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Access to benzo-fused nine-membered heterocyclic alkenes with a trifluoromethyl carbinol moiety *via* a double decarboxylative formal ring-expansion process under palladium catalysis†

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Direct access to pharmaceutically attractive benzo-fused nine-membered heterocyclic alkenes **3** with a trifluoromethyl carbinol moiety was achieved *via* a palladium-catalyzed double-decarboxylative formal ring-expansion process from six-membered trifluoromethyl benzo[d][1,3]oxazinones **1** to nine-membered trifluoromethyl benzo[c][1,5]oxazonines **3** in the presence of vinyl ethylene carbonates **2**. Generation of a Pd- π -allyl zwitterionic intermediate was proposed in the catalytic cycle. The trifluoromethyl group in the benzoxazinones **1** plays an important role throughout the transformation. Diastereoselective chemical transformations of products **3** were also demonstrated.

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Introduction

Fluoro-functionalized heterocycles with diverse ring sizes and ring systems have been well studied in pharmaceuticals and agrochemicals.¹ Thus, a remarkable number of publications have been dedicated to the development of efficient synthetic methods to construct fluoro-functionalized heterocycles.^{1,2} In particular, heterocyclic molecules with a trifluoromethyl carbinol moiety, *i.e.*, CF₃C(OR¹)R²R³, have gathered much attention^{3–6} on account of their promising biological properties. Efavirenz⁴ (anti-HIV), trifluoromethylated artemisinins⁵ (antimalarial), and fluralaner⁶ (insecticide and acaricide) are representative examples (Fig. 1).

In this context, our group has been engaged in the development of novel synthetic methodologies for fluorine-containing heterocycles for decades.⁷ Including our reports,⁷ the present synthetic strategies for fluorinated heterocyclic molecules are mostly limited to the construction of five- and six-membered ring systems,^{1,2,7} while the synthesis of medium- to large-sized fluoro-functionalized heterocycles such as derivatives of benzo-oxazepine⁸ and macrospheptide A⁹ (Fig. 1) is

extremely rare, despite the pharmaceutical importance of medium-sized heterocyclic compounds (non-fluorinated)¹⁰ and biologically active natural products.¹¹ Very recently, Liu and co-workers reported an elegant method for the construction of fluoroalkyl-functionalized medium-/large-sized carbocyclic alkenes *via* an intramolecular radical trifluoromethylation-cyclization process.¹² Recently, Zhao and co-workers successfully reported the palladium-catalyzed [5 + 4] and [6 + 4] cycloaddition reactions of azadienes with vinyl ethylene carbonates and vinyl oxetanes respectively in good yields and selectivities.¹³ We disclose herein the first synthesis of benzo-fused nine-membered heterocyclic alkenes **3** with a trifluoromethyl carbinol moiety and vinyl ethylene carbonates **2**¹⁴ (Scheme 1).



Fig. 1 Biologically active heterocycles containing a trifluoromethyl carbinol moiety.

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Scheme 1 Direct access to benzo-fused nine-membered heterocyclic alkenes **3** with a trifluoromethyl carbinol moiety from six-membered oxazinones **1** and vinyl ethylene carbonates **2** via palladium-catalyzed double decarboxylative cycloaddition and the further diastereoselective chemical transformations of **3**.

The resulting trifluoromethylated heterocycles **3** have a benzo[*c*][1,5]oxazinone skeleton, and are not only medicinally attractive fluorine-containing heterocycles,¹ but also expanded variants of well-known [1,4]oxazepine pharmaceuticals.¹⁵ Synthesis of the titled nine-membered compounds **3** were achieved from previously unknown trifluoromethylated benzoxazinones **1** (six-membered ring) via a formal ring-expansion pathway under palladium catalysis. The reaction proceeded via the double decarboxylation (DDC)¹⁶ of **1** and vinyl ethylene carbonates **2** followed by a [5 + 4] cycloaddition reaction. The formation of Pd-complex **I** as an intermediate was proposed by LC-MS spectrometric analysis. This method provides an expedient access to trifluoromethylated benzo[*c*][1,5]oxazinones **3** with diverse functional groups in the aromatic moiety, including electron-donating, electron-deficient, and halogenic groups. Moreover, the alkene moiety in products **3** was further functionalized by conventional chemical

