Introduction

The aromatic β-carboline skeleton is ubiquitous in many alkaloids,1 bioactive congeners,2 agrochemicals3 and functional materials.4 In view of the significance of β-carbolines in drug discovery, agricultural chemistry and material science, development of practical, efficient and environmentally benign methods for syntheses of β-carbolines is of considerable interest and has attracted much attention from chemists.5

Since 1,2,3,4-tetrahydro-β-carbolines (THβCs) can be readily and efficiently prepared via the Pictet–Spengler reaction,6 so the aromatization of THβCs via dehydrogenation or oxidation is an easy and good method to obtain β-carbolines. Dehydrogenation of THβCs usually employed precious metallic catalysts including Pd,7 Pt8 and complexes of Ru9 and Ir.10 Oxidation of THβCs normally needed stoichiometric strong oxidants such as KMnO4,11 MnO2,12 SeO2,13 DDQ,14 TCCA15 and IBX.16 However, uses of expensive metallic catalysts and hazardous strong oxidants are sometimes lack of cheapness, practicality and environmental friendliness, therefore novel practical, efficient and environmentally benign methods for the conversion of THβCs to β-carbolines are highly desirable.

Oxygen is an important component of air, which is one of the most abundant resources on the earth, so the air used as a clean and eco-friendly oxidant for various oxidation reactions in recent decades.17 On the other hand, copper is one of the most abundant metals on the earth’s crust, thus copper salts are normally very cheap, and moreover copper is a low toxic transition metal, so an increasing amount of copper-catalyzed reactions have been developed recently.18 Herein, we describe a new practical and very mild Cu(II)-catalyzed oxidative conversion of THβCs to β-carbolines using air as the clean oxidant.

Results and discussion

At first, we attempted to find out the optimized reaction conditions for the Cu-catalyzed oxidative conversion of THβCs 1 to β-carbolines 2. With the conversion 1-phenyl-THBC 1a to 1-phenyl-β-carboline 2a as the model reaction, we tried the reaction under various conditions, and results are summarized in Table 1. As can be seen from Table 1, various copper reagents have been tested as catalysts (Table 1, Entries 2–11), and it was found that cupric bromide is the best catalyst for the reaction. When 0.2 equivalents of CuBr2 was used as the catalyst, the aerobic oxidation of compound 1a took place smoothly at room temperature in DMSO in the presence of 2 equivalents of 1,8-diazabicyclo[5,4,0]undec-7-ene (DBU) to afford the desired compound 2a in high yield (Entry 2). Several amines such as DBU, 1,5-diazabicyclo[4,3,0]non-5-ene (DBN), 4-dimethylaminopyridine (DMAP), pyridine and trimethylamine have been tested as bases (Entries 2 and 12–15), DBU was found to be the most appropriate base for the reaction. Amount of DBU has significant effect on the reaction (Entries 2 and 16–19), almost no desired product 2a could be obtained in the absence of DBU (Entry 16); and the reaction was hard to be complete even for a longer time, if less than 2.0 equivalents of DBU were used (Entries 17–19). Several other solvents such as N,N-dimethylformamide (DMF), acetonitrile, ethanol, tetrahydrofuran (THF), dichloromethane, ethyl acetate and acetone have also been examined (Entries 20–26); DMSO is obviously better than them. Additionally, when the reaction temperature was...
elevated, the reaction velocity increased, but the yield of desired product 2a obviously decreased (Entries 27–29).

Subsequently, we attempted the CuBr$_2$-catalyzed oxidative conversion of variously substituted TH$_b$Cs 1 to $\beta$-carbolines 2 in DMSO with DBU as the base, and the results are summarized in Table 2. The scope of the reaction is very wide; almost all of the tested TH$_b$Cs could be smoothly converted to $\beta$-carbolines in good to excellent yields. All the conversions were performed under the standard reaction conditions (see footnote of the Table 2), and a total of twenty-four variously substituted $\beta$-carbolines 2a–2x were obtained in 78–96% yields.

A possible mechanism for the CuBr$_2$-catalyzed oxidative conversion of TH$_b$Cs 1 to $\beta$-carbolines 2 is proposed in Scheme 1. As can be seen from Scheme 1, TH$_b$Cs 1 would first undergo CuBr$_2$-catalyzed aerobic oxidation of C–N single bond to C–N double bond to produce 3,4-dihydro-$\beta$-carbolines I-A according to Adimurthy’s report.$^{19}$ 3,4-Dihydro-$\beta$-carbolines I-A would then undergo DBU-promoted reversible tautomerization$^{20}$ to form unstable enamine intermediates I-B, which would also

