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Palladium-Catalyzed Chemoselective Negishi Cross-Coupling of Bis[(pinacolato)boryl]methylzinc Halides with Aryl (Pseudo)Halides

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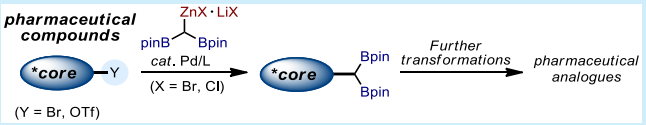
Supporting Information

ABSTRACT: We describe a palladium-catalyzed chemoselective Negishi cross-coupling of a bis[(pinacolato)boryl]methylzinc halide with aryl (pseudo)halides. This reaction affords an array of benzylic 1,1-diboronate esters, which can serve as useful synthetic handles for further transformations. The developed coupling reaction is compatible with various functional groups and can be easily scaled up. The coupling of bis[(pinacolato)boryl]methylzinc halides with pharmaceuticals and the subsequent late-stage manipulations demonstrate the power of the developed protocol.



Palladium-catalyzed cross-coupling reactions are of central importance in organic and medicinal chemistry as a prominent route for the construction of carbon−carbon bonds.[1] Over the past decades, these types of reactions have enabled synthetic chemists to increase the complexity and diversity of their target molecules. Recent advances in this field have established efficient tools for the production of diverse complex molecules via the sequential couplings of bifunctionalized reagents.[2] In this context, Transition-metal-catalyzed chemoselective cross-coupling has been successfully developed by using organo di(pseudo)halides.[3] The cross-coupling reaction of substrates containing both electrophilic and nucleophilic groups is also well established.[4] Chemoselective cross-coupling reactions involving diorganometallics, which comprise two metal centers bound to the same or different carbons, have recently been achieved.[5,6] However, despite the extensive efforts invested in this research field, the transition-metal-catalyzed chemoselective cross-coupling of polyorganometallics that have three organometallic moieties at the single sp^3-hybridized carbon center have rarely been studied (Scheme 1a). In 1999, Matsubara and Utimoto prepared dizincborylmethane from dibromomethane via three-step sequences;[6] however, the synthetic applications of the organometallic species were very limited due to the instability of the compound. Williams and Knochel synthesized bis(silyl)methyl magnesium bromide or bis(silyl)methylzinc chloride from bis(silyl)methyl halides, but the disilicon units of these compounds were less effective for further chemical modifications.[7] Although protocols for synthesizing diborylsilylmethanes[8] and triborylalkanes[9] have also been reported, functionalization of one of the boron units of the obtained species required the use of a strong base. More importantly, the low functional group tolerance of these organometallic intermediates makes them unsuitable for further synthetic applications.

Recently, our group reported an efficient transmetalation of bis[(pinacolato)boryl]methyllithium and zinc(II) halides to synthesize bis[(pinacolato)boryl]methylzinc halides.[10] These species have two identical boron moieties and a zinc halide moiety bound to the same sp^3-hybridized carbon center, and undergo reactions that proceed with unique chemoselectivity to give 1,1-diboron-substituted products bearing useful synthetic handles for further transformations. We envisioned a reaction wherein a bis[(pinacolato)boryl]methylzinc halide is coupled with an organo (pseudo)halide via palladium catalysis. Herein, we describe the chemoselective palladium-catalyzed cross-coupling with organo (pseudo)halides and their utilities in late-stage diversifications of drug-like intermediates (Scheme 1b).

