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Cross-dehydrogenative coupling enables enantioselective access to CF₃-substituted allcarbon quaternary stereocenters†

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A cross-dehydrogenative coupling strategy for enantioselective access to acyclic CF₃-substituted allcarbon quaternary stereocenters has been established. By using catalytic DDQ with MnO₂ as an inexpensive terminal oxidant, asymmetric cross coupling of racemic δ -CF₃-substituted phenols with indoles proceeded smoothly, providing CF₃-bearing all-carbon quaternary stereocenters with excellent chemo- and enantioselectivities. The generality of the strategy is further demonstrated by efficient construction of all-carbon quaternary stereocenters bearing other polyfluoroalkyl and perfluoroalkyl groups such as CF₂Cl, C₂F₅, and C₃F₇.

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Introduction

Enantiopure molecules bearing a trifluoromethyl-containing stereogenic center often possess desirable properties.1 Therefore, practical and robust approaches for their enantioselective synthesis are highly attractive.² On the other hand, the catalytic enantioselective construction of all-carbon guaternary stereocenters remains one of the great challenges in organic chemistry.3 In this context, enantioselective construction of acyclic CF₃-substituted all-carbon quaternary centers is particularly daunting.4-7 Since the seminal work by Shibata, current strategies are restricted to 1,4-conjugate addition to β,β-disubstituted CF₃-enones or nitroolefins (Scheme 1a),⁴ and two isolated methods including substitution of a propargyl electrophile (Scheme 1b),⁵ and hydrohydroxymethylation of CF₃-bearing allenes (Scheme 1c).6 All of these methods rely on reactive functional groups, and extra steps are usually involved for their incorporation. Developing a strategically different C-H functionalization approach for enantioselective construction of CF₃bearing all-carbon quaternary centers is highly desirable.

Enantioselective cross-dehydrogenative coupling (CDC) of two easily accessible C–H substrates represents a straightforward and economical approach in organic synthesis.⁸ Existing studies predominantly focused on C–H bonds adjacent to a heteroatom.^{9,10} But surprisingly, asymmetric CDC involving

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functionalization of acyclic benzylic C–H bonds has rarely been explored.^{11,12} Elegant works from the groups of Cozzi and Gong reported enantioselective CDC of 3-arylmethylindoles with aldehydes^{11*a*} and malonates.^{11*b*} In addition, CDC technology for enantioselective construction of all-carbon quaternary stereocenters has remained elusive.¹³ Recently, our group disclosed a chiral imidodiphosphoric acid catalyzed asymmetric CDC of 2,2-diarylacetonitriles with (hetero)arenes, furnishing triarylmethanes bearing all-carbon quaternary stereocenters with excellent enantioselectivity.^{13*c*} Given the importance of optically active hetero-di- and hetero-triarylmethanes in chemistry,

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b) Substitution of a propargyl electrophile (Nishibayashi)

$$P_{3C}(O)C_{6}F_{5}$$
 Nu
 F_{3C} (Nu = indole) P_{3C} Ar

c) Hydrohydroxymethylation of CF3-bearing allenes (Krische)



d) CDC strategy (this work)



Scheme 1 Overview of enantioselective access to acyclic CF_3 -substituted all-carbon quaternary stereocenters.

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biology, material science, and medicine,¹⁴ we decided to explore the asymmetric CDC of racemic *p*-hydroxybenzyl CF₃ moieties with heteroarenes for construction of these motifs containing CF₃-substituted all-carbon quaternary stereocenters (Scheme 1d).

Three main challenges might obstruct the reaction design. First, regioselective oxidation of C_{δ} –H bond adjacent to strong electron-withdrawing CF₃ group is difficult to achieve, which might be accompanied by competitive oxidation of C_{α} –H bond to 1,2-benzoquinones.¹⁵ Second, even if the expected oxidation proceeded smoothly, the CDC reaction might still be precluded by the potential incompatibility of electron-rich heteroarenes with strongly oxidative conditions. Third, the oxidized intermediate is expected to be highly unstable δ -CF₃-substituted *para*-quinone methide (*p*-QM).¹⁶ Effective and enantioselective addition to highly congested CF₃-substituted carbon of reactive *p*-QM intermediate under strongly oxidative conditions is substantially challenging.^{17–19}

