh_3</td>
<td>DMF</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>AsPh_3</td>
<td>Octane</td>
<td>84</td>
</tr>
<tr>
<td>12</td>
<td>[\text{Ir(Cl)(cod)}]</td>
<td>AsPh_3</td>
<td>Octane</td>
<td>84</td>
</tr>
<tr>
<td>13a</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>( \text{BF}_3)</td>
<td>AsPh_3</td>
<td>0</td>
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<tr>
<td>14</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>AsPh_3</td>
<td>Octane</td>
<td>99 (87)</td>
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<tr>
<td>15</td>
<td>[\text{Ir(O(CF}_3)(cod)}]</td>
<td>AsPh_3</td>
<td>Octane</td>
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<td>16</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>AsPh_3</td>
<td>Octane</td>
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<td>17</td>
<td>[\text{Ir(OMe)(cod)}]</td>
<td>AsPh_3</td>
<td>Octane</td>
<td>6</td>
</tr>
</tbody>
</table>

*Reaction conditions: \( 1a \) (0.5 mmol), \( 2 \) (0.55 mmol), \( \text{Ir}^+ \) precursor (0.0025–0.0075 mmol), ligand (0.01–0.03 mmol), solvent (3 mL). \( 3 \) mol\%/\([\text{Ir(cod)}]\)BF_3 was used. Reaction was carried out at 80 °C. 0.5 mol\%/\([\text{Ir(OMe)}(\text{cod})]\) and 2.0 mol\%/AsPh_3 were used. 5.0 equiv of \( 1a \) with respect to 2 were used. \( \text{HBpin} \) (0.55 mmol) was used. 3 mol\%/dipy was used. Yield was determined by GC analysis. Reaction time 1 h. Isolated yield.

yield. Even the more sterically congested substrates isopropyl ester \( 1e \) and tert-butyl ester \( 1d \) showed good reactivity at 120 °C, to afford the corresponding \( 3c \) and \( 3d \) in 77% and 85% yields, respectively. Reaction of phenyl ester \( 1e \) gave only the vinilic borylation product \( 3e \) in 96% yield at 80 °C. It is noteworthy that the phenyl group, which has five (sp^2)-H bonds and would be reactive in Ir-catalyzed borylation, remained intact in the reaction of \( 1e \).\(^{13}\) Although some transition-metal complexes exhibit high reactivity toward C–Cl bonds, 3-chloropropyl ester \( 1f \) underwent borylation at the vinilic C–H bond, in high yield, without any side reactions involving the C–Cl bond (86%). We then examined the borylation of \( \text{CF}_3 \)containing ester \( 1g \); the \( \text{CF}_3 \) group is very important in drug design because it enhances biological activity. The reaction of \( 1g \) afforded \( 3g \) in 93% yield. The 3-methoxy ester \( 1h \) reacted completely with 2 within 1 h to produce \( 3h \) in high yield (83%). The reactions of ketone \( 1i \), ester \( 1j \), and carbamate \( 1k \) proceeded at 120 °C to afford \( 3i \) (65%), \( 3j \) (74%), and \( 3k \) (72%), respectively. Although competitive coordination of the carbonyl group in the side-chain would inhibit directed borylation, these results showed that the side-chain carbonyl group did not have a seriously detrimental effect on the reactivity of the borylation. Epoxide \( 1l \) reacted without substrate decomposition, and the borylation product \( 3l \) was obtained in 79% yield after 0.5 h. Unlike the cyclohexene-type substrate discussed above, the reactions of cycloalkenyl substrates with five-, seven-, and eight-membered rings resulted in low product yields, even under harsh reaction conditions (120 °C with 2.5 mol\%/\([\text{Ir(OMe)}(\text{cod})]\) and 10 mol\%/AsPh_3) than those used for the cyclohexene-type substrate. Although the five-membered ring \( 1m \) and \( 1n \) were completely consumed in the reaction, the product \( 3m \) was obtained in low yield (20%). The reactions of the seven-membered ring \( 1n \) and eight-membered ring \( 1o \) also gave the alkenylboronates \( 3n \) and \( 3o \) in low yields, though the substrates were completely consumed. We speculate that \( 1m-1o \) decomposed under the reaction conditions.

### Table 2. C–H borylation of various esters


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C–H bond to A produces the pseudo metallacycle C. After reductive elimination, the Ir–hydride complex D and the product 3a are produced. Finally, oxidative addition of B2 pin to D, followed by reductive elimination of HBpin, regenerates A. In pathway 2, involving a 1,4-insertion and β-hydride elimination, the 1,4-insertion of the carbonyl-coordinated complex E produces the iridium enolate F. The subsequent isomerization of F affords the Ir complex G, which has an Ir–C bond with a syn configuration between the Ir center and the β-H. The product 3a and D are then formed through β-hydride elimination from the C-enolate Ir complex G.

