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Valence Tautomerism in Titanium Enolates: Catalytic Radical Haloalkylation and Application in the Total Synthesis of Neodysidenin

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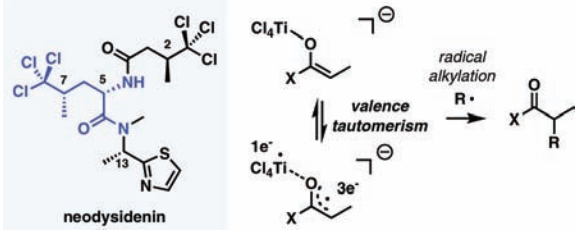
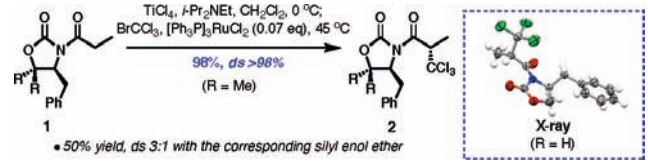
Among more than 4000 halogenated natural products identified to date,[1] neodysidenin and other trichloroleucine-derived marine metabolites comprise a unique group.[2] For the majority of chlorinated natural products, a reasonable biosynthetic pathway involving an electrophilic chlorination can be proposed.[3] On the other hand, the trichloromethyl group in neodysidenin and related compounds arises from a remarkable direct chlorination of the *pro-R* methyl group of L-leucine carried out by nonheme Fe^{II} halogenases requiring oxygen, chloride, and α-ketoglutarate for their activity.[4] In contrast, availability of synthetic methods for stereoselective trichloromethylation is highly limited,[5] whereas chlorinated natural products are attracting increasing attention as targets for chemical synthesis.[6]

In this communication we describe a practical, efficient method for highly stereoselective direct chloroalkylation of titanium enolates and its application in the total synthesis of neodysidenin that can be readily adopted for the synthesis of other bioactive natural products in this class.[7] Guided by an extension of the classic Kharasch reaction[8] described by Eguchi and co-workers,[9] our early efforts involved Ru(II)-catalyzed[10] redox trichloromethylation of trimethylsilyl enol ethers generated from chiral *N*-acyl oxazolidinones such as **1** (Scheme 1).[11] Although encouraging results were obtained with silyl ketene acetals (~50% yields, ds 3:1), the recent characterization of valence tautomerism in titanium enolates provided a conceptual foundation for the development of a *direct* radical chloroalkylation of *N*-acyl oxazolidinones.[12,13]



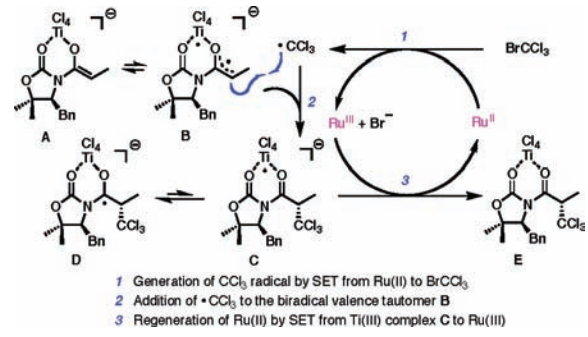
The unconventional biradical character of titanium enolates described by Moreira and co-workers suggests that these intermediates should be efficient radical acceptors.[12] Indeed, when the Ti enolate derived from **1**[14] was treated with $BrCCl_3$ in the presence of $[Ph_3P]_3RuCl_2$ as a readily available redox catalyst (7 mol %), product **2** was obtained in an essentially quantitative yield with exquisite stereocontrol (Scheme 1). The mechanistic hypothesis in Scheme 1 is based on the well-established redox activity of $[Ph_3P]_3RuCl_2$ widely used in atom-transfer radical polymerization (ATRP)[15] and is similar to that proposed by Eguchi for a related process with silyl enol ethers.[9] A major advantage, however, is that the radical addition product should be stabilized by electron delocalization onto titanium, not feasible with silyl enol ethers. Thus, in the first step of the process, the CCl_3 radical is formed upon an electron transfer from the Ru(II) complex to $BrCCl_3$. Addition of the electrophilic radical to biradical **B** should be particularly favorable because the product is a titanium(III) complex **C**, which is likely to be substantially more stable than a carbon-centered radical (such as **D**) expected from a radical addition to silyl enol ethers or other enolates. Reduction of Ru(III) species with the Ti(III) intermediate should regenerate the catalyst and provide the initial product as a Ti(IV) chelate **E**. In addition, the chelated nature of the titanium enolates ensures conformational rigidity required for stereocontrol.[14]



Next, a series of experiments were carried out to evaluate the scope of *N*-acyl oxazolidinone and of chloroalkylating components in this Ru-catalyzed process. Table 1 illustrates that functionalized *N*-acyl oxazolidinones are excellent substrates. Different Evans-type chiral auxiliaries can be used without loss of stereoselectivity, but the highest yields are achieved with the 5,5-dimethyl oxazolidinones.[16] Aromatic, heterocyclic, and ethereal substituents are compatible with the reaction conditions. As evident from entry 5, a direct competition with Kharasch reaction reveals that the more sterically demanding titanium enolate is a superior trichloromethyl radical acceptor than a terminal double bond. With 3 equiv of $BrCCl_3$, the bis-trichloromethylation product was isolated in a virtually quantitative yield. The stereoselectivity is generally very high; in no case were we able to observe or isolate the minor diastereomer.

