

Published in final edited form as:

Angew Chem Int Ed Engl. 2014 April 7; 53(15): 3877–3880. doi:10.1002/anie.201310517.

Regio- and Stereoselective 1,2-Dihydropyridine Alkylation/ Addition Sequence for the Synthesis of Piperidines with Quaternary Centers**

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Abstract

The first example of C-alkylation of 1,2-dihydropyridines with alkyl triflates and Michael acceptors was developed to introduce quaternary carbon centers with high regio- and diastereoselectivity. Hydride or carbon nucleophile addition to the resultant iminium ion also proceeded with high diastereoselectivity. Carbon nucleophile addition results in an unprecedented level of substitution to provide piperidine rings with adjacent tetrasubstituted carbons.

Keywords

piperidine; alkylation; tetrasubstituted carbon; diastereoselective; dihydropyridine

Piperidines are valuable and prevalent substructures in biologically active natural products and in medicines that have been enormously important in managing disease.^[1-3] As entry to this important class of compounds, a number of powerful methods for the synthesis of 1,2-dihydropyridines have been developed.^[4,5] In this context, we previously disclosed an

**This work was supported by the NIH Grant GM069559 (to J.A.E.). R.G.B. acknowledges funding from the DOE, DE-AC02-05CH11231.

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Supporting information for this article is available on the WWW under <http://dx.doi.org/10.1002/anie.2013xxxxx>

approach to rapidly assemble highly substituted 1,2-dihydropyridines by a Rh(I)-catalyzed C–H alkenylation/electrocyclization cascade from readily available α,β -unsaturated imines and alkynes.^[6] We have further recently described that these 1,2-dihydropyridine products are versatile intermediates for the preparation of highly substituted tetrahydropyridines by regio- and diastereoselective protonation followed by hydride or carbon nucleophile addition (Scheme 1a).^[7-9] Herein, we demonstrate that C-alkylation of 1,2-dihydropyridines, which to our knowledge has not previously been reported, can be achieved with alkyl triflates and Michael acceptors with high regio and diastereoselectivity to provide quaternary carbon centers within the piperidine core (Scheme 1b).^[10-12] Moreover, reduction or carbon nucleophile addition to the resultant iminium ion can also be accomplished with high diastereoselectivity. In the case of carbon nucleophile addition, an unprecedented level of substitution is achieved to provide piperidine rings with adjacent tetrasubstituted carbons.

We initially explored the addition of methyl iodide and dimethyl sulfate to dihydropyridine **1** (R = Me) (Table 1). However, methylation was not observed using a variety of solvents such as THF, toluene and CH₂Cl₂ even with heating to 60 °C in a sealed reaction vessel (data not shown). We consequently evaluated the considerably more reactive methyl triflate, which resulted in complete conversion to the methylated iminium product at rt (entry 1). Successful alkylation with ethyl triflate demonstrated that less reactive alkylating agents also couple efficiently (entry 2). Moreover, ethylation established that the reaction proceeds with very high diastereoselectivity. To further test the generality of the alkylation protocol, the reactivity of dihydropyridine **1** (R = H) was investigated because it results in a more highly destabilized aldiminium product (entry 3). While generally complete and stereoselective alkylation was observed in toluene with an 14–18 h reaction time, at shorter reaction times CH₂Cl₂ as solvent proved to be more effective (entry 4–7). Given the instability of benzyl triflates, benzyl chloride and bromide were instead evaluated, but no alkylation was observed for either reagent (entries 8 and 9). Lewis acid-mediated activation of benzyl bromide was therefore investigated, with ZrCl₄ providing the benzylated product in >95% conversion within 2 h at –78 °C to rt and with good diastereoselectivity (entry 10).