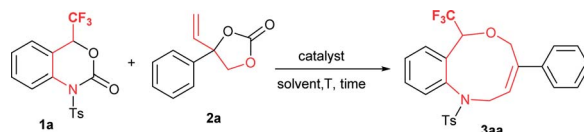
transformations such as epoxidation to **4** and reduction to **5** (Scheme 1) with high diastereoselectivities which make this novel trifluoromethylated nine-membered skeleton more attractive as a template for drug discovery research. The presence of a trifluoromethyl group on **1** plays a pivotal role for their successful transformation to **3** based on comparative studies using non-CF₃-variants of **1**.

Results and discussion

We started a preliminary investigation with the reaction of trifluoromethyl (CF₃) benzoxazinone **1a** and phenyl vinyl ethylene carbonate **2a** in the presence of suitable palladium precursors and/or phosphine ligands (Table 1). We first attempted our reaction of **1a** using similar Pd₂(dba)₃·CHCl₃ conditions in the presence or absence of phosphine ligands, but the results were disappointing (entries 1–4). Moving on to Pd(PPh₃)₄ as a palladium precursor at 50 °C in THF furnished exclusively a nine-membered ring in good yield of 70% (entry 5). Motivated by this result, further optimization was carried out in different solvents. In toluene, a slight decrease in yield was observed, at 66% (entry 6), while in dichloroethane yield improved to 79% (entry 7). Lowering the temperature to room temperature (rt) furnished good yield (70%), but 40 hours were required to complete the reaction (entry 8). An excellent yield of 91% (89%) was observed by increasing the temperature to 80 °C (entry 9). Increasing the temperature further decreased yield dramatically (entry 10, see ESI for more details†).

Based on the optimized reaction conditions, the flexibility of the DDC reaction was scrutinized by using a broad array of vinyl ethylene carbonates (VECs) **2a–m** with **1a**. The results are summarized in Table 2. Both electron-withdrawing and electron-donating groups on the phenyl ring of **2** furnished

Table 1 Optimization conditions^a



Entry	Pd catalyst (with or without ligand)	Solvent	T [°C]	t [h]	Yield ^c [%]
1 ^b	10 mol% Pd ₂ (dba) ₃ ·CHCl ₃	DCM	rt	24	—
2 ^b	5 mol% Pd ₂ (dba) ₃ ·CHCl ₃	THF	40	24	—
3	5 mol% Pd ₂ (dba) ₃ ·CHCl ₃ /10 mol% PCy ₃	THF	40	24	—
4	5 mol% Pd ₂ (dba) ₃ ·CHCl ₃ /10 mol% dtbpm	THF	40	24	—
5	5 mol% Pd(PPh ₃) ₄	THF	50	7	75(70)
6	5 mol% Pd(PPh ₃) ₄	Toluene	50	36	68(66)
7	5 mol% Pd(PPh ₃) ₄	DCE	50	12	83(79)
8	5 mol% Pd(PPh ₃) ₄	DCE	rt	40	79(70)
9	5 mol% Pd(PPh ₃) ₄	DCE	80	12	91(89)
10	5 mol% Pd(PPh ₃) ₄	DCE	Reflux	12	40(34)

^a Experiments were performed with **1a** (0.1 mmol), **2a** (0.15 mmol), 5 mol% Pd(PPh₃)₄ (0.05 mmol) in 1.0 mL solvent. ^b **2a** (0.12 mmol) was used. ^c Yields are ¹⁹F NMR yields with internal standard PhCF₃ and yields (isolated) are also given in parentheses. dtbpm = 1,2-bis(di-*tert*-butylphosphinomethyl)benzene. DCE = 1,2-dichloroethane.