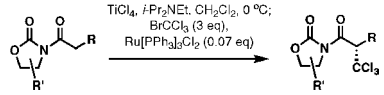
The scope of the haloalkylating reagent investigated in this study is illustrated in Table 2. For most of these examples, the more active commercially available ATRP redox catalyst $Cp^*Ru[PPh_3]_2Cl$ was required to attain optimal yields.[15] Since a number of chlorinated natural products contain a 5,5-dichloroleucine subunit, it is notable that a direct dichloromethylation can be performed in useful yields using bromodichloromethane (Table 2, entry 2). A range of other functionalized haloalkylating reagents proved to be suitable with this catalyst, including dichloro- and trichloroacetates, 1,1,1-trichloroethane, 1-chloro-1-bromo-2,2,2-trifluoroethane, and $Cl_3CCH_2OCO_2Bn$. The

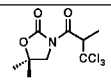
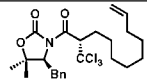
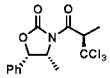
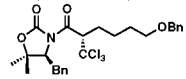
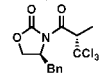
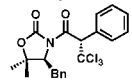
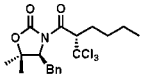
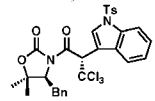
Scheme 1. Biradical Character of Titanium Enolates in Radical Addition Reactions Catalyzed by Ruthenium(II)



10.1021/ja910154f

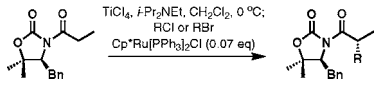
Table 1. Radical Trichloromethylation: *N*-Acyloxazolidinone Scope[a]

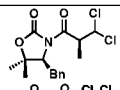
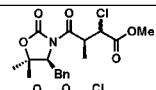
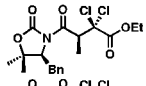
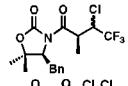
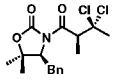
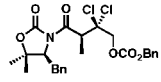


entry	product (dr, yield)[b]	entry	product (dr, yield)[b]
1	 95%	5	 63% (91% brsm), >98:2 [c]
2	 89%, >98:2	6	 87%, >98:2
3	 86%, >98:2	7	 91%, >98:2
4	 99%, >98:2	8	 61%, >98:2

[a] See Supporting Information for experimental details. [b] All yields are of isolated products; dr determined by 500 MHz ^{1}H NMR of the crude mixture of products. [c] 1.0 equiv of $BrCCl_3$ was used, with 3 equiv of the double addition product isolated in 97% yield (dr >98:2).

Table 2. Radical Haloalkylation: Haloalkylating Agent Scope



entry	product	yield dr[a]	entry	product	yield dr[a]
1		64% >98:2	4		75% 1.3:1[b]
2		83% >98:2	5		71% 1.6:1[b]
3		71% >98:2	6		76% >98:2

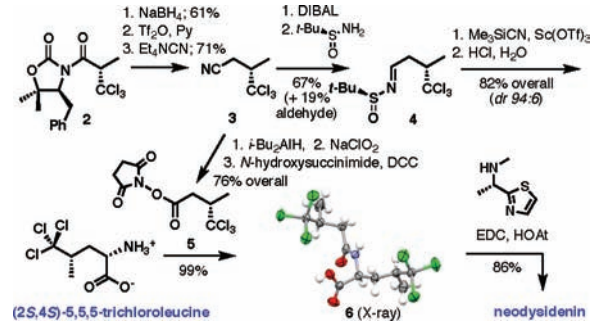
[a] All reported yields are of isolated products; dr was determined by 500 MHz ^{1}H NMR. [b] At the indicated stereocenter.

remainder of the mass balance for the reactions in Table 2 is the substrate, with all yields based on recovered starting material exceeding 90%.

On the basis of this methodology, the total synthesis of neodysidenin through the intermediacy of (2*S*,4*S*)-5,5,5-trichloroleucine was accomplished (Scheme 2). Imide **2** was advanced to Ellman-type *N*-sufinimine **4** in 5 steps.[17] Sc-Catalyzed Strecker synthesis with Me_3SiCN followed by hydrolysis delivered (2*S*,4*S*)-5,5,5-trichloroleucine (82%, dr 94:6).[18] Using this modular approach, all stereoisomers of 5,5-di- or 5,5,5-trichloroleucine may be accessed in a straightforward manner. Subsequent *N*-acylation of the amino acid with reagent **5**, also derived from nitrile **3**, readily afforded dipeptide **6**, which has been advanced to neodysidenin in one additional amidation step (EDC, HOAt, THF, 86% yield).[19]

In summary, a direct ruthenium-catalyzed radical chloroalkylation capitalizing on the valence tautomerism of titanium enolates has been developed. This method served as the centerpiece in the enantioselective total synthesis of trichloroleucine-derived marine natural product neodysidenin.

Scheme 2. Enantioselective Total Synthesis of Neodysidenin



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Supporting Information Available: Experimental procedures and copies of ^{1}H and ^{13}C NMR spectra. This information is available free of charge via the Internet at http://pubs.acs.org.

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