Scheme 1. 1,1,1-Triorganometallics for Sequential Functionalizations

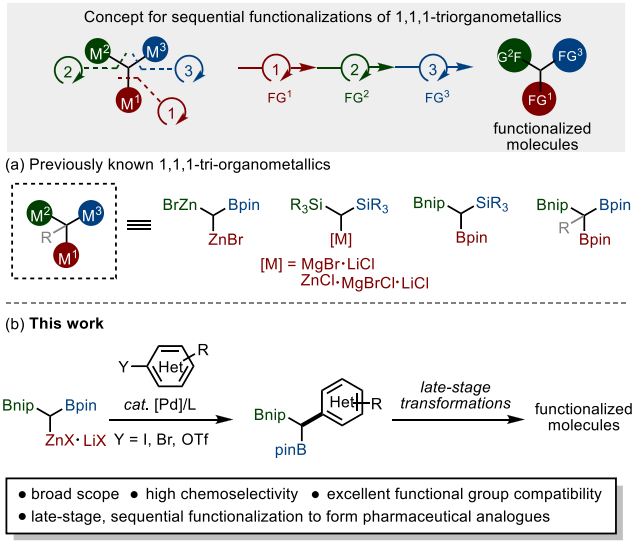


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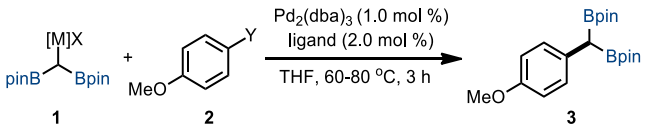
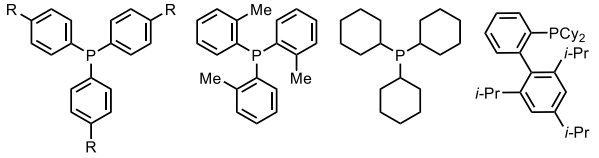
Table 1. Optimization Study for the Palladium-Catalyzed Coupling of 1-ZnX with Aryl (Pseudo)Halide[a]



entry	[M]X	Y	ligand	yield (%)[b]
1	ZnBr·LiBr (**1-ZnBr**)	Br (**2-Br**)	**L1**	53
2	ZnBr·LiBr (**1-ZnBr**)	Br (**2-Br**)	**L2**	68
3	ZnBr·LiBr (**1-ZnBr**)	Br (**2-Br**)	**L3**	26
4	ZnBr·LiBr (**1-ZnBr**)	Br (**2-Br**)	**L4**	99 (82)[c]
5	ZnBr·LiBr (**1-ZnBr**)	Br (**2-Br**)	**L5**	74
6	ZnBr·LiBr (**1-ZnBr**)	Br (**2-Br**)	**L6**	95
7	ZnBr·LiBr (**1-ZnBr**)	Br (**2-Br**)	**L4**	11
8	ZnCl·LiCl (**1-ZnCl**)	Br (**2-Br**)	**L4**	95
9	ZnI·LiI (**1-ZnI**)	Br (**2-Br**)	**L4**	22
10	ZnBr·LiBr (**1-ZnBr**)	I (**2-I**)	**L4**	85
11	ZnBr·LiBr (**1-ZnBr**)	Cl (**2-Cl**)	**L4**	<1
12	ZnBr·LiBr (**1-ZnBr**)	OTf (**2-OTf**)	**L4**	<1
13	ZnBr·LiBr (**1-ZnBr**)	OTf (**2-OTf**)	**L6**	73
14[d]	ZnBr·LiBr (**1-ZnBr**)	OTf (**2-OTf**)	**L6**	85
15[d]	ZnCl·LiCl (**1-ZnCl**)	OTf (**2-OTf**)	**L6**	99 (83)[c]
16	Li (**1-Li**)	Br (**2-Br**)	**L4**	<1
17[d]	Li (**1-Li**)	OTf (**2-OTf**)	**L6**	<1

[a]Conditions: **2** (0.20 mmol), **1** (1.5 equiv), $Pd_2(dba)_3$ (1.0 mol %), ligand (2.0 mol %), and THF (1.0 mL) at 60 °C for 3 h. [b]^1H NMR yield of **3** using 1,1,2,2-tetrachloroethane as an internal standard. [c]The numbers in parentheses indicate isolated yields. [d]The reaction was performed at 80 °C. pin = pinacolato. dba = dibenzylideneacetone.