(eV)) while that of **5b** containing CH₃ at the C-4 position (3.33) was lower (Table S6, Fig. S1 in ESI for details†).

Interestingly, the X-ray crystallographic analysis of starting substrate **1a** revealed that **1a** has a sterically unfavourable *cis*-configuration between CF₃ and tosyl groups (Fig. 2). Although the reasons for the stabilization of **1a** in this configuration are not sure,¹⁹ the steric repulsion might be the additional factor for the high reactivity of **1a** for decarboxylation reaction.

To demonstrate the synthetic applicability of CF₃-substituted tetrahydrobenzoxazinones **3**, epoxidation and hydrogenation reactions were carried out as displayed in Scheme 3 based on the classical work of Still and Hoveyda.²⁰ By using the Zhao's condition^{13a} we performed the epoxidation of **3aa** in the presence of *m*-CPBA at 0 °C to rt successfully transformed to epoxide **4** with 67% yield and >20 : 1 diastereoselectivity through the peripheral attack. The X-ray crystallographic structure of **4** (CCDC 1589030†) suggested that epoxidation proceeded *via* a less hindered convex approach. Hydrogenation of **3aa** with H₂ in the presence of Pd-C at rt furnished the desired product **5** (5 : 1 dr) in 74% yield (isolated as a single isomer) (Scheme 3).

A plausible reaction mechanism of the palladium-catalyzed DDC reaction of **1a** with **2a** to **3aa** is portrayed in Scheme 4. The catalytic cycle is first initiated by the oxidative addition of Pd(0) with **2** followed by decarboxylation, which generates the π-allyl-Pd(II) complex **II**. The extremely nucleophilic nature of the alkoxide oxygen of **II** attacks the most electrophilic carbon atom attached to the CF₃ group of **1a** which triggers the opening of benzoxazinone ring to generate reactive species **III**. Due to its highly reactive nature, species **III** immediately transforms into Pd-complex **I** *via* decarboxylation. Recently, Kleij *et al.* disclosed the similar kind of six membered Pd-complex with the



Scheme 4 Plausible mechanism.

support of DFT calculations.²¹ In our case, the formation of Pd-complex **I** was confirmed by LC-MS spectrometry (Fig. S2 in ESI for detail†) but we could not detect it by NMR (Fig. S3, in ESI for detail†).

From complex **I**, there might be two possible pathways for the formation of two different cyclized products. Attack at the terminal position of the Pd-complex (path A) would generate the [5 + 4] cycloaddition product **3aa** while internal attack (*i.e.*, path B) of Pd-complex could result in [4 + 3] cycloaddition to furnish a seven-membered heterocycle **8**. However, we did not obtain the [4 + 3] cycloaddition adduct **8**. This may be attributed to steric hindrance of **8**, *i.e.*, the NTs group as well as the tetra-substituted tertiary carbon center on **8**.

Conclusions

In conclusion, we have established a novel and highly efficient methodology for the synthesis of benzo-fused nine-membered heterocyclic alkenes with a trifluoromethyl carbinol moiety through a palladium-catalyzed double decarboxylative formal ring expansion process. A combination of trifluoromethylated six-membered benzoxazinones with vinyethylene carbonates resulted in direct access to previously unknown trifluoromethyl-functionalized nine-membered heterocycles. The trifluoromethyl substituent at the C-4 position of benzoxazinones plays an important role in this transformation. Diastereoselective transformations of the benzo-fused nine-membered heterocyclic alkene were also achieved to demonstrate the synthetic utility of the products. Investigation of the formation of other medium-sized rings as well as enantioselective variants of the reaction are presently under way in our laboratory.

Conflicts of interest

There are no conflicts to declare.

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Fig. 2 X-ray crystallographic analysis of **1a** (CCDC 1575062†) revealed a sterically unfavourable *cis*-configuration between CF₃ and tosyl groups.



Scheme 3 Diastereoselective derivatizations of tetrahydrobenzoxazinone **3aa**.



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