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Cobalt-Catalyzed 1,4-Hydrovinylation of Styrenes and 1-Aryl-1,3-butadienes

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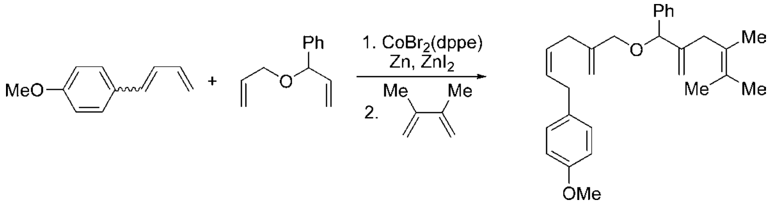
ABSTRACT

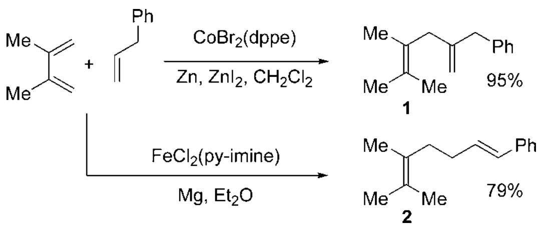


The application of aryl-substituted starting materials such as styrene and 1-aryl-substituted 1,3-butadiene derivatives in the cobalt-catalyzed 1,4-hydrovinylation reaction has been investigated. The use of unsymmetrical α,ω-dienes in the hydrovinylation with 1-aryl-1,3-butadiene led chemoselectively to the 1:1 or the 1:2 adducts depending on the stoichiometry of the starting materials.

The transition-metal-catalyzed hydrovinylation reaction is an excellent example for an atom economic transformation leading to the formation of a new carbon−carbon bond. Two very successful procedures can be distinguished. First, simple olefins such as styrene or norbornene derivatives are converted in a transition-metal-catalyzed 1,2-hydrovinylation reaction with ethene to the corresponding adducts.[1] Second, the 1,4-hydrovinylation of 1,3-dienes with terminal alkenes leads to 1,4-diene products.[2] Alongside diverse methodological investigations,[2b−d] we were able to utilize the cobalt-catalyzed 1,4-hydrovinylation reaction of a terminal alkene as the key step in the short synthesis of *moenocinol*.[3]

In a recent report, Ritter described the first application of low-valent iron complexes in the regioselective 1,4-hydrovinylation of 1,3-dienes.[4] Of considerable interest is the fact that the 1,4-hydrovinylation of allyl benzene with 2,3-dimethyl-1,3-butadiene (Scheme 1) led to different results when the applied transition metal was varied. While under cobalt catalysis, the branched product **1** with a 1,4-diene

Scheme 1. Cobalt- and Iron-Catalyzed 1,4-Hydrovinylation of Allylbenzene with 2,3-Dimethyl-1,3-butadiene



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(1) For reviews on hydrovinylations, see: (a) Grabulosa, A.; Muller, G.; Ordinas, J. I.; Mezzetti, A.; Maestro, M. A.; Font-Bardia, M.; Solans, X. *Organometallics* **2005**, *24*, 4961. (b) RajanBabu, T. V. *Chem. Rev* **2003**, *103*, 2845. See also: (c) Saha, B.; Smith, C. R.; RajanBabu, T. V. *J. Am. Chem. Soc.* **2008**, *130*, 9000. (d) Shirakura, M.; Suginome, M. *J. Am. Chem. Soc.* **2008**, *130*, 5410. (e) Saha, B.; RajanBabu, T. V. *J. Org. Chem.* **2007**, *72*, 2357. (f) Zhang, A. B.; RajanBabu, T. V. *J. Am. Chem. Soc.* **2006**, *128*, 54. (g) Zhang, A.; RajanBabu, T. V. *Org. Lett.* **2004**, *6*, 1515. (h) Zhang, A.; RajanBabu, T. V. *Org. Lett.* **2004**, *6*, 3159. (i) Kumareswaran, R.; Nandi, M.; RajanBabu, T. V. *Org. Lett.* **2003**, *5*, 4345. (j) RajanBabu, T. V.; Nomura, N.; Jin, J.; Nandi, M.; Park, H.; Sun, X. *J. Org. Chem.* **2003**, *68*, 8431. (k) Park, H.; RajanBabu, T. V. *J. Am. Chem. Soc.* **2002**, *124*, 734. (l) Bogdanovi, B.; Pauling, H.; Wilke, G.; Meister, B.; Henc, B. *Angew. Chem., Int. Ed.* **1972**, *11*, 1023.