We investigated the feasibility of the palladium-catalyzed, cross-coupling reaction of **1-ZnX** with aryl (pseudo)halides. The reaction of 4-bromoanisole (**2-Br**) and **1-ZnBr** in the presence of 1.0 mol % of $Pd_2(dba)_3$ and 2.0 mol % of PPh_3 (**L1**) in THF at 60 °C afforded the desired benzylic 1,1-diboronate ester **3** in 53% yield (Table 1, entry 1). Notably, the reaction proceeded with excellent chemoselectivity, and both boron moieties remained intact after the transformation. When the reaction was conducted using P(*p*-tolyl)$_3$ (**L2**) as a ligand instead of **L1**, a slightly higher yield of **3** was obtained (entry 2); when **L1** was replaced by P(*p*-$CF_3C_6H_4$)$_3$ (**L3**), the yield of the reaction decreased (entry 3). An almost quantitative yield of **3** was obtained when P(*o*-tolyl)$_3$ (**L4**) was used as a ligand (entry 4). The use of tricyclohexylphosphine (**L5**) as a ligand also afforded product **3**, albeit with a diminished yield (entry 5). The use of dicyclohexylphosphino-2′,4′,6′-triisopropyl biphenyl (X-Phos, **L6**) as a ligand was also proved facile in the reaction, leading to the formation of **3** in a high yield (entry 6). Lowering the reaction temperature from 60 °C to room temperature gave a poor yield of **3** (entry 7). The use of **1-ZnCl** (entry 8) as a coupling reagent produced a similar yield as the reaction with **1-ZnBr**, while **1-ZnI** deteriorated the reaction efficiency (entry 9). Solvent screening showed that THF was the most effective solvent for the coupling process.[11] We found that 4-iodoanisole was proved to be a competent substrate for the coupling with **1-ZnBr** (entry 10), whereas 4-chloroanisole (entry 11) and 4-methoxyphenyl triflate (**2-OTf**) (entry 12) did not provide the product **3** in the presence of **L4** as a ligand. Considering that various compounds of pharmaceutical interest contain a phenol moiety and that can be easily converted to organotriflates, we tried to optimize the reaction further by employing **2-OTf** as an electrophile. The results from optimization experiments indicated that the reaction of **2-OTf** with **1-ZnX** was very sensitive to the identity of the added ligand. When **L4** was replaced by **L6**, the corresponding 1,1-diboronate ester **3** was obtained in a good yield (entry 13). By performing the reaction at an elevated temperature (80 °C), the yield of **3** was improved (entry 14), and the highest yield was obtained when **1-ZnCl** was used (entry 15) as a coupling reagent. No reaction with either **2-Br** or **2-OTf** (entries 16 and 17) occurred when **1-Li** was utilized instead of **1-ZnBr** or **1-ZnCl** under the standard coupling conditions. These results indicated that the generation of **1-ZnX** is the key to the success of the desired transformation.

With the optimal conditions in hand, the scope of aryl (pseudo)halides as substrates was examined (Scheme 2). Aryl bromides with electron-donating substituents (**3**, **4**, **5**, and **6**), an electron-neutral substituent (**7**), and an electron-withdrawing substituent (**8**) in the C4 position of the arene ring afforded the corresponding benzylic 1,1-diboronate esters in good yields. Note that product **6** was isolated by recrystallization using *n*-hexane under a N_2 atmosphere because **6** easily underwent oxidation or decomposition after exposure to air. Intriguingly, the coupling process developed is compatible with a wide range of functional groups. Aryl bromides bearing halides (**9** and **10**), a silyl-protected phenol (**11**), an ester (**12**), a nitrile (**13**), an acetyl-protected amine (**14**), and a Bpin (pin = pinacolato) group (**16**) provided the desired products in good-to-moderate yields, although **13** required use of **L6** as a ligand for the full conversion. Intriguingly, when 4-bromophenyltriflate was treated with **1-ZnBr** in the presence of 1.0 mol % $Pd_2(dba)_3$ and 2.0 mol % **L4** at 60 °C in THF, the bromo group reacted preferentially and yielded the triflate-containing benzylic 1,1-diboronate ester **15** in good yield. On the contrary, the use of **L6** as a ligand instead of **L4** resulted in poor chemoselectivity; the reaction provided in this case is a mixture of mono- and dicoupled products.[11] These results reveal that the chemoselectivity of coupling reactions involving di(pseudo)halogenated arenes as substrates could be controlled by the choice of ligand.[1] Coupling reactions involving aryl bromides with substituents in *meta*- and *ortho*-positions proceeded smoothly, thus providing the corresponding products **16**, **17**, and **18** in excellent yields. 2-Bromonaphthalene also participated in the coupling process, resulting in the formation of **19** in high yield. In addition to aryl bromides, various aryl triflates smoothly reacted with **1-ZnCl** in the presence of 1.0 mol % of $Pd_2(dba)_3$ and 2.0 mol % of X-Phos in THF at 80 °C to produce the corresponding benzylic 1,1-diboronate esters in good-to-excellent yields, which were comparable with those of reactions involving aryl bromides (**3**−**5**, **7**−**13**, and **17**−**19**).

Thereafter, we investigated the scope of heteroaryl bromides as substrates. The reactions of electron-rich *N*-heteroaryl bromides, such as 3-bromothiophene, 3-bromofuran, 5-bromo-*N*-Ts-indole, 2-bromobenzothiophene, 3-bromo-9-ethyl-carbazole, and 4-bromodibenzofuran, with **1-ZnBr** delivered the