Results and discussion

Initially, chiral phosphoric acid catalyzed asymmetric CDC of p-hydroxybenzyl CF₃ **1a** with indole **2a** was selected as a model

reaction for optimization (Table 1).20 To explore a suitable oxidation system, the reaction involving an initial oxidation of 1a followed by 3a catalyzed nucleophilic addition of 2a was conducted in a two-step, one-pot manner. As expected, efficient oxidation of 1a proved to be challenging. Common reagents for phenol oxidation, such as K₃Fe(CN)₆, (NH₄)₂S₂O₈, Ag₂O, PhI(OAc)₂, and MnO₂, proved to be futile (entries 1 and 2, Table 1). Reaction with DDQ provided expected 4a in 10% yield with 26% ee, though the majority of 1a (83%) was recovered (entry 3, Table 1). Increasing the loading of DDQ did not improve oxidation conversion (entry 4, Table 1). We envisioned that oxidation of 1a with DDQ might be a reversible process, and adopting a DDQ-catalyzed oxidation system might be beneficial for breaking the equilibrium and driving the oxidation process. A screen of terminal oxidants towards metal oxides revealed that use of DDQ (25 mol%) as catalyst and MnO₂ as stoichiometric oxidant furnished a complete and clean oxidation, and the CDC process afforded 4a in 70% yield with 55% ee (entries 5-7, Table 1).²¹ Reversal of the procedure by adding all the components prior to oxidation gave an inferior result (entry 8,





^{*a*} Reaction conditions: **1a** (0.1 mmol) and oxidant (0.12 mmol) in CH₂Cl₂ at 60 °C for 8 h, followed by **2a** (0.1 mmol), **3** (5 mol%), 3 Å molecular sieves (20 mg) at -78 °C for 1 h. ^{*b*} Yield of isolated product. ^{*c*} Determined by chiral HPLC analysis. ^{*d*} K₃Fe(CN)₆, (NH₄)₂S₂O₈, Ag₂O, and PHI(OAc)₂ as oxidant. ^{*e*} 2.0 equiv. of DDQ used. ^{*f*} 25 mol% DDQ with 3.0 equiv. of terminal oxidant. ^{*g*} **2a** and **3a** added before oxidation. ^{*h*} 2.0 equiv. of K₂CO₃ as additive. ^{*i*} **2a** (0.3 mmol) used. n.d. = not determined.

Scheme 2 Scope of δ -alkynyl-substituted substrates for CF₃-containing hetero-diarylmethanes. ^aReaction with **3b** (5 mol%) and **2a** (1.1 equiv.) without K₂CO₃ additive. ^bAsymmetric nucleophilic addition of **2a** was performed at 0 °C.

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Table 1). Optimization of chiral phosphoric acid catalysts identified 3c to be optimal (entries 7 and 9–12, Table 1). K₂CO₃ as a basic additive proved to be beneficial for improving the enantiocontrol (entry 13, Table 1). Increasing the loading of 2a was beneficial to the reaction by slowing down the nucleophilic addition process, and 4a was isolated in 86% yield with 93% ee (entry 14, Table 1).

The scope of asymmetric CDC of δ -CF₃- δ -alkynyl substituted **1** with **2a** was investigated (Scheme 2). In general, substrates bearing a wide range of electronically varied aryl acetylenes with different substitution patterns were tolerated, affording respective hetero-diarylmethanes **4a–4g**, **4j**, and **4k** in good yields with excellent ee. Polyarene naphthalene substituted acetylene **1h** and thiophene substituted **1i** proved to be competent coupling partners. δ -Alkyl acetylene-containing **1l–1p** were also compatible with the asymmetric CDC process, furnishing corresponding **4l–4p** in 66–73% yields with up to 93% ee. The process exhibited a good functional group tolerance, with common functionalities like halides (**4d** and **4e**), primary alcohol (**4n**), propargyl chloride (**4o**), and silyl group (**4p**) well tolerated for further manipulation.

Asymmetric CDC of a variety of δ -aryl substituted 5 with 2a proceeded smoothly, affording respective CF₃-bearing heterotriarylmethanes **6a–6f** with 90–97% ee (Scheme 3). To our knowledge, this is the first example of direct and asymmetric construction of CF₃-substituted tri-arylmethanes.⁵

The substituent effect of indoles was next evaluated (Scheme 4). A broad range of indoles 2 bearing either electron-donating or -withdrawing groups at different positions (C_4 , C_5 , C_6 , and C_7) on aryl rings participated in the CDC process, furnishing corresponding **7a–7h** in 75–88% yields with 90–96% ee. Additionally, C_2 -substituted indoles proved to be competent components, as demonstrated by the generation of **7i** in 70% yield with 92% ee. Besides indole moieties, 2-substituted pyrroles were also identified to be suitable coupling partners in asymmetric CDC reaction, as illustrated by the formation of **9** in 65% yield with 93% ee (Scheme 5). While the scope of 2-



Scheme 3 Scope of δ -aryl-substituted substrates for CF₃-containing hetero-triarylmethanes. ^aReaction with 2a (1.1 equiv.).



Scheme 4 Scope of the indole components



Scheme 5 Asymmetric CDC with 2-substituted pyrrole. ^a1.0 equiv. of 8 used.

substituted pyrroles was not exclusively explored, the result afforded a proof-of-concept for the modularity of the method for asymmetric preparation of diversely functionalized heterodiarylmethanes bearing CF_3 -substituted all-carbon quaternary stereocenters.