(2) (a) Sanchez, R. P.; Connell, B. T. *Organometallics* **2008**, *27*, 2902. (b) Hilt, G.; Luers, S.; Schmidt, F. *Synthesis* **2004**, 634. (c) Hilt, G.; Luers, S. *Synthesis* **2002**, 609. (d) Hilt, G.; du Mesnil, F. X.; Lüers, S. *Angew. Chem., Int. Ed.* **2001**, *40*, 387.

(3) Hilt, G.; Treutwein, J. *Chem. Commun* **2009**, 1395.

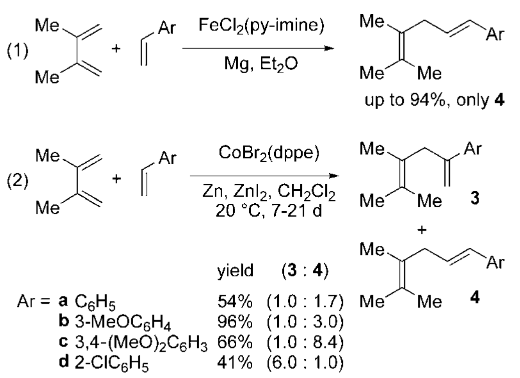
(4) Moreau, B.; Wu, J. Y.; Ritter, T. *Org. Lett.* **2009**, *11*, 337.

10.1021/ol901064p CCC: $40.75

subunit is formed,[2] and the iron-catalyzed process led to the formation of **2** with a 1,5-diene subunit after double bond migration under the reaction conditions. In this respect, the two methodologies are complementary, each leading to different products when starting from identical educts.[5] A significant exception is observed when utilizing styrene derivatives. These are excellent starting materials in the iron-catalyzed process, and under cobalt catalysis, the 1,4-hydrovinylation of styrenes was observed with a very low rate.

Inspired by the report by Ritter we reinvestigated the cobalt-catalyzed 1,4-hydrovinylation of styrene derivatives with 2,3-dimethyl-1,3-butadiene (eq 1, Scheme 2). To our regret, the reaction rates were rather low, and mostly incomplete conversions were encoutered (eq 2). Also, the two possible regioisomers **3** and **4** concerning the newly formed carbon−carbon bond were formed generally as a mixture in the range of 6.0:1.0 to 1.0:8.4.

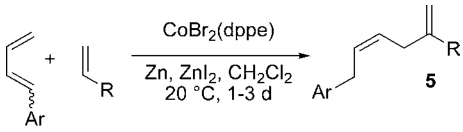
Scheme 2. Cobalt- and Iron-Catalyzed Hydrovinylation of Styrene Derivatives



Electronically different styrene derivatives were used to investigate electronic effects upon the regiochemisty of the hydrovinylation process. Electron-withdrawing substituents such as the trifluoromethyl-substituted arene substituent slightly favored the formation of the linear product of type **4**. The branched product of type **4** was strongly preferred when electron-donating substituents such as in the methoxy-substituted benzene derivatives were used. Of considerable interest is the application of the 2-chloro-substituted styrene. In this case, the branched product of type **3** was clearly favored, although the conversion was far from completion. The reaction of 2-vinyl thiophene led to the desired hydrovinylation product in acceptable yield, and for no obvious reason the linear product of type **4** was the only isomer isolated. The characterization of the products was complicated by the fact that the separation of the unreacted starting materials from the branched products **3** and the linear products **4** to give analytically pure samples could be accomplished in only two cases. Therefore, only a limited number of examples were investigated as shown in Scheme 2.