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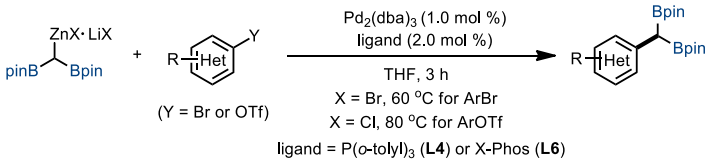
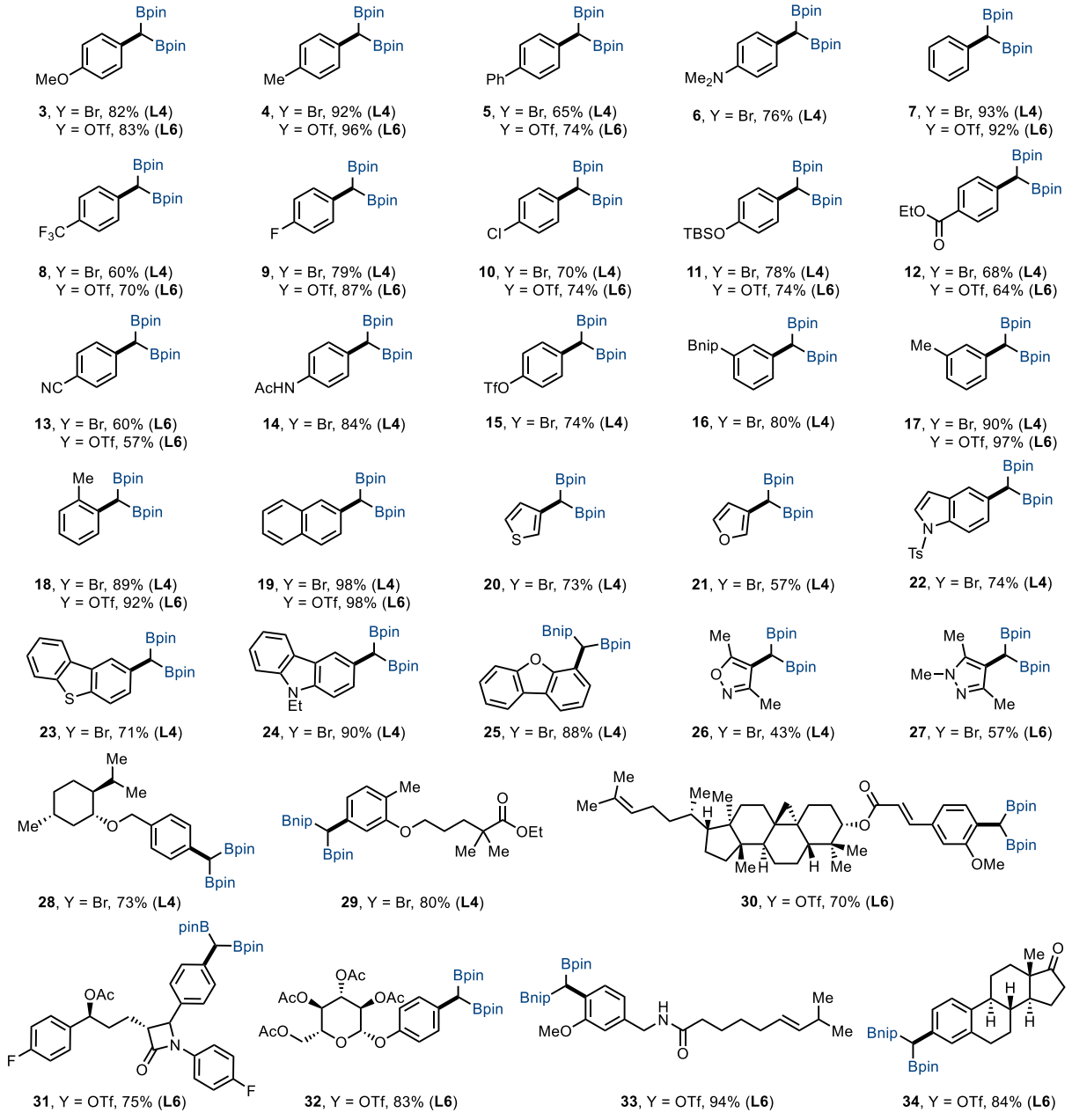
Scheme 2. Substrate Scope of (Hetero)Aryl Electrophiles in the Palladium-Catalyzed Coupling with 1-ZnX[a]





[a]Conditions A: aryl bromide (0.20 mmol), **1-ZnBr** (1.5 equiv), $Pd_2(dba)_3$ (1.0 mol %), **L4** (2.0 mol %), THF (1.0 mL) at 60 °C for 3 h. Conditions B: aryl triflate (0.20 mmol), **1-ZnCl** (1.5 equiv), $Pd_2(dba)_3$ (1.0 mol %), **L6** (2.0 mol %), THF (1.0 mL) at 80 °C for 3 h. In all cases, isolated yields were indicated.