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**Table 1** Optimization of reaction conditions for the Cu-catalyzed aerobic oxidative conversion of 1-phenyl-TH$_b$C 1a to 1-phenyl-$\beta$-carboline 2a

| Entry | Catalyst | Base | Solvent | $T$ (°C) | $t$ (h) | Yield (%)
|-------|----------|------|---------|---------|--------|--------|
| 1     | None     | DBU  | DMSO    | 25       | 18     | 0      |
| 2     | CuBr$_2$ | DBU  | DMSO    | 25       | 18     | 95     |
| 3     | CuCl$_2$ | DBU  | DMSO    | 25       | 18     | 90     |
| 4     | Cu(OAc)$_2$ | DBU | DMSO    | 25       | 18     | 86     |
| 5     | CuBr     | DBU  | DMSO    | 25       | 18     | 85     |
| 6     | CuCl     | DBU  | DMSO    | 25       | 18     | 84     |
| 7     | CuI      | DBU  | DMSO    | 25       | 18     | 82     |
| 8     | CuSO$_4$ | DBU  | DMSO    | 25       | 24     | <5     |
| 9     | CuCO$_3$ | DBU  | DMSO    | 25       | 24     | <5     |
| 10    | CuO      | DBU  | DMSO    | 25       | 24     | <5     |
| 11    | CuBr$_2$ | DBN$^g$ | DMSO    | 25       | 20     | 88     |
| 12    | CuBr$_2$ | DMAP$^h$ | DMSO    | 25       | 20     | 19     |
| 13    | CuBr$_2$ | Py    | DMSO    | 25       | 20     | 12     |
| 14    | CuBr$_2$ | Et$_3$N | DMSO    | 25       | 20     | 10     |
| 15    | CuBr$_2$ | None  | DMSO    | 25       | 18     | 0      |
| 16    | CuBr$_2$ | (0.5)$^i$ | DMSO    | 25       | 60     | 75     |
| 17    | CuBr$_2$ | (1.0)$^i$ | DMSO    | 25       | 30     | 83     |
| 18    | CuBr$_2$ | (1.5)$^i$ | DMSO    | 25       | 25     | 92     |
| 19    | CuBr$_2$ | DBU   | DMF$^l$ | 25       | 24     | 82     |
| 20    | CuBr$_2$ | DBU   | CH$_2$CN | 25       | 24     | 65     |
| 21    | CuBr$_2$ | DBU   | EtOH    | 25       | 24     | 23     |
| 22    | CuBr$_2$ | DBU   | THF$^m$ | 25       | 24     | 30     |
| 23    | CuBr$_2$ | DBU   | CH$_2$Cl$_2$ | 25   | 24     | 27     |
| 24    | CuBr$_2$ | DBU   | EtOAc   | 25       | 24     | 12     |
| 25    | CuBr$_2$ | DBU   | Me$_2$CO | 25      | 24     | 14     |
| 26    | CuBr$_2$ | DBU   | DMSO    | 45       | 13     | 90     |
| 27    | CuBr$_2$ | DBU   | DMSO    | 65       | 9      | 84     |
| 28    | CuBr$_2$ | DBU   | DMSO    | 85       | 6      | 76     |

$^a$ All reactions were performed at $T$ °C for $t$ hours under an atmosphere of air. $^b$ 20% (mol%) of the catalyst was used. $^c$ 2.0 equivalents of the base were used unless otherwise indicated. $^d$ Isolated yields. $^e$ 1,8-Diazabicyclo[5,4,0]undec-7-ene. $^f$ Dimethyl sulfoxide. $^g$ 1,5-Diazabicyclo[4,3,0]non-5-ene. $^h$ 4-Dimethylaminopyridine. $^i$ 0.5 equivalent of DBU was used. $^j$ 1.0 equivalent of DBU was used. $^k$ N,N-Dimethylformamide. $^m$ Tetrahydrofuran.

**Table 2** CuBr$_2$-catalyzed oxidation of variously substituted TH$_b$Cs 1 to $\beta$-carbolines 2 using air as the clean oxidant

| R$^1$ | R$^2$ | Reaction conditions: TH$_b$Cs 1 (2 mmol), CuBr$_2$ (0.4 mmol), DBU (4 mmol), DMSO (6 mL), stirring at room temperature (25 °C) under an atmosphere of air. $^a$ Reaction time. $^b$ Isolated yields.
|-------|------|---------|---------|--------|--------|
| 2a    | 2b   | CuBr$_2$, DBU, DMSO, r.t., air ($O_2$) | 25       | 18     | 88     |
| 2d    | 2e   | CuBr$_2$, DBU, DMSO, r.t., air ($O_2$) | 25       | 18     | 82     |
| 2g    | 2h   | CuBr$_2$, DBU, DMSO, r.t., air ($O_2$) | 25       | 18     | 80     |
| 2i    | 2j   | CuBr$_2$, DBU, DMSO, r.t., air ($O_2$) | 25       | 18     | 77     |

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undergo the CuBr₂-catalyzed aerobic oxidation of C–N single bond to afford β-carbolines. Actually, dihydro-β-carbolines 1-A could be isolated if the reaction was stopped in the midway. For example, when the CuBr₂-catalyzed oxidative conversion of 1-phenyl-THβC 1 to 1-phenyl-β-caroline 2a was stopped at 8 h, 1-phenyl-3,4-dihydro-β-caroline was obtained in 36% yield.