The generality of the CDC approach is further demonstrated by enantioselective construction of all-carbon quaternary stereocenters bearing other polyfluoroalkyl or perfluoroalkyl groups, such as CF_2Cl (**11a**), C_2F_5 (**11b**), and C_3F_7 (**11c**) (Scheme 6).

The synthetic utilities of the method were next examined (Scheme 7). The phenolic hydroxyl group in **4a** was removed through triflation followed by hydrogenation affording **12** in 86% yield (Scheme 7a). Phenol **4a** can also undergo triflation followed by palladium-catalyzed cross-coupling reaction, furnishing biaryl **13** efficiently (Scheme 7b). Notably, the ee



Scheme 6 Enantioselective access to other polyfluoroalkyl-bearing all-carbon quaternary stereocenters.



values of the products remain highly reserved in these processes.

Control experiments were performed to gain further insights into the mechanism (Scheme 8). Upon completion of oxidation of 1a, δ -CF₃- δ -alkynyl-substituted *p*-QM 14 was isolated in 11% yield (Scheme 8a). The low yield might be ascribed to the poor stability of δ -CF₃-substituted *p*-QM compound. Subjecting 14 to standard CDC conditions in the absence of oxidation elements furnished 4a with comparable yield and ee to those observed in the one-pot process, thus indicating the intermediacy of p-QM 14 (Scheme 8b). No invertible reaction was observed for 14 and 2,3-dichloro-4,5-dicyanohydroquinone (DDQH₂), the reduction product of DDQ (Scheme 8c). The asymmetric 1,6-conjugate addition to 14 was not influenced by introducing stoichiometric amount of acidic DDQH₂ (Scheme 8d). K₂CO₃ was found to be beneficial for improving the enantiocontrol (entry 13, Table 1). Accordingly, chiral potassium-organophosphate 3f was prepared in situ for real catalyst identification (Scheme 8e). No enantioselective catalytic reactivity was observed for 3f, implying that 3c but not 3f should be the real catalyst, and the hydroxyl group in chiral phosphoric acid is requisite. No reaction was observed for p-methoxybenzyl CF₃ 15, indicating the significance of the hydroxyl moiety in the *in situ* formation of *p*-QM intermediate (Scheme 8f). According to the above experiments, a plausible mechanism was recommended (Scheme 8g). Racemic p-hydroxybenzyl CF₃ moiety **1a** might be oxidized by catalytic amount of DDQ, giving p-QM 14 together with the generation of DDQH₂. Stoichiometric MnO₂ as terminal oxidant proved to be crucial to the complete oxidation of 1a to 14 by converting DDQH₂ to DDQ for the catalytic cycle.²¹ Chiral phosphoric acid 3c catalyzed asymmetric 1,6-conjugate addition of indole 2a to 14 yielding expected 4a.²² Asymmetric CDC of 1a with N-methyl protected indole 19 provided inferior ee to unprotected 2a, implying that the N-H moiety might act as a hydrogen bond donor (Scheme 8h). A plausible transition state was proposed in Scheme 8i, in which chiral phosphoric acid acts as a bifunctional role for activation of both coupling partners and remote stereocontrol by hydrogen bonding. p-QM intermediates can be generated in situ through chiral phosphoric acid catalyzed dehydration of p-hydroxybenzyl alcohols.¹⁷ Accordingly, δ-CF₃-substituted *p*-hydroxybenzyl alcohol 21 was subjected to the CDC condition without oxidation elements (Scheme 8j). However, no reaction was observed even at an elevated temperature, thus demonstrating the uniqueness



Scheme 8 Control experiments and the proposed mechanism.

of the oxidation strategy in generating unstable $\delta\text{-}CF_3\text{-}$ substituted p-QM intermediates.

Conclusions

In summary, CDC strategy for enantioselective construction of CF_3 -substituted all-carbon quaternary stereocenters has been established for the first time. By using catalytic DDQ with MnO₂ as an inexpensive terminal oxidant, asymmetric cross-coupling of racemic *p*-hydroxybenzyl CF_3 moieties with indoles and pyrroles proceeded smoothly, providing acyclic CF_3 -bearing all-carbon quaternary centers with excellent chemo- and enantio-selectivity. The generality of the strategy is further demonstrated by efficient formation of all-carbon quaternary centers bearing other polyfluoroalkyl and perfluoroalkyl groups such as CF_2Cl , C_2F_5 , and C_3F_7 . We envisioned that the strategically different approach described here will provide an attractive platform for enantioselective access to all-carbon quaternary stereocenters bearing diverse perfluoroalkyl groups that are otherwise difficult to be prepared by existing methods.

Conflicts of interest

There are no conflicts to declare.

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