corresponding benzylic 1,1-diboronate esters (**20**–**25**) in moderate-to-good yields under $Pd_2(dba)_3$/**L4** catalytic conditions. We found that 3-bromoisooxazole and 4-bromo-1,3,5-trimethyl-pyrazole were also suitable electrophiles for the coupling reaction and afforded **26** and **27** in synthetically acceptable yields. Although several examples of the synthesis of benzylic 1,1-diboronate esters have been reported that proceed via the transition-metal-catalyzed C–H activation of methyl arenes[9f,12] or carbon insertion of diazo compounds into B_2pin_2,[13] these strategies showed a limited scope, particularly in the case of heteroaryl substrates. Therefore, the developed procedure provides a convenient and complementary synthetic route that enables heteroaryl containing benzylic 1,1-diboronate esters to be obtained.

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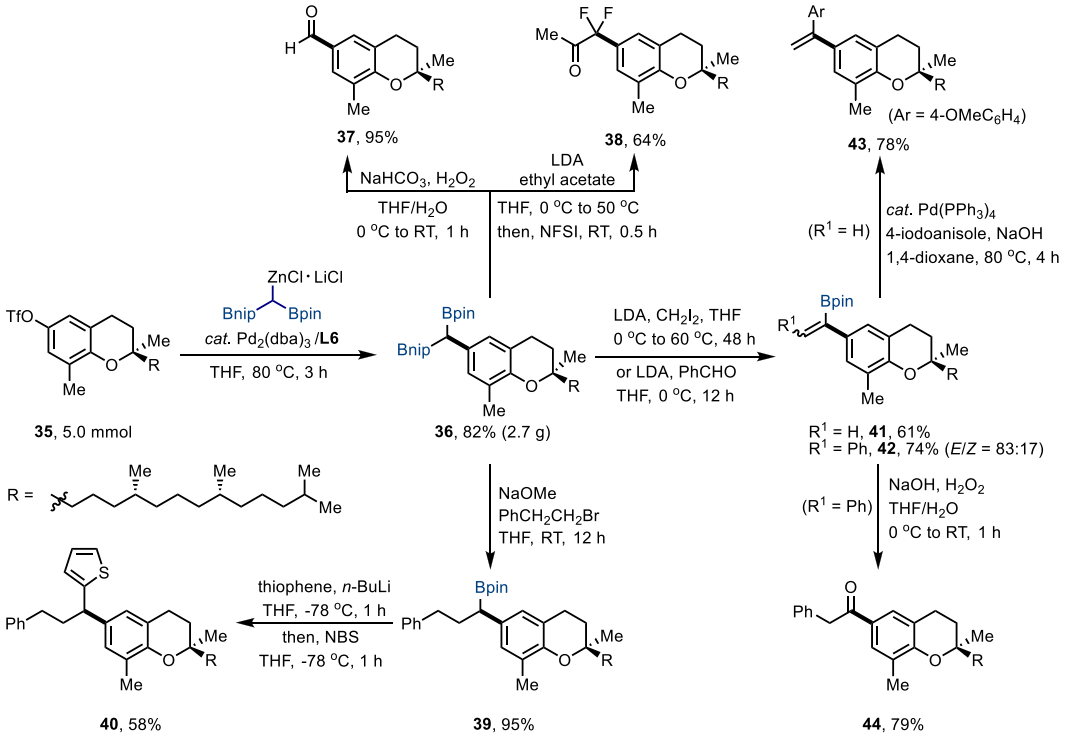
Scheme 3. Scale-up Reaction and the Late-Stage Sequential Functionalization of δ-Tocopherol



Next, we attempted the coupling of **1-ZnBr** or **1-ZnCl** with various compounds of pharmaceutical relevance. To our delight, (−)-menthol and lopid derivatives bearing a bromide on the arene ring readily underwent coupling with **1-ZnBr** in the presence of 1.0 mol % of $Pd_2(dba)_3$ and 2.0 mol % of **L4** in THF at 60 °C, affording the corresponding 1,1-diboronate esters **28** and **29** in good yields. Aryl triflates derived from γ-oryzanol, ezetimibe, arbutin, capsaicin, and estrone were also amenable to the coupling reaction with **1-ZnCl** under $Pd_2(dba)_3$/**L6** catalytic conditions in THF at 80 °C, leading to the formation of **30**−**34** in good-to-excellent yields.