We then focused our attention upon the application of 1-aryl-substituted 1,3-butadienes as starting materials in the 1,4-hydrovinylation process.[6] The starting materials can be easily generated from aromatic aldehydes by a Wittig olefination with allyl triphenyl phosphonium bromide as a mixture of *E*/*Z*-1,3-dienes in good yields. The cobalt-catalyzed conversion of these 1,3-dienes with terminal olefins led to the formation of products of type **5** (Scheme 3). The good to excellent yields indicate that both isomers of the *E*/*Z*-mixture are well accepted as starting materials. Because complete conversion of the 1,3-diene is observed, it follows that the cobalt catalyst converts both isomers to a single 1,2-disubstituted and *Z*-configured double bond in **5**. Also, the reaction times were drastically reduced, and the complete conversions eliminate purification problems. The newly formed carbon−carbon bond was generated exclusively at the less hindered side of the 1,3-diene, and with nonactivated alkenes only branched products of type **5** were observed. The results of this investigation are summarized in Table 1.

Scheme 3. Cobalt-Catalyzed 1,4-Hydrovinylation of 1-Aryl-Substituted 1,3-Butadienes



Besides the exomethylene double bond generated from the terminal alkene, the internal double bond from the 1,3-diene was generated exclusively as the *Z*-isomer. Both electron-donating as well as electron-withdrawing substituents on the aryl substituent gave equally good results, and several terminal alkenes were applied successfully (entries 1−5). Also, interesting results were obtained for the application of 1,5-hexadiene (entries 6 and 7). The bisadduct **5g** could be obtained as a single isomer in quantitative yield utilizing an excess of the 1,3-diene. The monoadduct **5f** was obtained in a good 77% yield when an excess of the 1,5-hexadiene was used accompanied by 17% **5g**. The application of a ferrocenyl-substituted 1,3-diene (entry 8) gave the hydrovinylation product **5h** in good yields with no interference by the redox-active ferrocene subunit. As prototypes of heterocyclic compounds, the N-tosylated heterocyclic-

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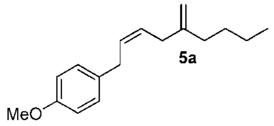
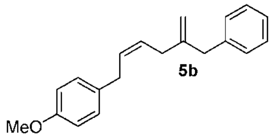
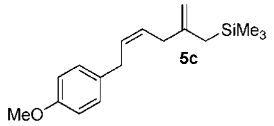
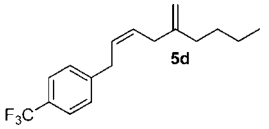
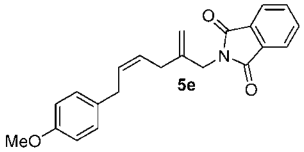
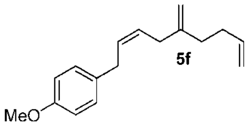
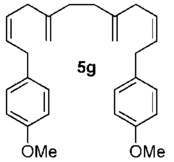
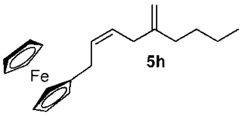
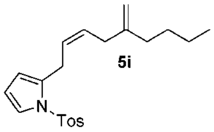
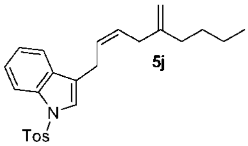
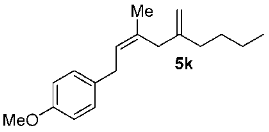
(5) For regio- and stereodivergent reactions, see: (a) Webster, R.; Boing, C.; Lautens, M. *J. Am. Chem. Soc.* **2009**, *131*, 444. (b) Lu, Z.; Ma, S. *Angew. Chem.* **2008**, *120*, 264; *Angew. Chem., Int. Ed* **2008**, *47*, 258. (c) Graening, T.; Schmalz, H.-G. *Angew. Chem.* **2003**, *115*, 2684; *Angew. Chem., Int. Ed* **2003**, *42*, 2580. (d) Trost, B. M.; Crawley, M. L. *Chem. Rev.* **2003**, *103*, 2921. (e) Trost, B. M.; Lee, C. B. *Catalytic Asymmetric Synthesis II*; Ojima, I., Eds.; Wiley-VCH: 2000, 593. (f) PfaltzA.; Lautens, M. *Comprehensive Asymmetric Catalysis*; Jacobsen, E. N., Pfaltz, A., Yamamoto, H., Eds.; Springer: 1999; Vol. 2, p 833. (g) Helmchen, G. *J. Organomet. Chem.* **1999**, *576*, 203. (h) Johannsen, M.; Jørgensen, K. A. *Chem. Rev.* **1998**, *98*, 1689. (i) Trost, B. M.; Van Vranken, D. L. *Chem. Rev.* **1996**, *96*, 395. (j) Frost, C. G.; Howarth, J.; Williams, J. M. J. *Tetrahedron:Asymmetry* **1992**, *3*, 1089.

