

stabilities, the nucleobases close to the 3'-ends have to be taken into account. Biological phenomena that concern the accuracy of ribosomal translation should, particularly, be newly analysed in terms of their codon context. In this sense, we are extending the current studies towards a systematic comparison of coded and recoded codon-anticodon complexes encountered during ribosomal tRNA slippage, in order to reveal differences in the base-stacking patterns as a determinant for frameshift events.^[15]

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A Convenient and General Tin-Free Procedure for Radical Conjugate Addition**

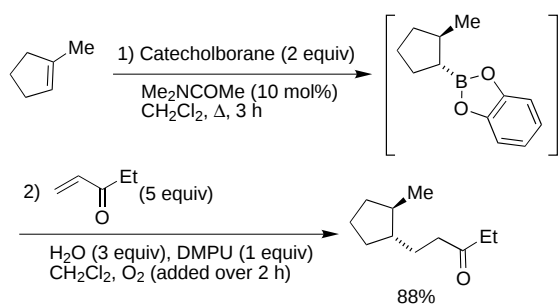
Cyril Ollivier and Philippe Renaud*

Radical reactions are becoming an extremely useful tool in organic synthesis, particularly for the formation of carbon-carbon bonds in intra- and intermolecular processes.^[1] The very rapid development of these reactions could be attributed to the emergence of highly efficient ways to conduct them. Among these methods, the tin hydride mediated addition of radicals to activated alkenes has played a major role.^[2] However, the application of this reaction for the synthesis of pharmaceuticals is severely limited by the toxicity of the tin reagents and by the difficulty in removing traces of organotin residues from the final products. Therefore, alternative ways of running radical reactions are under intensive investigation.^[3] Recently, we have reported a modified version of the Brown-Negishi reaction^[4] where efficient hydroborations with catecholborane and radical additions to enones and enals were performed in a one-pot procedure (Scheme 1).^[5a] This oxygen-initiated reaction proved to be efficient with enones and enals. However, other classical radical traps such as unsaturated esters, amides, and sulfones failed to react. Herein, we present an efficient procedure to run one-pot hydroboration for radical addition to any kind of activated alkenes. The reaction is based on the use of a Barton carbonate as radical chain transfer reagent (RCTR).^[6]

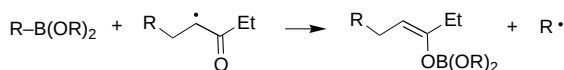
The failure of our modified version of the Brown-Negishi reaction with classical radical traps such as acrylate moieties was interpreted as a consequence of an inefficient propagation step resulting from the reaction between the radical adducts and *B*-alkylcatecholboranes. This inefficiency is caused by the lower density of unpaired electrons at the

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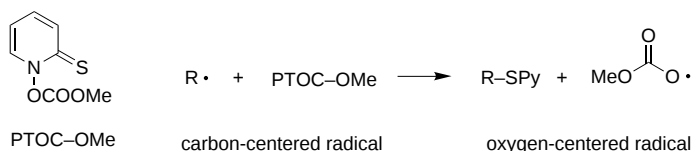


Propagation step:



Scheme 1. Modified Brown–Negishi reaction involving *B*-alkylcatecholboranes.^[5a]

oxygenatom of these radicals relative to ketone–enolate and aldehyde–enolate radicals.^[7, 8] Based on this assumption, we thought that, for radical traps other than enones and enals, the use of a chain transfer reagent able to convert the carbon-centered radical adduct into an oxygen-centered radical was necessary. The Barton carbonate PTOC-OMe (PTOC = pyridine-2-thione-*N*-oxycarbonyl),^[9] easily prepared by reacting the commercially available sodium salt of *N*-hydroxypyridine-2-thione and methyl chloroformate, should possess the necessary reactivity to act as RCTR (Scheme 2). The yellow solution of the Barton carbonate PTOC-OMe is stable in the dark and is expected to furnish, upon irradiation with a standard lamp, the methoxycarbonyloxyl radical (MeO-COO•). Decarboxylation of this radical to afford the methoxyl radical cannot be excluded; however, this process is known to be slow.^[10]



Scheme 2. The radical chain transfer reagent (RCTR) PTOC-OMe converts a carbon-centered into an oxygen-centered radical.