**Scheme 3. Proposed catalytic cycle.**

In summary, an iridium complex consisting of [Ir(OMe)(cod)]2 and AsPh3 was found to be an efficient catalyst for the vinylic C–H borylation of 1-cycloalkene-carboxylic derivatives with B. This borylation proceeded at vinylic position with good selectivity, even though substrates have a phenyl group which would be reactive in Ir-catalyzed borylation. Additionally, the borylation of substrates containing various functional groups such as halogen, acyl, alkoxycarbonyl, carbamoyl, and epoxy groups afforded the corresponding products. Bipyridine, phosphine, and NHC ligands have been used for aromatic and alkenyl C–H borylations, but the present results are the first vinylic C–H borylation using AsPh3. Additionally, a one-pot borylation/cross-coupling procedure for the rapid synthesis of a drug candidate was also conducted, and shows the synthetic usefulness of this reaction.

This work was supported by a Grant-in-Aid for Scientific Research (B) (No. 21350049) from the Ministry of Education, Culture, Sports, Science and Technology, Japan, and the Funding Program for Next Generation World-Leading Researchers (NEXT Program, no. GR002).

**Notes and references**

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**Electronic Supplementary Information (ESI) available:** experimental procedures and spectral analyses. See DOI: 10.1039/b000000x/
Supporting information


Materials were obtained from commercial suppliers and purified by standard procedures unless otherwise noted. Solvents were also purchased from commercial suppliers, degassed via N₂ bubbling, and further dried over molecular sieves (MS 4Å). NMR spectra were recorded on JEOL JNM-ECS400P and JNM-ECS400 spectrometer (¹H: 400 MHz and ¹³C: 100 MHz). Tetramethylsilane (¹H) and CDCl₃ (¹³C) were employed as external standards, respectively. [Ir(OMe)(cod)] was synthesized according to the reported procedure.¹ Tetradecane was used as an internal standard to determine GC yield. GLC analyses were conducted with a Shimadzu GC-2014 or GC-2025 equipped with ULBON HR-1 glass capillary column (Shimna Chemical Industries) and a FID detector. Elemental analyses and high-resolution mass spectra were recorded at the Center for Instrumental Analysis, Hokkaido University.

2. General Experimental Procedures.

A Representative Procedure for the Iridium(I)-Catalyzed Vinylic C-H Borylation of 1a (Table 1).

[Ir(OMe)(cod)] (4.97 mg, 0.0075 mmol) and bis(pinacolato) diboron (B₃H₉) (2) (1.40 g, 5.5 mmol), AsPh₃ (91.9 mg, 0.3 mmol) were placed in an oven-dried two neck flask. The flask was connected to a vacuum/nitrogen manifold through a rubber tube. It was evacuated and then backfilled with nitrogen. This cycle was repeated three times. Octane (3 mL) was added in the flask through the rubber septum, and stirred at room temperature for 10 min. Then, 1a (701 mg, 0.5 mmol) was added to the reaction mixture, and stirred at 80 or 120 °C. After the reaction was complete, the reaction mixture was concentrated and purified by flash column chromatography (SiO₂, EtOAc/hexane, 1:99–5:95) to give the corresponding alkenylboronate 3a as a colorless oil.

The Procedure for One-pot Synthesis of 4.

[Ir(OMe)(cod)] (49.7 mg, 0.15 mmol) and B₃H₉ (2) (1.40 g, 5.5 mmol), AsPh₃ (91.9 mg, 0.3 mmol) were placed in an oven-dried two neck flask. The flask was connected to a vacuum/nitrogen manifold through a rubber tube. It was evacuated and then backfilled with nitrogen. This cycle was repeated three times. Octane (15 mL) was added in the flask through the rubber septum via a syringe, and stirred at room temperature for 10 min. Then, 1a (701 mg, 5.0 mmol) was added to the reaction mixture, and stirred at 80 °C for 16 h. The reaction mixture was cooled to r.t., and H₂O (1.5 ml) was added and stirred for 10 min. Without purification, PdCl₂(dppf) (92.0 mg, 0.125 mmol), K₂PO₄ (1.59 g, 7.50 mmol), and 2-bromonaphthalene (518 mg, 2.50 mmol) were added to the reaction mixture and stirred at 80 °C for 8 h. After the reaction was complete, the reaction mixture was cooled to r.t. and extracted with EtOAc three times. The combined organic layer was dried over MgSO₄. After filtration, the solvents were removed by evaporation. The crude product was purified by flash column chromatography to obtain 4 (271.3 mg, 47% (78% GC yield)) as a syrup. ¹H NMR (400 MHz, CDCl₃, δ): 1.76–1.85 (m, 4H), 2.44–2.55 (m, 4H), 3.37 (s, 3H), 7.28 (dd, J = 7.0, 1.8 Hz, 1H), 7.42–7.48 (m, 2H), 7.58–7.62 (m, 1H), 7.77–7.82 (m, 3H). ¹³C NMR (100 MHz, CDCl₃, δ): 21.9 (CH₃), 22.5 (CH₃), 26.7 (CH₃), 32.6 (CH₃), 51.2 (CH₃), 125.0 (CH), 125.59 (CH), 125.64 (CH), 125.9 (CH), 127.4 (CH), 127.6 (CH), 127.9 (CH), 128.0 (C), 132.4 (C), 133.2 (C), 140.8 (C). 145.7 (C), 170.3 (C). HRMS-ESI (m/z): [M+Na]⁺ calcd for C₁₄H₂₄O₂Na, 289.11990; found, 289.12018.