(6) For an application of 1-aryl-substituted 1,3-dienes in cobalt-catalyzed Diels−Alder reactions, see: Hilt, G.; Danz, M. *Synthesis* **2008**, 2257.

Table 1. Results of the Cobalt-Catalyzed 1,4-Hydrovinylation Reaction with 1-Aryl-Substituted 1,3-Dienes[a]

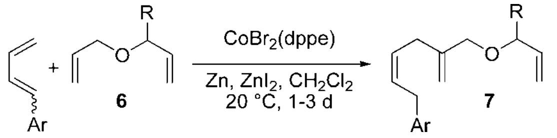
entry	product 5	yield[a]
1	 **5a**	90%[c]
2	 **5b**	73%
3	 **5c**	94%
4	 **5d**	94%[c]
5	 **5e**	90%
6	 **5f**	77%[b] (+ 17% **5g**)
7	 **5g**	99%[c]
8	 **5h**	90%
9	 **5i**	29%
10	 **5j**	84%[d]
11	 **5k**	59%[d]

[a] Catalyst system: $CoBr_2$(1,2-bisdiphenylphosphinoethane) 10 mol %; zinc dust 20 mol %; zinc iodide 20 mol %, CH_2Cl_2, rt, overnight. [b] Excess of the 1,5-hexadiene (3.0 equiv) was used. [c] Excess of the 1,3-diene (3.0 equiv) was used. [d] Twice the amount of the catalyst system (footnote a) was used. [e] Half the amount of the catalyst system (footnote a) was used.

substituted 1,3-dienes were applied with moderate to good success in the synthesis of **5i**/**5j** (entries 9 and 10). In these cases, it seems evident that the tosyl functionality reduces the reactivity of the 1,3-diene when attached in proximity to the diene subunit as illustrated by the reduced yield of **5i**. Also, a 1-aryl-3-alkyl-substituted 1,3-diene could be applied in the reaction (entry 11) with an acceptable yield of the adduct **5k**.

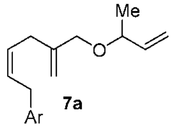
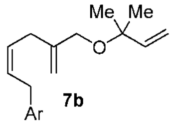
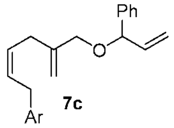
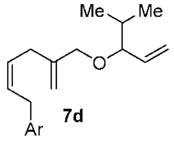
The transformation to give **5f** indicates that the aryl-substituted 1,3-diene is quite reactive and is mostly consumed in the reaction. This intriguing result encouraged us to investigate the question if an unsymmetrical α,ω-diene as starting material could react chemoselectively. For this purpose, readily available bisallyl ethers of type **6** with one substituent (R) in the allylic position were utilized in the cobalt-catalyzed 1,4-hydrovinylation reaction (Scheme 4).