In a preliminary study, we have checked that the methoxycarbonyloxyl radical, generated by the simple irradiation of PTOC-OMe with a 150 W tungsten lamp, was able to react with *B*-alkylcatecholborane and to propagate efficiently the chain reaction. A one-pot procedure starting from the alkene was examined [Eq. (1)]. After hydroboration with catecholborane,^[11] the in situ generated alkylborane was treated with three equivalents of PTOC-OMe and the solution was irradiated with a standard 150 W lamp for 12 h at 10 °C; the results are summarized in Table 1. Under these conditions,

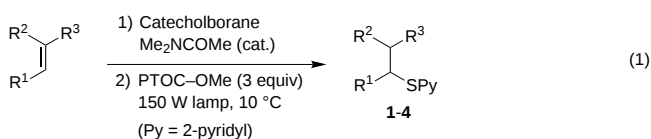


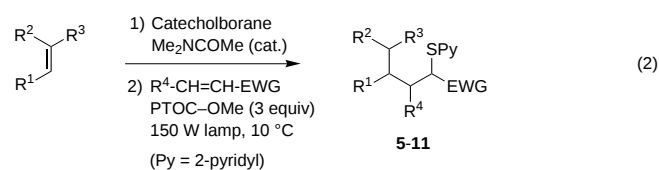
Table 1. Preparation of sulfur-containing derivatives by the hydroboration procedure shown by Equation 1.

Entry	Alkene	Product	Yield ^[a] [%]	Stereoselectivity
1			74 (50 ^[b])	
2			62	d.r. = 82:18 ^[c]
3			75	d.r. = 90:10 ^[c]
4			52	

[a] All reactions used 3 mmol of the olefin. [b] Using 1 equiv of PTOC-OMe. [c] Only major isomer is shown.

sulfur-containing derivatives were easily prepared from primary and secondary alkyl radicals in 62 % to 75 % yield (Table 1, entries 1–3). Use of only one equivalent of PTOC-OMe led to a decrease of the yield (Table 1, entry 1); however, the cyclohexyl 2-pyridyl sulfide **1** was still isolated in 50 % yield proving that the propagation step of the reaction is quite effective. The radical nature of the reaction was proved by the reaction with 2-carene, which gave the cyclohexene derivative **4** resulting from the ring opening of the intermediate cyclopropylmethyl radical (Table 1, entry 4).

Based on these encouraging results, a similar reaction procedure involving hydroboration with catecholborane, irradiation in the presence of five equivalents of an activated alkene as radical trap, and three equivalents of PTOC-OMe as mediator was examined [Eq. (2)]. Despite the greater complexity of this reaction sequence relative to the reaction depicted in Equation 1, we were pleased to notice that the yields were similar, and in several cases even higher, than in the absence of radical traps (Table 2).



In the first set of experiments, hydroboration of cyclohexene followed by reaction with different radical traps such as methyl acrylate, dimethyl fumarate, *N*-phenyl maleimide, or phenyl vinyl sulfone was examined (Table 2, entries 1–4). Yields between 70 % (methyl acrylate) and 94 % (dimethyl fumarate) were obtained. Interestingly, only small amounts of products from the direct reaction of the cyclohexyl radical with PTOC-OMe were observed when using a simple one-pot procedure. Indeed, all reagents are mixed together before irradiation and slow addition of the PTOC-OMe is not required. Similar results were obtained with phenylcyclopentene (Table 2, entry 5). In this case, the *trans* isomer of **9** is formed with a good diastereoselectivity (*trans*:*cis* 97:3). A

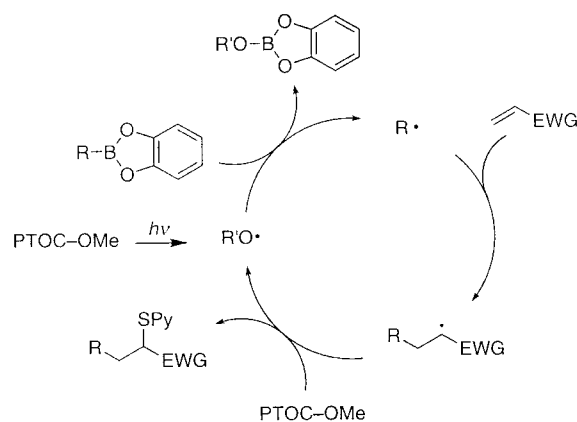
Table 2. Hydroboration and conjugate addition according to Equation 2.

