



C–C Coupling

From Alkenylsilanes to Ketones with Air as the Oxidant**

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The Tamao–Kumada–Fleming oxidation is not only a fundamental transformation of organosilicon compounds but also a method of great importance for the synthesis of alcohols.^[1] This oxidation typically exploits hydrogen peroxide as the oxidant. On the other hand, oxidative cleavage of silicon–

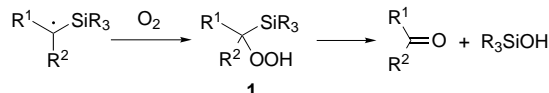
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[**] This work was supported by a Grant-in-Aid for Scientific Research (No. 14703026) from the Ministry of Education, Culture, Sports, Science, and Technology, Japan. We thank Prof. Tamejiro Hiyama for helpful discussions.



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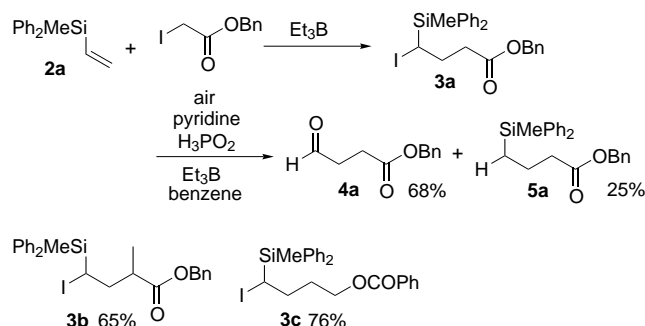
carbon bonds with molecular oxygen has not been well investigated.^[2] We have recently reported a synthesis of acylsilanes through aerobic oxidation of 1,1-disilylalkylcopper compounds.^[3] We then envisaged that a silyl hydroperoxide **1**—generated from a carbon-centered radical and molecular oxygen^[4]—would yield a carbonyl compound (Scheme 1). If this were the case, this oxidation of a Si–C



Scheme 1. Formation of carbonyl compounds from silyl hydroperoxides.

bond could be combined with a variety of radical processes. Herein we wish to report what amounts effectively to the oxidative cleavage of a Si–C bond with air. A tandem radical addition–oxidation sequence which converts alkenylsilanes into ketones is also described.

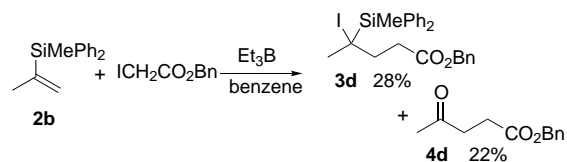
At the outset of this research, we examined the reaction of α -silylalkyl iodides **3** with a radical mediator in air (Scheme 2). The iodide **3a** employed can be easily prepared



Scheme 2. Aldehyde formation from α -iodosilanes.

from vinylsilane **2a** in an iodine-atom-transfer radical reaction.^[5] To a mixture of iodide **3a**, H_3PO_2 ,^[6] and pyridine in benzene, a solution of Et_3B ^[7] (3.0 equiv) in hexane was added in five portions at intervals of 1 h at room temperature. To our delight, aldehyde **4a** was obtained in 68% yield after purification. The use of **3b** or **3c** as the iodide also furnished the corresponding aldehydes in good yields. Phosphinic acid as the radical chain carrier is a crucial component: tris(trimethylsilyl)silane instead of phosphinic acid provided the reduction product **5a** exclusively. The choice of the silyl group in **3** is also important, and the reaction of a trimethylsilyl analog of **3a** provided aldehyde **4a** in only 49% yield along with **5a** in 35% yield.

We next turned our attention toward the synthesis of ketones from alkenylsilanes. In the preparation of the starting alkyl iodide **3d**^[8] through an iodine-atom transfer reaction with 2-silylpropene **2b**, we came across the formation of methyl ketone **4d** as a byproduct (22% yield, Scheme 3). Obviously, ketone **4d** is nothing but the desired product in the



Scheme 3. Formation of a methyl ketone.

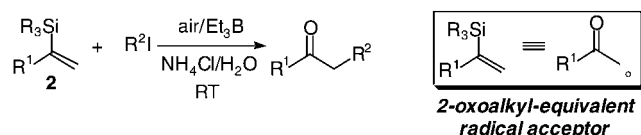
oxidation of **3d** in air. Consequently, we then focused on a tandem radical addition–oxidation reaction with 2-silyl-1-alkenes. The use of an excess amount of triethylborane (2.0 equiv) in air afforded methyl ketone **4d** as the major product. After several experiments, we found that water is an excellent solvent to provide **4d** in 80% yield (see Table 1, entry 1).^[9,10] The addition of ammonium chloride is important as without it, the yield of **4d** lowered to 62%, and vinylsilane **2b** was recovered in 11%.