To showcase the synthetic utility of the above-described method for the CuBr₂-catalyzed oxidative conversion of THβCs 1 to β-carbolines 2, we have successively applied the methodology to the efficient and practical total syntheses of two β-carboline alkaloids perlolyrine 3 and flazin 4.

Perlolyrine 3 and flazin 4 are both strongly fluorescent 1-furanyl-β-caroline alkaloids. These two particular alkaloids are widespread in nature, and have been isolated from plants, bacteria, Japanese sake and soy sauce.18,21 Several total syntheses of perlolyrine 3 and flazin 4 have been reported hitherto,21 we herein report novel practical total syntheses of them, which are depicted in Scheme 2. Pictet–Spengler reaction of tryptamine and tryptophan methyl ester with 2-furaldehyde first gave THβCs 5 and 6 in 82% and 83% yields, respectively. CuBr₂-catalyzed oxidation of compounds 5 and 6 with air then furnished β-carbolines 7 and 8 in 89% and 90% yields, respectively. Next, hydroxymethylation of compounds 7 and 8 with HCHO in AcOH produced perlolyrine 3 and compound 9 in 86% and 85% yields, respectively. Hydrolysis of the ester 9 afforded flazin 4 in 92% yield. Thus, perlolyrine 3 was synthesized from tryptamine in 3 steps in 63% overall yield; and flazin 4 was synthesized from tryptophan methyl ester in 4 steps in 58% overall yield.

Conclusions

In conclusion, we have developed a novel method for the CuBr₂-catalyzed oxidative conversion of THβCs to β-carbolines. This method has some advantages as follows: (a) the process was carried out at room temperature with air as the clean oxidant, so it is very mild and environmentally benign; (b) CuBr₂ as the catalyst is inexpensive and low-toxic; (c) all products were obtained in good to excellent yields; (d) the reaction has very good tolerance of functional groups, it seemed to be applicable to all the tested substrates; (e) experiment operation is quite easy. In addition, novel practical total syntheses of β-carboline alkaloids perlolyrine and flazin were performed with the above-described CuBr₂-catalyzed mild oxidation of THβCs as the key step.

Experimental

General

1H NMR and 13C NMR spectra were acquired on a Bruker AM 400 instrument, chemical shifts are given on the δ scale as parts per million (ppm) with tetramethylsilane (TMS) as the internal standard. IR spectra were recorded on a Nicolet Magna IR-550 instrument. Mass spectra were performed with a HP1100 LC-MS spectrometer. Melting points were measured on a Met-Temp II melting point apparatus. Column chromatography was performed on silica gel (Qingdao Chemical Factory). All reagents and solvents were analytically pure, and were used as such as received from the chemical suppliers.

General procedure for the preparation of various THβCs 1. 1-Substituted tryptamine (3 mmol) was dissolved in CH₂Cl₂ (10 mL), an aldehyde (3.3 mmol) was added. The resulting solution was cooled to 0 °C, TFA (0.686 mg, 6.016 mmol) was added. The mixture was then stirred at 0–5 °C for 2–6 h. After the reaction was complete (checked by TLC, eluent: EtOAc/CH₂Cl₂ = 1 : 4), solvent was removed under vacuum, the residue was then partitioned between EtOAc (30 mL) and an aqueous solution of K₂CO₃ (10% w/w, 20 mL). Two phases were separated, and the aqueous phase was extracted again with EtOAc (20 mL). Organic extracts were combined, and dried over anhydrous MgSO₄. Evaporation of solvent under vacuum gave crude product, which was purified by flash chromatography (eluent: MeOH/CH₂Cl₂ = 1 : 20–1 : 10) to afford THβCs 1a–1x in 70–95% yields.

General procedure for the CuBr₂-catalyzed oxidative conversion of THβCs 1 to β-carbolines 2. THβCs 1 (2 mmol) was dissolved in DMSO (5 mL). DBU (609 mg, 4.000 mmol) and
anhydrous CuBr₂ (89.5 mg, 0.401 mmol) were added. The resulting solution was then stirred under air at room temperature (around 25 °C) for 12–24 h (see Table 2). After the reaction was complete (checked by TLC, EtOAc/CH₂Cl₂ = 1 : 1:4), the reaction solution was poured into the mixed solution of EtOAc (30 mL) and aqueous ammonia (5% w/w, 25 mL). After the mixture was stirred for 5 minutes, two phases were separated. The aqueous layer was extracted again with EtOAc (20 mL). The organic extracts were combined and washed with brine (10 mL). The organic solution was dried over anhydrous MgSO₄, and then was concentrated under vacuum to give the crude product, which was purified by flash chromatography (eluents: EtOAc/CH₂Cl₂ = 1 : 2 to 1 : 15) to afford pure β-carbolines 2 in 78–96% yield as indicated in the Table 2. Characterization data of the β-carbolines 2a–2x are given in the ESI† of this paper.