3. Preparation of Substrates.

Preparation of methyl cyclohex-1-ene carboxylate (1a).

In a vacuum dried three-necked, 500 mL, round bottomed flask, cyclohexanecarboxylic acid (50.3 mL, 400 mmol) and thionyl chloride (36.3 mL, 500 mL) was added and stirred at 90 °C for 2 h. Then the reaction mixture was cooled to 80 °C and red phosphorus (0.65 g) was added with stirring. Bromine (25.8 mL, 500 mmol) was added dropwise as temperature was maintained below 100 °C. The reaction mixture was heated at 100 °C for an additional 5 h and then cooled to 0 °C and dry methanol (85.0 mL, 2.10 mol) was added dropwise. The reaction mixture was heated to reflux for 1 h. After that, the reaction mixture was quenched by addition of ice-cold water and extracted with Et₂O four times. The combined organic layer was washed with 1M Na₂SO₄ aq. once and saturated NaHCO₃ aq. three times and saturated NaCl aq. once. The combined organic layer was dried over MgSO₄. After filtration, the solvents were removed by evaporation. The crude product was purified by vacuum distillation to obtain methyl 1-bromocyclohexanecarboxylate (86.5 g, 392 mmol, 98%) as a colorless oil.
In a vacuum dried 300 mL of a round bottomed flask, methyl 1-bromocyclohexanecarboxylate (86.2 g, 390 mmol) and quinoline (74.0 mL, 624 mmol) was added and the flask was heated to 120 °C for 2 h under nitrogen atmosphere. After 15 min of heating, a slight exothermic reaction was noted and the mixture separated into two layers. The reaction mixture was cooled and quenched by addition of 20% HCl aq. and extracted with hexane four times. The combined organic layer was washed with 10% HCl aq. and saturated NaHCO₃ aq. and saturated NaCl aq. and was dried over MgSO₄. After filtration, the solvents were removed by evaporation. The crude product was purified by vacuum distillation to obtain 1a (37.8 g, 270 mmol, 69%) as a colorless oil.

\[ ^{1}H \text{ NMR (400 MHz, CDCl}_3, \delta): 1.55–1.73 (m, 4H), 2.14–2.32 (m, 4H), 3.73 (s, 3H), 6.95–7.00 (m, 1H). ^{13}C \text{ NMR (100 MHz, CDCl}_3, \delta): 21.3 (CH), 21.9 (CH), 24.0 (CH), 25.6 (CH), 51.3 (CH), 130.1 (C), 139.6 (CH), 167.9 (C). HRMS-ESI (m/z): [M]^+ calcd for C_{12}H_{18}O_2, 191.0964; found, 191.0965. \]

Preparation of ethyl cyclohex-1-ene-carboxylate (1b).

\[ \text{1b (5.94 g, 38.5 mmol, 39%, colorless oil) was prepared from cyclohexanecarboxylic acid (12.8 g, 100 mmol) and ethanol (24.2 g, 525 mmol) according to the procedure described above.} ^{1}H \text{ NMR (400 MHz, CDCl}_3, \delta): 1.29 (t, J = 7.4 Hz, 3H), 1.56–1.68 (m, 4H), 2.16–2.28 (m, 4H), 4.18 (q, J = 7.2 Hz, 2H), 6.97–7.00 (m, 1H). ^{13}C \text{ NMR (100 MHz, CDCl}_3, \delta): 13.7 (CH), 21.0 (CH), 21.6 (CH), 23.6 (CH), 25.2 (CH), 59.5 (CH), 129.9 (C), 138.7 (CH), 166.8 (C). HRMS-ESI (m/z): [M]^+ calcd for C_{12}H_{18}O_2, 154.09938; found, 154.09907. \]

Preparation of isopropyl cyclohex-1-ene-carboxylate (1c).

\[ \text{1c (2.44 g, 14.5 mmol, 73%, colorless oil) was prepared from cyclohexanecarboxylic acid (2.56 g, 20.0 mmol) and propan-2-ol (6.01 g, 100 mmol) according to the procedure described above.} ^{1}H \text{ NMR (400 MHz, CDCl}_3, \delta): 1.26 (d, J = 6.4 Hz, 6H), 1.56–1.68 (m, 4H), 2.15–2.27 (m, 4H), 5.06 (sep, J = 6.2 Hz, 1H), 6.94–6.97 (m, 1H). ^{13}C \text{ NMR (100 MHz, CDCl}_3, \delta): 21.4 (CH), 21.8 (CH), 22.0 (CH), 24.0 (CH), 25.6 (CH), 67.1 (CH), 130.7 (C), 138.9 (CH), 167.0 (C). HRMS-ESI (m/z): [M+Na]^+ calcd for C_{12}H_{18}O_2Na, 191.10425; found, 191.10468. \]

Preparation of tert-Butyl cyclohex-1-ene-carboxylate (1d).