With the feasibility of the key alkylation step established, we next focused on the preparation of the desired tetrahydropyridines **3** by reduction of the reactive iminium ion **2** (Table 2). We first explored the alkylation/reduction sequence for 1,2-dihydropyridines **1** unsubstituted at the R² position (R² = H), because this avoids introducing a stereocenter in the reduction step. After alkylation, Me₄NBH(OAc)₃ served as a mild and inexpensive reducing agent for the synthesis of tetrahydropyridines **3a** to **3f** in good to high overall yields. Notably, in the key alkylation step, methyl (**3a** and **3d**), ethyl (**3b** and **3e**), functionalized 2-methoxyethyl (**3c**), and benzyl (**3f**) groups were all successfully incorporated. The overall yields for the methylation products **3a** and **3d** were somewhat lower than for the other electrophiles due to competitive methylation at nitrogen when R² = H. However, for all of the other alkylating agents, which are less reactive than methyl triflate, no alkylation at nitrogen was detected and high diastereoselectivities were observed. For ethylation (**3b** and **3e**) and 2-methoxyethylation (**3c**), only a single diastereomer was obtained. Alkylation consistently occurs opposite to the R⁶ group as rigorously established by X-ray structural analysis of **3e** as well as for multiple other alkylation products (**3g**, **3m**,

3n, **3p**, **6d** and **6g**, vide infra).^[13] The Lewis acid mediated benzylation provided a more modest 5:1 ratio (**3f**).

We next investigated the alkylation/reduction sequence for 1,2-dihydropyridines substituted at the R² position, which introduces added complexity because a stereocenter is generated in the reduction step (**3g** to **3r**, Table 2). The sequence was first performed by methylating dihydropyridines **1** where R³ = Me such that a stereocenter is only introduced in the reduction step (**3g** – **3l**). In all cases only a single diastereomer was produced as determined by ¹H NMR analysis. Hydride addition opposite the R⁶ group was rigorously established for **3g** by X-ray structural analysis and is consistent with the face selectivity observed for reduction in our previously reported protonation/reduction sequence.^[7] The methylation/reduction sequence proceeded in excellent overall yields for a range of substituents with diverse steric and electronic properties (75-94%). At the R¹ position on nitrogen both the *N*-benzyl (**3g**) and the comparatively deactivating *N*-phenyl (**3h**) group provided high yields. The R⁴ position could be substituted with alkyl (**3g**, **h**, **k** and **l**), phenyl (**3i**) and furanyl (**3j**) groups, while alkyl and phenyl groups could be placed at both the R⁵ and R⁶ positions (**3g** versus **3k**). A 91% yield was observed when the *tert*-butyl group was placed at the R⁶ position (**3l**), although reduction with K(*i*-PrO)₃BH at -78 °C instead of Me₄NBH(OAc)₃ at 0 °C was necessary to achieve high selectivity.

For products **3m** to **3r**, two stereocenters are introduced, the first in the alkylation step and the second in the reduction step. High overall yields and good stereoselectivities were observed for methylation (**3r**), ethylation (**3m** to **3o**), benzylation (**3p**) and introduction of the 2-methoxyethyl group (**3q**). Moreover, different substituents at the R² through R⁴ positions were tolerated, including a bicyclic dihydropyridine that resulted in the *cis*-fused product **3r**. However, to achieve high reduction stereoselectivity for many of these substrates, it was necessary to use more reactive hydride reagents at -78 °C. In particular, for **3m**, **3n** and **3o**, reduction with LiBEt₃H was optimal, and for **3l**, **3p** and **3q**, reduction with K(*i*-PrO)₃BH proved to be the most effective. The relative configurations of the two newly formed stereocenters were rigorously determined by X-ray structural analysis for the ethylation/reduction products **3m** and **3n** and the benzylation/reduction product **3p**.^[13] These X-ray structures establish that upon introducing alkyl groups R larger than a methyl group, steric interactions that result from the newly formed and adjacent quaternary stereocenter control the face selectivity of reduction rather than the more distant R⁶ substituent.

Michael additions to α,β -unsaturated esters were explored to introduce the ester group as a versatile functionality for further elaboration (Scheme 2). Direct addition of the dihydropyridine to methyl acrylate did not proceed, but after evaluating a variety of Lewis acids, we established that TMSOTf results in high conversion to the silyl enol ether intermediate **4** as an approximately 1:1 E/Z isomer mixture. To obtain tetrahydropyridine **5a**, reduction with Me₄NBH(OAc)₃ was most effective, while for **5b** LiBHET₃ provided the highest diastereoselectivity and overall yield.