To demonstrate the practicability of the developed process, we conducted the coupling reaction on a gram scale (Scheme 3). The palladium-catalyzed coupling reaction of δ-tocopherol-derived triflate (**35**, 5.0 mmol) with **1-ZnBr** under the standard reaction conditions afforded the corresponding 1,1-diboronate ester **36** with a yield of 82% (2.7 g). Because the benzylic 1,1-diboronate ester could serve as a valuable synthetic intermediate for further manipulations, we immediately tried to convert **36** to various functionalized molecules. The oxidation of the diboron groups of **36** in the presence of H_2O_2 and $NaHCO_3$ in THF afforded the corresponding aldehyde **37**, which could be used as a valuable synthon in various organic transformations. After the generation of the diboryllithium species via the treatment of **36** with lithium diisopropylamide (LDA) in THF at 0 °C, the reaction with ethyl acetate at 50 °C generated an α-boron enolate, which could be readily trapped by *N*-fluorobenzenesulfonimide (NFSI) to benzylic 1,1-difluorinated ketone **38**.[14] In addition, we could achieve the deborylative alkylation of **36** with (3-bromopropyl)benzene in the presence of NaOMe, giving the corresponding benzylic boronate ester **39** in excellent yield.[15] The reaction of **39** with C2-lithiated thiophene and subsequent quenching of the reaction with *N*-bromosuccinimide resulted in the formation of **40** in moderate yield.[16] The boron-Wittig type reaction between the *in situ* generated diboryllithium species of **36** and CH_2I_2 at 60 °C provided the internal alkenyl boronate ester **41**.[17c] Compound **41** could be converted to the 1,1-diarylated alkene **43** via palladium-catalyzed cross-coupling with 4-iodoanisole. An analogous boron-Wittig reaction between **36** and benzaldehyde gave the alkenyl boronate ester **42** in good yield and 83:17 *E*/*Z* selectivity.[12a,17] Alkenyl boronate ester **42** transformed to the corresponding ketone **44** by oxidation with NaOH and H_2O_2. We believe that these late-stage modifications of 1,1-diboron groups would provide efficient and streamlined routes for the synthesis of various pharmaceutical libraries.

In conclusion, we have developed the palladium-catalyzed cross-coupling reaction of bis[(pinacolato)boryl]methylzinc halides with aryl (pseudo)halides, which offers a unique platform for the modular, late-stage functionalization of pharmaceutical analogues. The reaction leads to the synthesis of a broad range of benzylic 1,1-diboronate esters, which are easy-to-handle intermediates for further transformations, with excellent functional-group tolerance. Furthermore, the reaction is suitable for gram-scale synthesis, and pharmaceutically interesting compounds can be used as substrates for it. We also demonstrate the late-stage functionalization of the diboron groups of the coupling products, thus offering a powerful method for the divergent synthesis of pharmaceutical analogues. Further efforts are underway in our laboratory to utilize bis[(pinacolato)boryl]methyl metallic species in other metal-catalyzed transformations, and the relevant developments of this research efforts will be reported in due course.

■ ASSOCIATED CONTENT

Supporting Information

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Experimental procedures, characterization of all new compounds (PDF)

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) For selected reviews, see: (a) Negishi, E.-i. *Angew. Chem., Int. Ed.* **2011**, *50*, 6738. (b) Suzuki, A. *Angew. Chem., Int. Ed.* **2011**, *50*, 6722. (c) Johansson Seechurn, C. C. C.; Kitching, M. O.; Colacot, T. J.; Snieckus, V. *Angew. Chem., Int. Ed.* **2012**, *51*, 5062. (d) Sore, H. F.; Galloway, W. R. J. D.; Spring, D. R. *Chem. Soc. Rev.* **2012**, *41*, 1845. (e) Molander, G. A. *J. Org. Chem.* **2015**, *80*, 7837. (f) Haas, D.; Hammann, J. M.; Greiner, R.; Knochel, P. Recent Developments in Negishi Cross-Coupling Reactions. *ACS Catal.* **2016**, *6*, 1540.

(2) (a) Tobisu, M.; Chatani, N. *Angew. Chem., Int. Ed.* **2009**, *48*, 3565. (b) Wang, C.; Glorius, F. *Angew. Chem., Int. Ed.* **2009**, *48*, 5240. (c) Lennox, A. J. J.; Lloyd-Jones, G. C. *Chem. Soc. Rev.* **2014**, *43*, 412. (d) Li, J.; Grillo, A. S.; Burke, M. D. *Acc. Chem. Res.* **2015**, *48*, 2297. (e) Nambo, M.; Crudden, C. M. *ACS Catal.* **2015**, *5*, 4734. (f) Xu, L.; Zhang, S.; Li, P. *Chem. Soc. Rev.* **2015**, *44*, 8848.