\[ \text{MgSO}_4 (4.81 g, 40.0 mmol) was placed in an oven-dried two neck flask. The flask was connected to a vacuum/nitrogen manifold through a rubber tube, evacuated and backfilled with nitrogen. CHCl}_3 (40 mL) was added in the flask through the rubber septum. Then, HSO}_3 (0.53 mL, 10.0 mmol) was added dropwise at room temperature. After the addition of HSO}_4 was complete, cyclohex-1-ene-carboxylic acid (1.26 g, 10.0 mmol) and 2-methylpropan-2-ol (3.71 g, 50.0 mmol) was added and stirred at room temperature. The reaction was quenched by addition of saturated NH}_4 aq. (75 mL) and extracted with CHCl}_3, three times. The combined organic layer was dried over MgSO}_4. After filtration, the solvents were removed by evaporation. The crude product was purified by flash column chromatography to obtain 1d (0.773 g, 4.24 mmol, 42%) as a colorless oil.} ^{1}H \text{ NMR (400 MHz, CDCl}_3, \delta): 1.48 (s, 9H), 1.55–1.67 (m, 4H), 2.15–2.23 (m, 4H), 6.87–6.90 (m, 1H). ^{13}C \text{ NMR (100 MHz, CDCl}_3, \delta): 21.4 (CH), 22.0 (CH), 24.0 (CH), 25.5 (CH), 27.9 (CH), 79.4 (C), 131.6 (C), 138.1 (CH), 166.7 (C). HRMS-ESI (m/z): [M+Na]^+ calcd for C_{12}H_{18}O_2Na, 201.11990; found, 205.12001. \]

Preparation of phenyl cyclohex-1-ene-carboxylate (1e).

\[ \text{In a vacuum dried 300 mL of a round bottomed flask, cyclohex-1-ene-carboxylic acid (2.52 g, 20.0 mmol) and phenol (2.07 g, 22.0 mmol) were dissolved in dry CHCl}_3 (110 mL) and the flask was cooled to 0 °C under nitrogen atmosphere. 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide (EDC) (4.60 g, 24.0 mmol) and N,N-dimethyl-4-aminopyridine (DMAP) (0.244 g, 2.0 mmol) were then added portion wise. After stirred for 14 h at room temperature, the reaction mixture was quenched by addition of saturated NH}_4 aq. and extracted with CHCl}_3, three times. The combined organic layer was then dried over MgSO}_4. After filtration, the solvents were removed by evaporation. The crude product was purified by flash column chromatography to obtain 1e (3.40 g, 16.8 mmol, 84%) as a solid.} ^{1}H \text{ NMR (400 MHz, CDCl}_3, \delta): 1.63–1.76 (m, 4H), 2.24–2.31 (m, 2H), 2.35–2.43 (m, 2H), 7.10 (d, J = 7.2 Hz, 2H), 7.20–7.26 (m, 2H), 7.38 (t, J = 9.0 Hz, 2H). ^{13}C \text{ NMR (100 MHz, CDCl}_3, \delta): 21.3 (CH), 22.0 (CH), 24.2 (CH), 26.0 (CH), 121.7 (CH), 125.5 (CH), 129.3 (CH), 129.8 (C), 141.9 (CH), 151.1 (C), 166.0 (C). HRMS-ESI (m/z): [M+Na]^+ calcd for C_{17}H_{14}O_2Na, 255.08860; found, 225.08847. \]

Preparation of 3-chloropropyl cyclohex-1-ene-carboxylate (1f).
Preparation of 3-hydroxybutanoate (1f).  

Preparation of 4,4,4-trifluorobutyl cyclohex-1-enecarboxylate (1g).  

Preparation of 3-methoxypropyl cyclohex-1-enecarboxylate (1h).  

Preparation of 4-oxopentyl cyclohex-1-enecarboxylate (1i).  

Preparation of 4-methoxy-4-oxobutyl cyclohex-1-enecarboxylate (1j).  

Preparation of 3-((methoxycarbonyl)(methyl)amino)propyl cyclohex-1-enecarboxylate (1k).
Preparation of 3-(oxiran-2-yl)propyl cyclohex-1-enecarboxylate (1l).

Pent-4-en-1-yl cyclohex-1-enecarboxylate (1.38 g, 7.00 mmol, 71%) was prepared from cyclohex-1-enecarboxylic acid (1.26 g, 10.0 mmol) and pent-4-en-1-ol (0.947 g, 11.0 mmol) according to the procedure described for phenyl cyclohex-1-enecarboxylate (4e). m-Chloroperbenzoic acid (1.45 g, 8.40 mmol) was placed in an oven-dried 200 mL of a round bottomed flask. The flask was connected to a vacuum/nitrogen manifold through a rubber tube, evacuated and backfilled with nitrogen. The solution of pent-4-en-1-yl cyclohex-1-enecarboxylate (1.38 g, 7.00 mmol) and dry CH₂Cl₂ (70 mL) was added dropwise to the flask. After the reaction was complete, the reaction mixture was extracted with CH₂Cl₂ and saturated NaHCO₃ aq. three times. The crude mixture was purified by flash column chromatography to obtain 1l (0.703 g, 3.34 mmol, 48%) as a colorless oil. ¹H NMR (400 MHz, CDCl₃, δ): 1.57–1.72 (m, 6H), 1.76–1.92 (m, 2H), 2.15–2.26 (m, 4H), 2.48–2.50 (m, 1H), 2.77 (t, J = 4.4 Hz, 1H), 2.93–2.98 (m, 1H), 4.18 (t, J = 6.6 Hz, 2H), 6.97–7.00 (m, 1H). ¹³C NMR (100 MHz, CDCl₃, δ): 21.4 (CH₃), 22.0 (CH₃), 24.1 (CH₃), 25.2 (CH₃), 25.7 (CH₃), 29.1 (CH₃), 47.0 (CH₃), 51.7 (CH₃), 63.6 (CH₂), 130.2 (C), 139.7 (CH), 167.5 (C). HRMS-ESI (m/z): [M+Na]+ calcd for C₁₅H₁₆O₂Na, 233.11492; found, 233.11494.