We next investigated the addition of carbon nucleophiles rather than hydride (Table 3). We first evaluated additions to 1,2-dihydropyridines **1** unsubstituted at the R² position because

the iminium intermediate that is generated upon alkylation lacks α -hydrogens and therefore cannot undergo competitive α -deprotonation. For these substrates phenyl Grignard adds cleanly to give **6a** and **6b**, with the yield for **6a** being somewhat lower due to competitive *N*-methylation of the dihydropyridine in the alkylation step (see previous discussion for **3a** and **3d**). While high diastereoselectivity was observed for **6a**, an attenuated 81:19 selectivity was observed for **6b**.

The remaining carbon nucleophile addition products (**6c** to **6g**) were prepared from 1,2-dihydropyridines with carbon substituents at R², which results in adjacent tetrasubstituted stereocenters being introduced in the alkylation/nucleophilic addition sequence. Each of these substrates has the potential for competitive α -deprotonation in the carbon nucleophile addition step. For this reason, less basic and more covalent organometallic reagents were more effective. Phenyl, alkyl and silyloxymethyl substituted alkynyl Grignard reagents all added diastereoselectively and in good yields (**6a** to **6e**).^[14] Allyl cerium reagents also added in high yields and with excellent diastereoselectivities (**6f** and **6g**),^[15] including for the preparation of cis-fused bicyclic piperidine **6g** with tetrasubstituted carbons at the two bridgehead positions. Finally, X-ray structural analysis of **6d** and **6g**^[13] establishes that when the alkylation step introduces a stereocenter the face selectivity for nucleophilic attack is controlled by steric interactions at this adjacent quaternary site consistent with that previously observed in the alkylation/reduction sequence (vide supra).

In conclusion, a 1,2-dihydropyridine alkylation/nucleophile addition sequence has been developed that proceeds in good yields and with high levels of regio- and diastereoselectivity to provide piperidine derivatives with unprecedented levels of substitution, including products with adjacent tetrasubstituted ring carbons. Because the 1,2-dihydropyridine starting materials are prepared in one step from simple precursors by a tandem C-H alkenylation/electrocyclization reaction cascade, the described alkylation/nucleophile addition sequence provides rapid access to densely substituted piperidines that would be extremely difficult to prepare by alternative methods.