Table 1 summarizes the results of the tandem radical addition–oxidation reactions of Scheme 4. This process can convert vinylsilanes into α -substituted ketones in one step.^[11]

Table 1: Synthesis of carbonyl compounds according to Scheme 4.^[a]

Entry	R ¹	R ² I	Product	Yield [%]
1	Me (2b)			4d 80
2	Me (2b)			4e 51 ^[b]
3	Ph (2c)			4f 77
4	Ph (2c)			4g 74
5	Ph (2c)			4h 60
6	Ph (2c)			4i 40
7	Ph (2c)			4j 84 ^[b]
8	Ph (2c)			4k 81
9	CO ₂ Me (2d)			4l 61
10	PhMe ₂ Si (2e)			4m 64 ^[b,c]
				4n 58 ^[d]

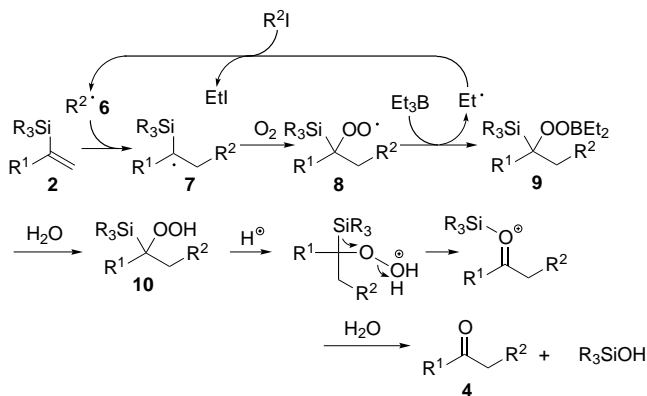
[a] Reaction conditions: alkenylsilane **2** (0.5 mmol), iodide (0.75 mmol), H_2O (5 mL), NH_4Cl (15 mmol), Et_3B (5×0.2 mmol), air atmosphere, room temperature (RT), 5 h. [b] Iodide (1.5 mmol) and Et_3B (5×0.4 mmol) were employed. [c] Yield determined by NMR spectroscopy with dibenzyl ether as the internal standard. [d] Yield after purification over a silica gel column.



Scheme 4. Synthesis of carbonyl compounds from alkenylsilanes **2** as 2-oxoalkyl-equivalent radical acceptors. **2b, c, d**: $R_3Si = Ph_2MeSi$, **2e**: $R_3Si = Me_2PhSi$. For details see Table 1.

One can hence regard vinylsilanes as a 2-oxoalkyl-equivalent radical acceptor. Several characteristics of this process are noteworthy: 1) The reaction of α -silylstyrene **2c** also afforded the desired ketones in good yields. 2) The reaction can employ iodo ketones as a radical source (entry 7). However, concurrent reduction of the iodo ketone via a water-unstable boron enolate occurred,^[12] and the use of excess iodo ketone (3.0 equiv) was required. 3) The reaction allows efficient introduction of a perfluoroalkyl group at the α position of ketones (entries 8 and 10). 4) Direct oxidation of the iodide can lower the yield of ketone (entry 6; the undesired oxidation product is 2-hydroxypropionate).^[4b] 5) Acylsilanes can be prepared from 1,1-disilyl ethene **2e**. The product **4m** was converted into α,β -unsaturated acylsilane **4n** during purification over silica gel (entry 10). 6) In all cases, silanol was obtained as a byproduct.

We propose the reaction pathway for the sequential radical addition–oxidation reaction as illustrated in Scheme 5. Addition of a radical **6** to alkenylsilane **2** provides an α -silyl radical **7**, which then reacts with oxygen to afford peroxy



Scheme 5. Proposed reaction pathway for the sequential radical addition–oxidation reaction studied.

radical **8**. The reaction of radical **8** with Et_3B furnishes peroxyborane **9**. Hydroperoxide **10**, derived from the peroxyborane by hydrolysis, is eventually converted into the carbonyl product **4** through migration of the silyl group to the internal oxygen atom.^[13] The ethyl radical which results from reaction **8**→**9** regenerates an alkyl radical from R^2I .

In conclusion, we have achieved the synthesis of aldehydes and ketones from alkenylsilanes under radical conditions with air as the oxidant. A tandem intermolecular radical addition–oxidation sequence can convert vinylsilanes

into ketones in good yields. This process demonstrates novel utility of vinylsilanes in organic synthesis. Further research on the oxidation of organosilicon compounds with molecular oxygen is currently under way in our laboratory.

Received: October 10, 2002 [Z50337]

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- [8] α -Iodosilane **3d** is stable in water at room temperature. None of the hydrolyzed alcohol could be detected.
- [9] **Caution:** The addition of Et_3B in methanol to an aqueous mixture in air may be flammable. Accordingly, the solution of Et_3B was introduced under argon atmosphere, and then the reaction flask was connected to a balloon filled with air. See Supporting Information.
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- [13] We carried out DFT calculations on the migration of the silyl group of a silylated hydroperoxide. See ref. [3].