Preparation of methyl cyclopent-1-enecarboxylate (1m).

1m (7.33 g, 58.2 mmol, 58%, colorless oil) was prepared from cyclopentanecarboxylic acid (11.4 g, 100 mmol) and methanol (21.3 mL, 525 mmol) according to the procedure described above. ¹H NMR (400 MHz, CDCl₃, δ): 1.96 (quint, J = 7.6 Hz, 2H), 2.42–2.61 (m, 4H), 3.74 (s, 3H), 6.77–6.79 (m, 1H). ¹³C NMR (100 MHz, CDCl₃, δ): 22.8 (CH₃), 31.0 (CH₂), 33.0 (CH₂), 50.9 (CH₂), 136.1 (C), 143.4 (CH), 165.3 (C). HRMS-APCI (m/z): [M+H]+ calcd for C₇H₁₂O₂, 127.07536; found, 127.07559.

Preparation of methyl cyclohept-1-enecarboxylate (1n).

1n (1.28 g, 8.30 mmol, 59%, colorless oil) was prepared from cycloheptanecarboxylic acid (1.99 g, 14.0 mmol) and methanol (2.24 g, 70.0 mmol) according to the procedure described above. ¹H NMR (400 MHz, CDCl₃, δ): 1.49–1.57 (m, 4H), 1.75–1.81 (m, 2H), 2.29 (dt, J = 6.3, 3.2 Hz, 2H), 2.51–2.54 (m, 2H), 3.72 (s, 3H), 7.18 (t, J = 7.0 Hz, 1H). ¹³C NMR (100 MHz, CDCl₃, δ): 25.6 (CH₃), 26.1 (CH₂), 27.2 (CH₂), 28.6 (CH₂), 31.9 (CH₂), 51.5 (CH₂), 136.3 (C), 144.3 (CH), 168.4 (C). HRMS-ESI (m/z): [M]+ calcd for C₉H₁₄O₂, 154.09958; found, 154.09963.

Preparation of (E)-methyl cyclooct-1-enecarboxylate (1o).

1o (0.972 g, 5.78 mmol, 58%, colorless oil) was prepared from cyclooctanecarboxylic acid (1.56 g, 10.0 mmol) and methanol (1.67 g, 52.0 mmol) according to the procedure described above. ¹H NMR (400 MHz, CDCl₃, δ): 1.43–1.51 (m, 4H), 1.54–1.62 (m, 4H), 2.28 (dt, J = 8.8, 4.0 Hz, 2H), 2.45–2.48 (m, 2H), 3.73 (s, 3H), 6.99 (t, J = 8.6 Hz, 1H). ¹³C NMR (100 MHz, CDCl₃, δ): 24.5 (CH₂), 25.7 (CH₂), 26.3 (CH₂), 27.0 (CH₂), 28.8 (CH₂), 28.9 (CH₂), 51.3 (CH₂), 132.9 (C), 142.3 (CH), 167.8 (C). HRMS-ESI (m/z): [M+Na]+ calcd for C₁₄H₂₁O₂Na, 191.10425; found, 191.10465.


Methyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohex-1-enecarboxylate (3a).

Product 3a (125.3 mg, 87% Isolated yield, 99% GC yield) was obtained from 1a (70.1 mg, 0.50 mmol) as an oil, according to the general procedure for the iridium(1)-catalyzed vinylic C–H borylation. ¹H NMR (400 MHz, CDCl₃, δ): 1.34 (s, 12H), 1.54–1.66 (m, 4H), 2.20–
2.24 (m, 4H), 3.74 (s, 3H). $^{13}$C NMR (100 MHz, CDCl$_3$, δ): 21.2 (CH$_3$), 21.6 (CH$_3$), 24.0 (CH$_3$), 24.6 (CH$_3$), 27.8 (CH$_3$), 51.6 (CH$_3$), 83.2 (C), 133.6 (C), 147.6 (br, B−C), 169.2 (C). HRMS-ESI (m/z): [M+Na$^+$] calc for C$_{15}$H$_{25}$BO$_2$Na, 288.16179; found, 288.16138.

Ethyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohex-1-enecarboxylate (3b).

