C–C Coupling

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Radical-Mediated Alkenylation, Alkynylation, Methanimination, and Cyanation of *B*-Alkylcatecholboranes**

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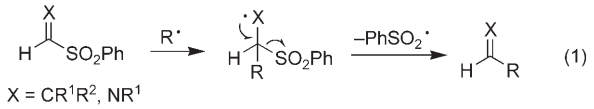
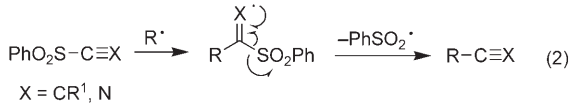
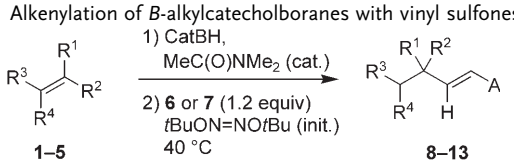
Organoboranes are very valuable synthetic intermediates that are used in numerous synthetic processes.[1–6] For example, the Suzuki–Miyaura reaction continually proves to be one of the most efficient methods for the formation of carbon–carbon bonds through cross-coupling reactions between organoboron derivatives and organic electrophiles.[7–9] From the earliest investigations by Brown, organoboranes have been identified as a source of radicals.[10–12] Recently, we have become interested in developing novel synthetic methods based on the use of organoboranes, and more particularly of *B*-alkylcatecholborane, as a source of radicals.[12–14] For example, we reported an efficient allylation procedure based on the use of readily available allyl sulfones.[15–18] Herein, we report alkenylations, acylations, cyanations, and alkynylations of alkylcatecholboranes, mediated by free-radicals. All of these reactions are based on a common process: radical addition to the carbon atom of a multiple (double or triple) bond bearing an arene sulfonyl group [Eqs. (1) and (2)].[19]

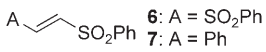


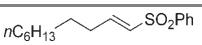
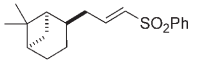
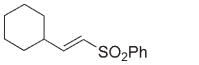
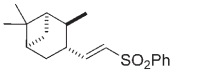
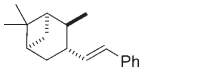
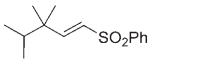


Russell et al.,[20,21] Ono et al.,[22] and others[23] have demonstrated the feasibility of radical alkenylation reactions.[24–27] Secondary and tertiary alkyl radicals, generated either by hydrogen atom abstraction as reported by Fuchs and co-workers[28,29] or from iodides and xanthates as reported by Zard and co-workers,[30] were alkenylated through α addition to vinyl sulfones. Intramolecular reactions involving sulfoxides, sulfoximines, and phosphine oxides have also been reported.[31–33] Interestingly, Nozaki and co-workers[34] reported the vinylation of trialkylboranes with styryl sulfoxides and sulfones. The mechanism proposed at that time involves the formation of vinyl radicals. More recently, Yao and co-workers[35,36] reported the alkenylation of trialkylboranes with β-nitrostyrene, but this nonchain reaction requires the use of a threefold excess of the trialkylborane. Therefore, we decided to investigate the reaction of *B*-alkylcatecholboranes with alkenyl sulfones. Hydroboration of the alkenes such as 1-octene (**1**, Table 1, entry 1), β-pinene (**2**, entry 2), cyclohexene (**3**, entry 3), α-pinene (**4**, entries 4 and 5), and tetramethylethylene (**5**, entry 6) with catecholborane was achieved by taking advantage of the very mild, efficient, and cost-effective hydroboration conditions developed by Garett and Fu[37] in which *N*,*N*-dimethylacetamide (10 mol%) was used as a catalyst in refluxing dichloromethane. In situ treatment of the *B*-alkylcatecholborane with vinyl sulfone **6** or **7** (1.2–3 equivalents) in the presence of di-*tert*-butylhyponitrite (3 mol%) as the initiator, afforded the expected alkenylated products **8**–**13** in reasonable yields (Table 1, entries 1–6). The bissulfone **6** proved to be a convenient reagent for the vinylation reaction and afforded alkenyl sulfones that are interesting starting materials for further functionalization.[38] Furthermore, the product resulting from the bissubstitution of the two sulfonyl groups was not detected. The use of phenyl 2-phenylvinyl sulfone (**7**) allows the introduction of a styryl group (Table 1, entry 5).

Table 1: Alkenylation of *B*-alkylcatecholboranes with vinyl sulfones.





Entry		Alkene	Sulfone		Product	Yield [%]
1	**1**		**6**	**8**		55
2	**2**		**6**	**9**		58
3	**3**		**6**	**10**		72
4	**4**		**6**	**11**		64
5	**4**		**7**	**12**		66[a]
6	**5**		**6**	**13**		60

[a] Using 3 equiv of **7**. CatBH = Catecholborane.

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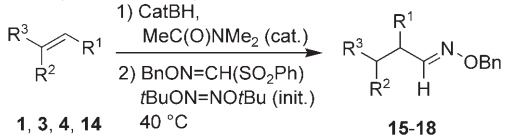
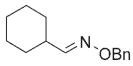
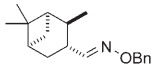
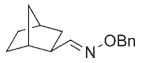
Supporting information for this article (experimental procedures and characterizations of compounds **3**–**8**, **15**–**18**, and **22**–**27**) is available on the WWW under http://www.angewandte.org or from the author.