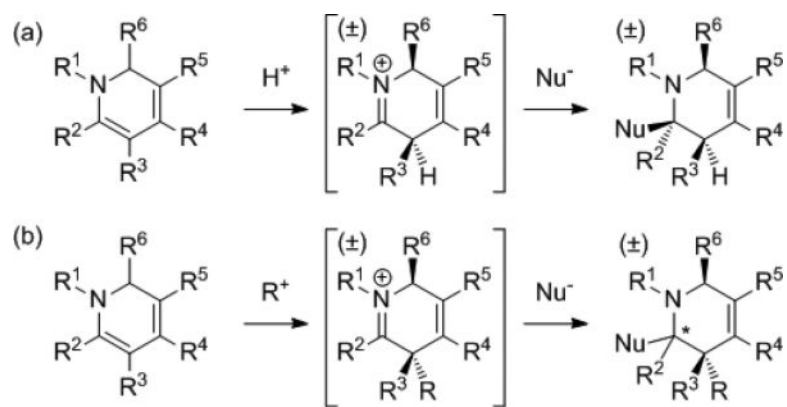
Supplementary Material

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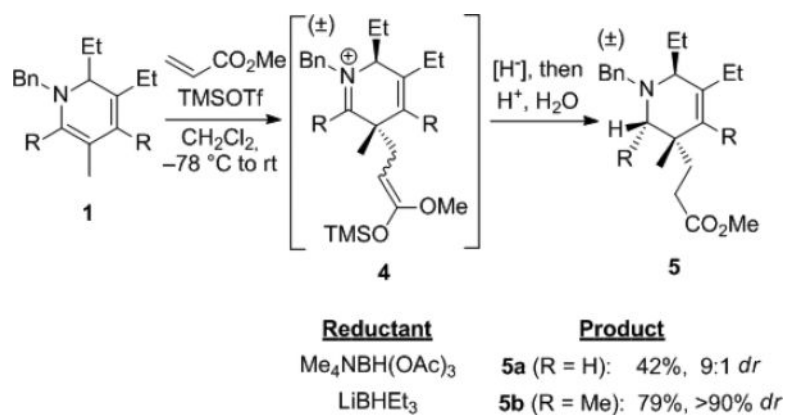
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13. Synthetic details, characterization, and molecular structures obtained by X-ray structural analysis of compounds are described in the Supporting Information under CCDC Nos: 974855 (3e), 974821 (3g), 974854 (3m), 974857 (3n), 974819 (3p), 974856 (6d), and 974820 (6g). These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.
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15. We previously observed that allyl cerium reagents minimize competitive iminium ion deprotonation, see ref 7b.

**Scheme 1.**

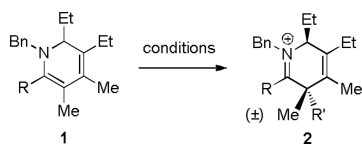
- a) Previously reported 1,2-dihydropyridine protonation and nucleophilic addition sequence.
b) Transformation developed in this study: Reaction with carbon electrophiles (R^+) followed by addition of hydride or carbon nucleophiles.

**Scheme 2.**

Michael addition of dihydropyridines to methyl acrylate.

Table 1

Optimization of dihydropyridine alkylation conditions.



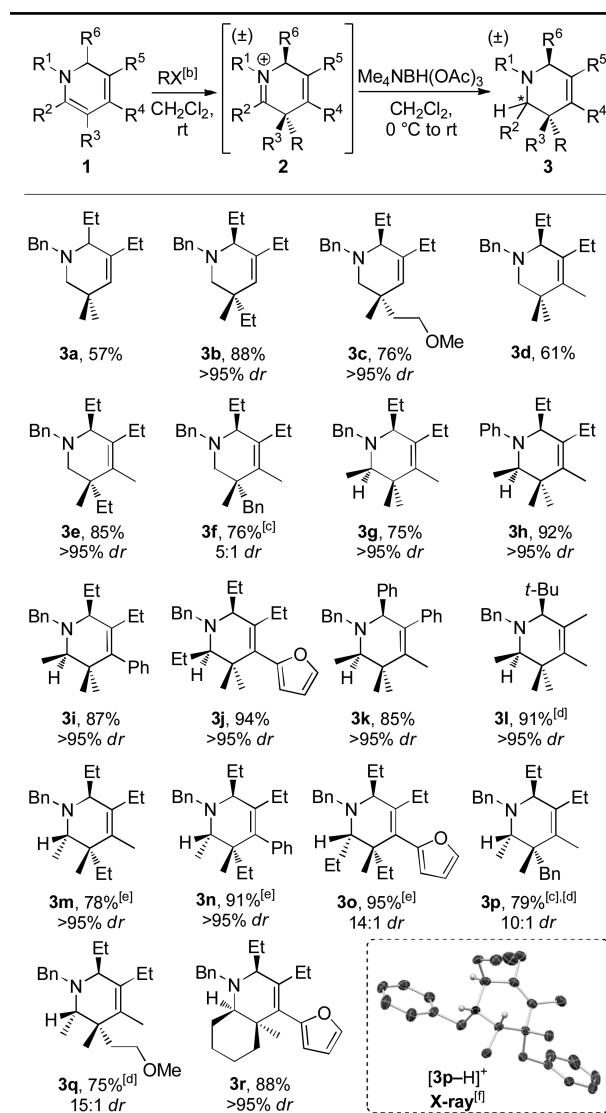
entry	R	R'X	solvent	time	<i>dr</i> [a]	conv [b]
1	Me	MeOTf	toluene	16 h	-	>95%
2	Me	EtOTf	toluene	14 h	>95%	>95%
3	H	MeOTf	toluene	18 h	-	>95%
4	Me	MeOTf	CH ₂ Cl ₂	1.5 h	-	>95%
5	Me	EtOTf	CH ₂ Cl ₂	1.5 h	>95%	>95%
6	H	MeOTf	CH ₂ Cl ₂	1.5 h	-	>55%
7	H	EtOTf	CH ₂ Cl ₂	1.5 h	>95%	>95%
8	Me	BnCl	CH ₂ Cl ₂	16 h	nd	<5%
9	Me	BnBr	CH ₂ Cl ₂	16 h	nd	<5%
10 ^[c]	Me	BnBr	CH ₂ Cl ₂	2 h	>90%	>95%