(3) (a) Littke, A. F.; Dai, C.; Fu, G. C. *J. Am. Chem. Soc.* **2000**, *122*, 4020. (b) Guan, B.-T.; Wang, Y.; Li, B.-J.; Yu, D.-G.; Shi, Z.-J. *J. Am. Chem. Soc.* **2008**, *130*, 14468. (c) Tobisu, M.; Shimasaki, T.; Chatani, N. *Angew. Chem., Int. Ed.* **2008**, *47*, 4866. (d) Malhotra, S.; Seng, P. S.; Koenig, S. G.; Deese, A. J.; Ford, K. A. *Org. Lett.* **2013**, *15*, 3698. (e) Seath, C. P.; Fyfe, J. W. B.; Molloy, J. J.; Watson, A. J. B. *Angew. Chem., Int. Ed.* **2015**, *54*, 9976. (f) Steib, A. K.; Kuzmina, O. M.; Fernandez, S.; Malhotra, S.; Knochel, P. *Chem. - Eur. J.* **2015**, *21*, 1961. (g) Jiang, X.; Kulbitski, K.; Nisnevich, G.; Gandelman, M. *Chem. Sci.* **2016**, *7*, 2762. (h) Fyfe, J. W. B.; Fazakerley, N. J.; Watson, A. J. B. *Angew. Chem., Int. Ed.* **2017**, *56*, 1249. (i) Kalvet, I.; Magnin, G.; Schoenebeck, F. *Angew. Chem., Int. Ed.* **2017**, *56*, 1581. (j) Yadav, M. R.; Nagaoka, M.; Kashihara, M.; Zhong, R.-L.; Miyazaki, T.; Sakaki, S.; Nakao, Y. *J. Am. Chem. Soc.* **2017**, *139*, 9423. (k) Keaveney, S. T.; Kundu, G.; Schoenebeck, F. *Angew. Chem., Int. Ed.* **2018**, *57*, 12573.

(4) (a) Gillis, E. P.; Burke, M. D. *J. Am. Chem. Soc.* **2007**, *129*, 6716. (b) Nakao, Y.; Chen, J.; Tanaka, M.; Hiyama, T. *J. Am. Chem. Soc.* **2007**, *129*, 11694. (c) Noguchi, H.; Hojo, K.; Suginome, M. *J. Am. Chem. Soc.* **2007**, *129*, 758. (d) Gillis, E. P.; Burke, M. D. *J. Am. Chem. Soc.* **2008**, *130*, 14084. (e) Yamashita, Y.; Tellis, J. C.; Molander, G. A. *Proc. Natl. Acad. Sci. U. S. A.* **2015**, *112*, 12026. (f) Schmidt, J.; Choi, J.; Liu, A. T.; Slusarczyk, M.; Fu, G. C. *Science* **2016**, *354*, 1265. (g) Sun, S.-Z.; Börjesson, M.; Martin-Montero, R.; Martin, R. *J. Am. Chem. Soc.* **2018**, *140*, 12765.

(5) (a) Marek, I.; Normant, J.-F. *Chem. Rev.* **1996**, *96*, 3241. (b) Knochel, P.; Normant, J. F. *Tetrahedron Lett.* **1986**, *27*, 4427. (c) Marek, I.; Schreiner, P. R.; Normant, J. F. *Org. Lett.* **1999**, *1*, 929. (d) Shimizu, M.; Kitagawa, H.; Kurahashi, T.; Hiyama, T. *Angew. Chem., Int. Ed.* **2001**, *40*, 4283. (e) Carosi, L.; Lachance, H.; Hall, D. G. *Tetrahedron Lett.* **2005**, *46*, 8981. (f) Shimizu, M.; Nakamaki, C.; Shimono, K.; Schelper, M.; Kurahashi, T.; Hiyama, T. *J. Am. Chem. Soc.* **2005**, *127*, 12506. (g) Molander, G. A.; Sandrock, D. L. *J. Am. Chem. Soc.* **2008**, *130*, 15792. (h) Lee, J. C. H.; McDonald, R.; Hall, D. G. *Nat. Chem.* **2011**, *3*, 894. (i) Chen, M.; Roush, W. R. *Org. Lett.* **2013**, *15*, 1662. (j) Feng, X.; Jeon, H.; Yun, J. *Angew. Chem., Int. Ed.* **2013**, *52*, 3989. (k) Mlynarski, S. N.; Schuster, C. H.; Morken, J. P. *Nature* **2014**, *505*, 386. (l) Xu, L.; Ding, S.; Li, P. *Angew. Chem., Int. Ed.* **2014**, *53*, 1822. (m) Crudden, C. M.; Ziebenhaus, C.; Rygus, J. P. G.; Ghozati, K.; Unsworth, P. J.; Nambo, M.; Voth, S.; Hutchinson, M.; Laberge, V. S.; Maekawa, Y.; Imao, D. *Nat. Commun.* **2016**, *7*, 11065. (n) Chu, Z.; Wang, K.; Gao, L.; Song, Z. *Chem. Commun.* **2017**, *53*, 3078. (o) Yamazaki, A.; Nagao, K.; Iwai, T.; Ohmiya, H.; Sawamura, M. *Angew. Chem., Int. Ed.* **2018**, *57*, 3196.