Product 3b (87% GC yield) was obtained from 1b (77.1 mg, 0.50 mmol) as an oil, according to the general procedure for the iridium(I)-catalyzed vinylic C−H borylation. $^1$H NMR (400 MHz, CDCl$_3$, δ): 1.27 (t, J = 7.2 Hz, 3H), 1.33 (s, 12H), 1.54−1.66 (m, 4H), 2.17−2.27 (m, 4H), 4.21 (q, J = 7.2 Hz, 2H). $^{13}$C NMR (100 MHz, CDCl$_3$, δ): 13.9 (CH$_3$), 21.1 (CH$_3$), 21.6 (CH$_3$), 23.8 (CH$_3$), 24.4 (CH$_3$), 27.6 (CH$_3$), 60.4 (CH$_3$), 83.0 (C), 133.8 (C), 148.1 (br, B−C), 168.8 (C). HRMS-ESI (m/z): [M+Na$^+$] calc for C$_{15}$H$_{25}$BO$_2$Na, 302.17744; found, 302.17752.

Isopropyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohex-1-enecarboxylate (3c).

Product 3c (77% GC yield) was obtained from 1c (84.1 mg, 0.50 mmol) as an oil, according to the general procedure for the iridium(I)-catalyzed vinylic C−H borylation. $^1$H NMR (400 MHz, CDCl$_3$, δ): 1.24 (d, J = 6.6 Hz, 6H), 1.33 (s, 12H), 1.54−1.68 (m, 4H), 2.15−2.25 (m, 4H), 5.07 (sep, J = 6.6 Hz, 1H). $^{13}$C NMR (100 MHz, CDCl$_3$, δ): 21.2 (CH$_3$), 21.6 (CH$_3$), 21.6 (CH$_3$), 23.7 (CH$_3$), 24.5 (CH$_3$), 27.6 (CH$_3$), 67.8 (CH), 82.9 (C), 134.3 (C), 148.4 (br, B−C), 168.7 (C). HRMS-ESI (m/z): [M+Na$^+$] calc for C$_{15}$H$_{25}$BO$_2$Na, 316.19309; found, 316.19331.

tert-Butyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohex-1-enecarboxylate (3d).

Product 3d (85% GC yield) was obtained from 1d (91.1 mg, 0.50 mmol) as an oil, according to the general procedure for the iridium(I)-catalyzed vinylic C−H borylation. $^1$H NMR (400 MHz, CDCl$_3$, δ): 1.20−1.27 (m, 1H), 1.32 (s, 11H), 1.46 (s, 9H), 1.54−1.63 (m, 4H), 2.12−2.22 (m, 4H). $^{13}$C NMR (100 MHz, CDCl$_3$, δ): 21.4 (CH$_3$), 21.9 (CH$_3$), 24.0 (CH$_3$), 24.7 (CH$_3$), 27.5 (CH$_3$), 28.0 (CH$_3$), 80.8 (C), 82.9 (CH), 135.8 (C), 148.6 (br, B−C), 169.2 (C). HRMS-ESI (m/z): [M+Na$^+$] calc for C$_{15}$H$_{25}$BO$_2$Na, 330.20874; found, 330.20853.

Phenyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohex-1-enecarboxylate (3e).

Product 3e (96% GC yield) was obtained from 1e (101 mg, 0.50 mmol) as a powder, according to the general procedure for the iridium(I)-catalyzed vinylic C−H borylation. $^1$H NMR (400 MHz, CDCl$_3$, δ): 1.24 (s, 12H), 1.61−1.74 (m, 4H), 2.29−2.41 (m, 4H), 7.11 (d, J = 8.0 Hz, 2H), 7.21 (t, J = 7.6 Hz, 1H), 7.36 (t, J = 8.2 Hz, 2H). $^{13}$C NMR (100 MHz, CDCl$_3$, δ): 21.3 (CH$_3$), 21.8 (CH$_3$), 24.6 (CH$_3$), 24.8 (CH$_3$), 28.4 (CH$_3$), 83.7 (C), 121.9 (CH$_3$), 125.6 (CH$_3$), 129.2 (CH$_3$), 133.7 (C), 149.0 (br, B−C), 150.8 (C), 166.6 (C). HRMS-ESI (m/z): [M+Na$^+$] calc for C$_{15}$H$_{25}$BO$_2$Na, 350.17744; found, 350.17718.

3-Chloropropyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohex-1-enecarboxylate (3f).
Product 3f (86% GC yield) was obtained from 1f (101 mg, 0.50 mmol) as an oil, according to the general procedure for the iridium(I)-catalyzed vinylic C–H borylation. 1H NMR (400 MHz, CDCl3, δ): 1.20–1.28 (m, 2H), 1.34 (s, 10H), 1.55–1.66 (m, 4H), 2.12 (quint, J = 6.4 Hz, 2H), 2.19–2.26 (m, 4H), 2.61 (t, J = 6.6 Hz, 2H), 4.29 (t, J = 6.4 Hz, 2H). 13C NMR (100 MHz, CDCl3, δ): 21.2 (CH3), 21.7 (CH2), 24.0 (CH2), 24.6 (CH2), 27.9 (CH3), 31.6 (CH2), 41.1 (CH1), 61.3 (CH3), 83.2 (C), 133.6 (C), 148.9 (br, B–C), 168.7 (C). HRMS-ESI (m/z): [M+Na]+ calcd for C13H11BO3Na, 350.15412; found, 350.15387.