An acylation protocol was then tested using *N*-benzyloxy-1-(phenylsulfonyl)methanimine, as reported by Kim and co-workers.[39] Primary (Table 2, entry 1) and secondary alkyl radicals (Table 2, entries 2–4) react well to afford the stable oxime ethers. This transformation corresponds formally to a formylation of the *B*-alkylcatecholborane.

Table 2: Formylation of *B*-alkylcatecholboranes.



Entry	Alkene		Product		Yield [%]
1	**1**		**15**		73
2	**3**		**16**		74
3	**4**		**17**		74
4	**14**		**18**		53

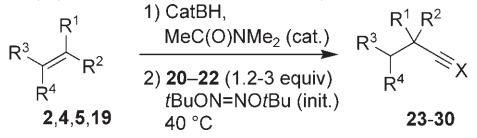
Bn = benzyl.

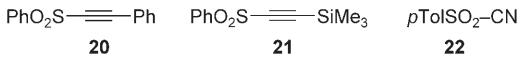
The reaction with alkynyl sulfones was investigated next. Following the seminal work of Russell and co-workers[20,21,40] as well as of Fuchs and co-workers,[28,41] we decided to investigate the alkynylation process (Table 3). This reaction is particularly interesting because, to the best of our knowledge, no palladium-catalyzed cross-coupling between alkylboranes and acetylene derivatives has been reported.[42,43] The reaction with phenyl phenylethynyl sulfone (**20**)[44] proved to be efficient with primary to tertiary alkyl radicals (Table 3, entries 1, 2, and 4). Interestingly, similar results were obtained with the phenyl trimethylsilylethynyl sulfone (**21**, Table 3, entry 3).[24] This result is best explained by the steric interaction of the Me_3Si group that favors an addition at the α-position to the sulfonyl group. The trimethylsilylacetylene derivative **25**, obtained in 72% yield, undergoes a facile desilylation[43] through treatment with aqueous sodium hydroxide to afford the desired terminal alkyne **26** in near quantitative yield.[45]

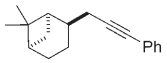
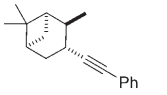
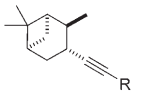
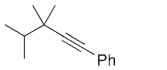
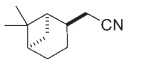
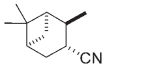
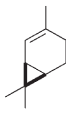
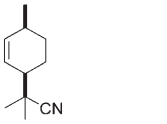
Finally, a related cyanation process was attempted using the commercially available *p*-toluenesulfonyl cyanide (**22**, Table 3).[46–48] Good yields were obtained with primary and secondary radicals (Table 3, entries 5 and 6). Reaction with (+)-carene (**19**) afforded monocyclic cyanide **30**, which results from the isomerization of the cyclopropylmethyl radical to a homoallyl radical. The cyanation of organoboranes also has no precedent in the literature, to the best of our knowledge.

We demonstrate here that hydroboration with commercially available catecholborane, followed by treatment with easily available reagents such as alkenyl or alkynyl phenyl sulfones in the presence of a radical initiator (di-*tert*-butylhyponitrite or oxygen), represents an effective and simple one-pot procedure for performing direct vinylation, formylation, alkynylation, and cyanation of *B*-alkylcatecholboranes. These radical transformations of alkylboranes represent powerful reactions that should find applications in the total syntheses of natural products. Furthermore, these transformations demonstrate the generality of the use of organoboranes for the generation of primary, secondary, and tertiary alkyl radicals. The use of nontoxic *B*-alkylcatecholboranes, which are easily prepared from alkenes and may contain additional functionality,[13,49] in addition to the mild reaction conditions, make this metal-free procedure very attractive for the formation of C–C bonds.

Table 3: Alkynylation and cyanation of *B*-alkylcatecholboranes.





Entry	Alkene		Sulfone	Product		Yield [%]
1	**2**		**20**	**23**		89[a]
2	**4**		**20**	**24**		84[b]
3	**4**		**21**	**25** (R = $SiMe_3$) **26** (R = H)[43]		72[b] 72[c]
4	**5**		**20**	**27**		83
5	**2**		**22**	**28**		75[a]
6	**4**		**22**	**29**		88[b]
7	**19**		**22**	**30**		90

[a] Diastereomeric ratio ≥97:3. [b] Diastereomeric ratio ≥95:5. [c] After treatment of the crude cyanide **25** with aqueous NaOH. Tol = tolyl.

Experimental Section

General procedure: Catecholborane (0.468 mL, 4.4 mmol) was added dropwise at 0 °C to a solution of olefin (2.0 mmol) and *N*,*N*-dimethylacetamide (0.019 mL, 0.20 mmol) in CH_2Cl_2 (2 mL) under nitrogen. The reaction mixture was heated to reflux for 5 h. *t*BuOH (0.234 mL, 2.5 mmol) was added at 0 °C and the solution was stirred for 15 min at RT. The sulfone (6 mmol) was then added and the solution was warmed to reflux and di-*tert*-butylhyponitrite (3 mol%) was added every 1 h. The reaction was monitored by GC-MS. By the end of the reaction, the solution had turned black. The crude product was purified by flash chromatography over silica gel.

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