(6) Matsubara, S.; Otake, Y.; Hashimoto, Y.; Utimoto, K. *Chem. Lett.* **1999**, *28*, 747.

(7) (a) Williams, D. R.; Morales-Ramos, Á. I.; Williams, C. M. *Org. Lett.* **2006**, *8*, 4393. (b) Werner, V.; Klatt, T.; Fujii, M.; Markiewicz, J.; Apeloig, Y.; Knochel, P. *Chem. - Eur. J.* **2014**, *20*, 8338. (c) Klatt, T.; Werner, V.; Maximova, M. G.; Didier, D.; Apeloig, Y.; Knochel, P. *Chem. - Eur. J.* **2015**, *21*, 7830.

(8) (a) La Cascia, E.; Cuenca, A. B.; Fernández, E. *Chem. - Eur. J.* **2016**, *22*, 18737. (b) Kim, J.; Cho, S. H. *ACS Catal.* **2019**, *9*, 230.

(9) (a) Castle, R. B.; Matteson, D. S. *J. Organomet. Chem.* **1969**, *20*, 19. (b) Matteson, D. S. *Synthesis* **1975**, *1975*, 147. (c) Nguyen, P.; Coapes, R. B.; Woodward, A. D.; Taylor, N. J.; Burke, J. M.; Howard, J. A. K.; Marder, T. B. *J. Organomet. Chem.* **2002**, *652*, 77. (d) Mita, T.; Ikeda, Y.; Michigami, K.; Sato, Y. *Chem. Commun.* **2013**, *49*, 5601. (e) Zhang, L.; Huang, Z. *J. Am. Chem. Soc.* **2015**, *137*, 15600. (f) Palmer, W. N.; Obligacion, J. V.; Pappas, I.; Chirik, P. J. *J. Am. Chem. Soc.* **2016**, *138*, 766. (g) Palmer, W. N.; Zarate, C.; Chirik, P. J. *J. Am. Chem. Soc.* **2017**, *139*, 2589. (h) Hu, J.; Zhao, Y.; Shi, Z. *Nat. Catal.* **2018**, *1*, 860.

(10) Lee, Y.; Park, J.; Cho, S. H. *Angew. Chem., Int. Ed.* **2018**, *57*, 12930.

(11) See the Supporting Information for details.

(12) (a) Cho, S. H.; Hartwig, J. F. *Chem. Sci.* **2014**, *5*, 694. (b) Palmer, W. N.; Obligacion, J. V.; Pappas, I.; Chirik, P. J. *J. Am. Chem. Soc.* **2016**, *138*, 766.

(13) (a) Abu Ali, H.; Goldberg, I.; Kaufmann, D.; Burmeister, C.; Srebnik, M. *Organometallics* **2002**, *21*, 1870. (b) Li, H.; Shangguan, X.; Zhang, Z.; Huang, S.; Zhang, Y.; Wang, J. *Org. Lett.* **2014**, *16*, 448. (c) Wommack, A. J.; Kingsbury, J. S. *Tetrahedron Lett.* **2014**, *55*, 3163. (d) Zhao, H.; Tong, M.; Wang, H.; Xu, S. *Org. Biomol. Chem.* **2017**, *15*, 3418.

(14) Iacono, C. E.; Stephens, T. C.; Rajan, T. S.; Pattison, G. *J. Am. Chem. Soc.* **2018**, *140*, 2036.

(15) Hong, K.; Liu, X.; Morken, J. P. *J. Am. Chem. Soc.* **2014**, *136*, 10581.

(16) Bonet, A.; Odachowski, M.; Leonori, D.; Essafi, S.; Aggarwal, V. K. *Nat. Chem.* **2014**, *6*, 584.

(17) (a) Endo, K.; Hirokami, M.; Shibata, T. *J. Org. Chem.* **2010**, *75*, 3469. (b) Endo, K.; Sakamoto, A.; Ohkubo, T.; Shibata, T. *Chem. Lett.* **2011**, *40*, 1440. (c) Coombs, J. R.; Zhang, L.; Morken, J. P. *Org. Lett.* **2015**, *17*, 1708. (d) Stephens, T. C.; Pattison, G. *Org. Lett.* **2017**, *19*, 3498.

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