4,4,4-Trifluorobuty1 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohex-1-encarboxylate (3g).

Product 3g (93% GC yield) was obtained from 1g (118 mg, 0.50 mmol) as a powder, according to the general procedure for the iridium(I)-catalyzed vinylic C–H borylation. 1H NMR (400 MHz, CDCl3, δ): 1.17–1.27 (m, 1H), 1.33 (s, 11H), 1.55–1.69 (m, 4H), 1.89–1.96 (m, 2H), 2.12–2.25 (m, 6H), 4.20 (t, J = 6.4 Hz, 2H). 13C NMR (100 MHz, CDCl3, δ): 21.1 (CH3), 21.4 (CH2), 21.6 (CH3), 23.9 (CH2), 24.5 (CH2), 27.8 (CH3), 30.5 (q, J=29.5 Hz, CH2), 62.7 (CH2), 83.2 (C), 126.7 (q, J=277 Hz, C), 133.5 (C), 149.2 (br, B–C), 168.6 (C). HRMS-ESI (m/z): [M+Na]+ calcd for C11H15BO3Na, 384.18048; found, 384.17999.

3-Methoxpropyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohex-1-encarboxylate (3h).

Product 3h (83% GC yield) was obtained from 1h (99.1 mg, 0.50 mmol) as an oil, according to the general procedure for the iridium(I)-catalyzed vinylic C–H borylation. 1H NMR (400 MHz, CDCl3, δ): 1.17–1.26 (m, 1H), 1.33 (s, 11H), 1.54–1.69 (m, 4H), 1.91 (quint, J = 6.4 Hz, 2H), 2.20–2.24 (m, 4H), 3.33 (s, 3H), 3.44 (t, J = 6.4 Hz, 2H), 4.23 (t, J = 6.6 Hz, 2H). 13C NMR (100 MHz, CDCl3, δ): 21.3 (CH3), 21.7 (CH2), 24.0 (CH2), 24.6 (CH3), 27.8 (CH2), 28.8 (CH2), 58.5 (CH2), 61.7 (CH2), 69.0 (CH3), 83.2 (CH2), 133.9 (C), 148.6 (br, B–C), 169.0 (C). HRMS-ESI (m/z): [M+Na]+ calcd for C16H20BO3Na, 346.20366; found, 346.20410.

4-Oxopentyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohex-1-encarboxylate (3i).

Product 3i (65% GC yield) was obtained from 1i (105 mg, 0.50 mmol) as an oil, according to the general procedure for the iridium(I)-catalyzed vinylic C–H borylation. 1H NMR (400 MHz, CDCl3, δ): 1.18–1.26 (m, 1H), 1.33 (s, 11H), 1.55–1.66 (m, 4H), 1.93 (quint, J = 6.6 Hz, 2H), 2.15 (s, 3H), 2.18–2.27 (m, 4H), 2.51 (t, J = 7.4 Hz, 2H), 4.15 (t, J = 6.4 Hz, 2H). 13C NMR (100 MHz, CDCl3, δ): 21.2 (CH3), 21.7 (CH2), 22.6 (CH2), 24.0 (CH2), 24.6 (CH2), 27.8 (CH2), 29.8 (CH2), 39.6 (CH2), 63.7 (CH2), 83.2 (C), 133.7 (C), 148.8 (br, B–C), 168.9 (C). HRMS-ESI (m/z): [M+Na]+ calcd for C16H20BO3Na, 358.20366; found, 358.20419.

4-Methoxy-4-oxobutyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohex-1-encarboxylate (3j).

Product 3j (74% GC yield) was obtained from 1j (113 mg, 0.50 mmol) as an oil, according to the general procedure for the iridium(I)-catalyzed vinylic C–H borylation. 1H NMR (400 MHz, CDCl3, δ): 1.17–1.26 (m, 1H), 1.33 (s, 11H), 1.56–1.66 (m, 4H), 1.98 (quint, J = 6.8 Hz, 2H), 2.19–2.24 (m, 4H), 2.41 (t, J = 7.4 Hz, 2H), 3.68 (s, 3H), 4.17 (t, J = 6.4 Hz, 2H). 13C NMR (100 MHz, CDCl3, δ): 21.1 (CH3), 21.6 (CH2), 23.7 (CH2), 23.9 (CH2), 24.5 (CH2), 30.2 (CH2), 51.3 (CH2), 63.5 (CH2), 83.2 (C), 133.6 (C), 148.7 (br, B–C), 168.8 (C), 173.0 (C). HRMS-ESI (m/z): [M+Na]+ calcd for C16H20BO3Na, 374.19857; found, 374.19894.