[a] Where applicable, the reaction *dr* was determined by ¹H NMR analysis.

[b] The reaction conversion was established by ¹H NMR analysis.

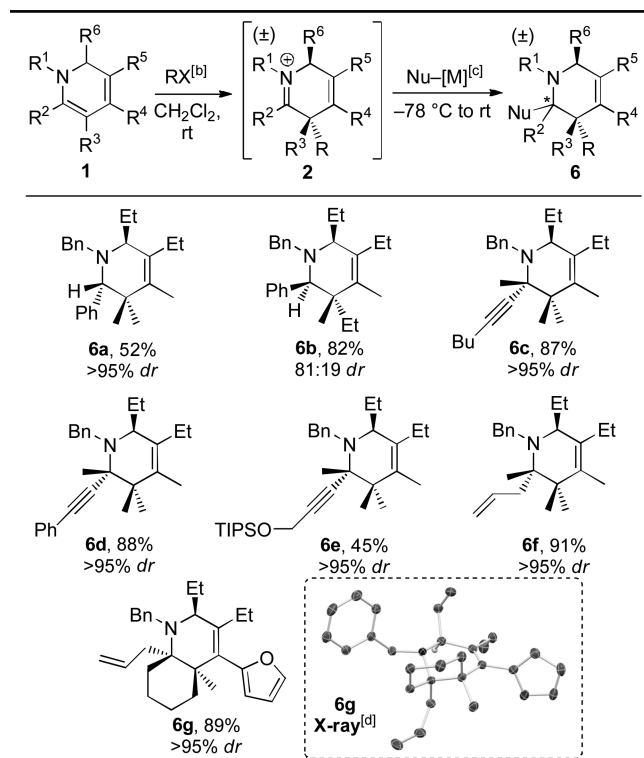
[c] With ZrCl₄ as a Lewis acid additive, -78 °C to rt.

Table 2

One-pot dihydropyridine alkylation and reduction.^[a]

[a] Yields are isolated yields after purification by chromatography. Diastereoselectivities were determined by NMR analysis. [b] Unless otherwise indicated, alkylation was performed with the corresponding triflate (1.5 - 2 equiv). [c] Benzylation was accomplished using BnBr (2.5 equiv) and ZrCl₄ (1.7 equiv) at -78 °C with warming to rt. [d] Reduction was performed by addition of K(*i*-PrO)₃BH in THF at -78 °C with warming to rt. [e] Reduction was performed by addition of LiEt₃BH in THF at -78 °C with warming to rt. [f] For details and other crystal structures unequivocally establishing relative configurations of the products, see Fig. S1-7 in the ESI.

Table 3

One-pot dihydropyridine alkylation and carbon nucleophile addition.^[a]

[a] Yields are isolated yields after purification by chromatography.

Diastereoselectivities were determined by NMR analysis. [b] Alkylation was performed with the corresponding triflate (1.5 - 2 equiv). [c] PhMgBr in ether (7 equiv) was used to prepare **6a** and **6b**; alkynylMgCl in ether (6-9 equiv) was used to prepare **6c-e**; $\text{allylcerium chloride}$ in THF (9 equiv) was used to prepare **6f** and **6g**. [d] For details and other crystal structures unequivocally establishing relative configurations of the products, see Fig. S1-7 in the ESI.