Entry	Alkene	Radical trap	Product	Yield ^[a] [%] (direct addition)	Stereoselectivity
1			5	70 (14)	
2			6	94 (≤ 2)	d.r. 77:23 ^[b]
3			7	81 (≤ 2)	d.r. > 98:2
4			8	75 (15)	
5			9	61 (21)	<i>trans</i> : <i>cis</i> 97:3 ^[c]
6			10	69 (15)	<i>cis</i> : <i>trans</i> 90:10 ^[c]
7			11	66 (≤ 2)	d.r. 53:47

[a] All reactions were run on 3 mmol scale. [b] Relative configuration of the major isomer attributed by analogy to related reactions, see ref. [12]. [c] Mixture (1:1) of isomers relative to the center bearing the *S*-pyridyl group.

primary alkyl radical was also generated from β -pinene and added to methyl acrylate with similar efficiency (Table 2, entry 6). In this example, the *cis/trans* stereochemistry was controlled during the hydroboration step. In entry 7, the first example of cyclization reaction starting from a diene is presented. The interesting chemo- and regioselective hydroboration of the terminal double bond followed by an intramolecular radical addition furnished the cyclopentane **11** in 66% yield. This cyclization procedure starting from a diene is particularly attractive due to the extremely easy preparation of the starting material. Indeed, no reactive radical precursor such as a bromide or an iodide has to be prepared before running the cyclization reaction. As already mentioned, the yields observed in the conjugate additions compare favorably with the simpler processes described in Equation 1. This could be rationalized by taking into account the polar effects in the chain reaction. The general mechanism of the conjugate addition is depicted in Scheme 3.

Irradiation of the PTOC-OMe initiates the reaction by providing a methoxycarbonyloxy or methoxyl radical ($R'O^\bullet$). This radical reacts with the borane to give the nucleophilic alkyl radical $R^\bullet$ that adds to the radical trap. The radical adduct has some electrophilic character due to its substitution by an electron-withdrawing group (EWG) and therefore reacts rapidly with the electron-rich thiocarbonyl group of the PTOC-OMe. This mechanism parallels nicely the tin hydride mediated reaction: The abstraction of a halide atom by the tin radical is replaced by the reaction of an alkoxy radical with a *B*-alkylcatecholborane. The three radicals involved in



Scheme 3. Radical chain mechanism for the conjugate addition of *B*-alkylcatecholboranes to activated olefins (R = alkyl group; EWG = electron withdrawing group; $R'O^\bullet$ = $MeOCO^\bullet$, $MeO^\bullet$).

the chain reaction all possess a different reactivity to allow efficient fulfillment of the selectivity criteria formulated by Giese.^[1a, 2d]

In conclusion, we believe that the present procedure represents a very valuable alternative to the tin hydride mediated reaction for the formation carbon–carbon bonds through a radical process. Good yields of the intermolecular reaction could be achieved in a simple one-pot procedure. Slow addition of the reagents is not necessary when activated radical traps are used. Moreover, the process is nonreductive and furnished products bearing a *S*-pyridyl group that can be

removed or transformed into a variety of functional groups as amply demonstrated by Barton.^[13] Since radical precursors are generated through a hydroboration step, this procedure could take advantage of the chemo- and regioselectivity of the hydroboration and offers a very simple and efficient method for the preparation of highly functionalized systems through inter- and intramolecular radical addition. Applications of this approach to cascade reactions starting from a polyene are currently under investigation. Finally, preparation of optically active materials through enantioselective hydroboration of prochiral alkenes should represent valuable entries into the synthesis of enantiomerically enriched compounds.