3-((Methoxycarbonyl)(methyl)amino)propyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohex-1-encarboxylate (3k).
Product 3k (72% GC yield) was obtained from 1k (128 mg, 0.50 mmol) as an oil, according to the general procedure for the iridium(I)-catalyzed vinylic C–H borylation. 1H NMR (400 MHz, CDCl₃, δ): 1.17–1.27 (m, 2H), 1.33 (s, 10H), 1.59–1.69 (m, 4H), 1.81–1.95 (m, 2H), 2.17–2.28 (m, 4H), 2.85–2.94 (m, 3H), 3.28–3.40 (m, 2H), 3.68 (s, 3H). HRMS-ESI (m/z): [M+Na]⁺ calcd for C₁₈H₂₃BO₄Na, 403.22512; found, 403.22465.

3-(Oxiran-2-yl)propyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohex-1-ene carboxylate (3l).

Product 3l (79% GC yield) was obtained from 1l (105 mg, 0.50 mmol) as an oil, according to the general procedure for the iridium(I)-catalyzed vinylic C–H borylation. 1H NMR (400 MHz, CDCl₃, δ): 1.17–1.27 (m, 1H), 1.33 (s, 11H), 1.53–1.71 (m, 6H), 1.74–1.88 (m, 2H), 2.19–2.24 (m, 4H), 2.49 (dd, J = 5.1, 2.6 Hz, 1H), 2.76 (t, J = 4.6 Hz, 1H), 2.92–2.97 (m, 1H), 4.14–4.25 (m, 2H). 13C NMR (100 MHz, CDCl₃, δ): 21.3 (CH₃), 21.8 (CH₃), 24.1 (CH₃), 24.7 (CH₃), 25.1 (CH₂), 27.9 (CH₃), 29.0 (CH₂), 47.0 (CH₂), 51.7 (CH), 64.2 (CH₂), 83.4 (C), 133.9 (C), 148.9 (br, B–C), 169.1 (C). HRMS-ESI (m/z): [M+Na]⁺ calcd for C₁₃H₂₀BO₄Na, 358.20366; found, 358.20327.

Methyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclopent-1-ene carboxylate (3m).

Product 3m (20% GC yield) was obtained from 1m (63.1 mg, 0.50 mmol) as an oil, according to the general procedure for the iridium(I)-catalyzed vinylic C–H borylation. 1H NMR (400 MHz, CDCl₃, δ): 1.26–1.27 (m, 1H), 1.34 (s, 11H), 1.94 (quint, J = 8.0 Hz, 2H), 2.61 (t, J = 7.6 Hz, 4H), 3.73 (s, 3H). 13C NMR (100 MHz, CDCl₃, δ): 24.0 (CH₃), 24.6 (CH₃), 33.3 (CH₂), 37.5 (CH₂), 51.3 (CH₃), 83.8 (C), 142.2 (C), 148.7 (br, B–C), 166.0 (C). HRMS-APCI (m/z): [M+H]⁺ calcd for C₁₃H₂₀BO₄, 252.16420; found, 252.16463.

Methyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclohept-1-ene carboxylate (3n).

Product 3n (43% GC yield) was obtained from 1n (77.1 mg, 0.50 mmol) as an oil, according to the general procedure for the iridium(I)-catalyzed vinylic C–H borylation. 1H NMR (400 MHz, CDCl₃, δ): 1.19–1.27 (m, 1H), 1.33 (s, 11H), 1.46–1.59 (m, 4H), 1.75–1.81 (m, 2H), 2.32–2.34 (m, 2H), 2.50–2.55 (m, 2H), 3.77 (s, 3H). 13C NMR (100 MHz, CDCl₃, δ): 24.7 (CH₃), 25.66 (CH₃), 25.69 (CH₂), 27.3 (CH₃), 31.0 (CH₃), 32.2 (CH₃), 52.4 (CH₃), 82.8 (C), 139.7 (C), 157.0 (br, B–C), 170.9 (C). HRMS-ESI (m/z): [M+Na]⁺ calcd for C₁₃H₂₀BO₄Na, 302.17744; found, 302.17709.

(E)-Methyl 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)cyclooct-1-ene carboxylate (3o).

Product 3o (35% GC yield) was obtained from 1o (84.1 mg, 0.50 mmol) as an oil, according to the general procedure for the iridium(I)-catalyzed vinylic C–H borylation. 1H NMR (400 MHz, CDCl₃, δ): 1.17–1.28 (m, 1H), 1.33 (s, 11H), 1.43–1.69 (m, 8H), 2.35 (t, J = 6.2 Hz, 2H), 2.44 (t, J = 6.0 Hz, 2H), 3.76 (s, 3H). 13C NMR (100 MHz, CDCl₃, δ): 24.7 (CH₃), 24.9 (CH₃), 26.20 (CH₃), 26.22 (CH₂), 28.7 (CH₂), 29.0 (CH₃), 29.7 (CH₃), 52.1 (CH₃), 83.1 (C), 136.9 (C), 170.1 (C). The carbon directly attached to the boron atom was not detected, likely due to quadrupolar relaxation. HRMS-ESI (m/z): [M+Na]⁺ calcd for C₁₃H₂₀BO₄Na, 316.19309; found, 316.19282.
References