Scheme 4. Chemoselective Cobalt-Catalyzed 1,4-Hydrovinylation Reaction of Bisallyl Ether Derivatives



The results for the generation of products of type **7** are summarized in Table 2. It was anticipated that the chemoselectivity would be dependent on the steric bulk of the substituent R of the bisallyl ether **6**. The hydrovinylation

Table 2. Results of the Cobalt-Catalyzed 1,4-Hydrovinylation Reaction Utilizing Bisallyl Ethers

entry	product (7)[a]	yield[b]
1	 **7a**	71%
2	 **7b**	84%
3	 **7c**	65%
4	 **7d**	95%

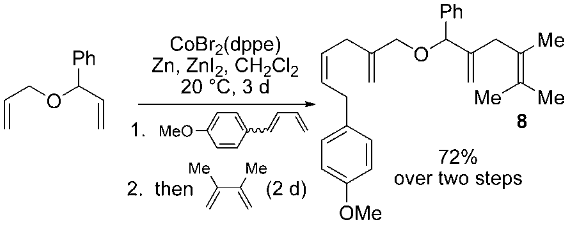
[a] Ar = 4-methoxyphenyl. [b] Catalyst system: $CoBr_2$(1,2-bisdiphenylphosphinoethane) 10 mol %; zinc dust 20 mol %; zinc iodide 20 mol %, CH_2Cl_2, rt, overnight.

reaction took place selectively at the less hindered allyl subunit even with the methyl group, which represents the smallest substituent used in our study.

The products of type **7** were isolated as single isomers in good to excellent yields utilizing a slight excess (1.1 equiv) of 1-(4-methoxyphenyl)-1,3-butadiene which was used as the test system in this investigation. The monoadduct **7b** with the geminal dimethyl subunit did not react with another aryl-1,3-diene even when 3 equiv of the diene was applied.

Accordingly, a sequential process was envisaged for the other hydrovinylation products such as **7a** where the monoadducts were then converted in another hydrovinylation reaction with a different 1,3-diene such as 2,3-dimethyl-2,3-butadiene to generate tetraene products of type **8** (Scheme 5). This procedure was realized utilizing 20 mol % of the cobalt catalyst, and the product **8** was isolated in 72% yield over the two consecutive reactions performed in a one-pot procedure (Scheme 5). In this case, the isolated yield of **8** was even higher than that of the monoadduct **7c** which is formed as an intermediate in this protocol.

Scheme 5. Sequential Chemoselective Cobalt-Catalyzed 1,4-Hydrovinylation Reaction of Unsymmetrical Bisallyl Ether Derivatives



In conclusion, we have demonstrated that aryl substituents are accepted without difficulties on the 1,3-diene substrate, whereas vinyl heteroaromatic and styrene derivatives gave mixtures and incomplete conversions. For the application of styrene, the iron-catalyzed procedure by Ritter is superior at the moment. However, a chemoselective 1,4-hydrovinylation reaction could be performed with an unsymmetrical bisallyl ether as a divalent substrate. Accordingly, a sequential transformation of these substrates generated the tetraene product **8** selectively. The triene and tetraene products generated by our method show potential as interesting substrates for other transformations such as alkene metathesis, hydroboration, or hydroformylation reactions, perhaps to permit elucidation of their chemoselectivity and reactivity when several differently substituted double bonds are present in a single substrate.

Supporting Information Available: Experimental procedures and full characterization of the compounds **5a**−**5k**, **7a**−**7d**, and **8**. This material is available free of charge via the Internet at http://pubs.acs.org.

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