Experimental Section

Sulfur inclusion into *B*-Alkylcatecholboranes: Catecholborane (0.64 mL, 6.0 mmol) was added dropwise at 0 °C to a solution of the olefin (3.0 mmol) and *N,N*-dimethylacetamide (28.0 µL, 0.3 mmol) in CH₂Cl₂ (2.0 mL). The mixture was heated under reflux for 3 h. Methanol (0.15 mL, 3.6 mmol) was added at 0 °C and the mixture was stirred for 15 min at room temperature. The CH₂Cl₂ was evaporated under vacuum with strict exclusion of O₂.^[14] A yellow solution of PTOC-OMe (9.0 mmol), freshly prepared by stirring for 1 h in the dark the sodium salt of *N*-hydroxypyridine-2-thione (1.41 g, 9.45 mmol) and methyl chloroformate (0.7 mL, 9.0 mmol) in benzene (15 mL), was added to the *B*-alkylcatecholborane followed by 1,3-dimethyl hexahydro-2-pyrimidone (DMPU; 0.36 mL, 3.0 mmol). The reaction mixture was irradiated at 10 °C with a 150 W tungsten lamp for about 14 h, and treated with 1N NaOH (20 mL). The aqueous layer was extracted with CH₂Cl₂ and the combined organic phases were washed with a saturated NaCl solution (30 mL), dried with MgSO₄, and concentrated in vacuo. The crude product was purified by flash chromatography (hexane/EtOAc).

Conjugate addition: Catecholborane (0.64 mL, 6.0 mmol) was added dropwise at 0 °C to a solution of the olefin (3.0 mmol) and *N,N*-dimethylacetamide (28.0 µL, 0.3 mmol) in CH₂Cl₂ (2.0 mL). The reaction mixture was heated under reflux for 3 h. Methanol (0.15 mL, 3.6 mmol) was added at 0 °C and the mixture was stirred for 15 min at room temperature. A yellow solution of PTOC-OMe (9.0 mmol), freshly prepared as previously described, was added to the *B*-alkylcatecholborane followed by the activated alkene (15 mmol) in benzene (15 mL) and DMPU (0.36 mL, 3.0 mmol). In the case of dimethyl fumarate as the alkene, CH₂Cl₂ (15 mL) was used instead of benzene. The reaction mixture was irradiated at 10 °C with a 150 W tungsten lamp for about 14 h, and treated with 1N NaOH (20 mL). The aqueous layer was extracted with CH₂Cl₂ and the combined organic phases were washed with a saturated NaCl solution (30 mL), dried with MgSO₄, and concentrated in vacuo. The crude product was purified by flash chromatography (hexane/EtOAc).

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“Naked” Phosphorus as a Bent Bridging Ligand**

Peter Kramkowski and Manfred Scheer*

*Dedicated to Professor Dirk Walther
on the occasion of his 60th birthday*

Only a small number of the complexes containing pnico-genido (E^{3−}) ligands of the heavier Group 15 elements (E = P, As, Sb, Bi)^[1] are known in which the ligands display low coordination numbers 1 and 2. Only in 1995 were the first complexes of type **A**,^[6] with terminal ligands and coordination number 1, synthesized and structurally characterized with the compounds [(Ar'RN)₃Mo≡P] (Ar' = 3,5-C₆H₃Me₂, R = C(CD₃)₂CH₃)^[2] and [(N₃N')M≡E] [N₃N' = N(CH₂CH₂NSiMe₃)₃; E = P, M = W, Mo;^[3] E = As, M = W,^[4] Mo^[5]]. We recently found the asymmetric linear coordination mode **B** with coordination number 2 in the complexes [(N₃N')M≡E → ML_m] (ML_m = GaCl₃,^[7] M(CO)₄, M = Cr, W^[5]) and [(RO)₃W≡P → M(CO)₅] (M = Cr, W; R = *t*Bu^[8], Ar (2,6-Me₂C₆H₃)^[9]). Symmetrical linearly bridged complexes of

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