**Total syntheses of perolylone 3 and flazin 4**

1-(Furan-2-yl)-1,2,3,4-tetrahydro-9H-pyrido[3,4-b]indole 5. A mixture of tryptamine (1.604 g, 10.01 mmol), 2-furaldehyde (1.076 g, 11.20 mmol) and CH₂Cl₂ (15 mL) was stirred and cooled to 0 °C by an ice-bath. TFA (2.285 g, 20.04 mmol) was slowly added, and then the reaction mixture was further stirred at 0 °C for 2 h. After the reaction was complete (checked by TLC, eluent: EtOAc/CH₂Cl₂ = 1 : 3), ethyl acetate (60 mL) and an aqueous solution of K₂CO₃ (10% w/w, 30 mL) were added. The mixture was vigorously stirred for 5 min, and then two phases were separated. Organic phase was extracted again with ethyl acetate (20 mL). Organic extracts were combined and dried over anhydrous MgSO₄, and then was concentrated under vacuum to give the crude product, which was purified by flash chromatography (eluents: MeOH/CH₂Cl₂ = 1 : 10) to afford pure compound 5 (1.957 g, 8.213 mmol) in 82% yield as white solid, mp 138–139 °C. ¹H NMR (CDCl₃, 400 MHz) δ 8.13 (s, 1H, NH in indole), 7.94 (s, 1H), 7.64 (d, J = 7.8 Hz, 1H), 7.48 (d, J = 3.2 Hz, 1H), 7.32 (d, J = 8.0 Hz, 1H), 7.18 (dd, J₁ = 8.0 Hz, J₂ = 7.9 Hz, 1H), 7.11 (dd, J₁ = 7.8 Hz, J₂ = 7.9 Hz, 1H), 6.96 (bs, 1H, NH), 6.66 (d, J = 3.7 Hz, 1H), 6.44 (dd, J₁ = 3.7 Hz, J₂ = 3.2 Hz, 1H), 3.90 (t, J = 7.3 Hz, 2H), 3.17 (t, J = 7.3 Hz, 2H). ¹³C NMR (CDCl₃, 100 MHz) δ 154.51, 142.52, 135.87, 131.84, 127.23, 121.91, 119.37, 118.34, 111.04, 110.35, 109.94, 107.76, 50.73, 41.46, 22.31. HRMS (ESI) m/z calcld for C₁₇H₁₃N₂O₃Na [M + Na]⁺: 321.1059, found: 321.1059.

1-(Furan-2-yl)-9H-pyrido[3,4-b]indole 7. Compound 5 (0.962 g, 4.037 mmol) was dissolved in DMSO (8 mL), DBU (1.225 g, 8.047 mmol) and anhydrous CuBr₂ (0.179 g, 0.801 mmol) were added. The resulting solution was then stirred under air at 25 °C for 16 h. After the reaction was complete (checked by TLC, eluent: EtOAc/CH₂Cl₂ = 1 : 1), the reaction solution was poured into the mixed solution of EtOAc (50 mL) and aqueous ammonia (5% w/w, 20 mL). After the mixture was stirred for 5 minutes, two phases were separated. The aqueous layer was extracted again with EtOAc (20 mL). The organic extracts were combined and washed with brine (10 mL). The organic solution was dried over anhydrous MgSO₄, and then was concentrated under vacuum to give the crude product, which was purified by flash chromatography (eluents: EtOAc/CH₂Cl₂ = 1 : 3) to afford pure compound 7 (0.842 g, 3.594 mmol) in 89% yield as white solid, mp 166–167 °C. ¹H NMR (DMSO-d₆, 400 MHz) δ 11.50 (s, 1H, NH in indole), 8.38 (d, J = 5.2 Hz, 1H), 8.25 (d, J = 7.8 Hz, 1H), 8.08 (d, J = 5.2 Hz, 1H), 7.99 (d, J = 1.6 Hz, 1H), 7.77 (d, J = 8.2 Hz, 1H), 7.58 (dd, J₁ = 7.6 Hz, J₂ = 7.8 Hz, 1H), 7.23–7.32 (m, 2H), 6.79 (dd, J₁ = 3.5 Hz, J₂ = 3.2 Hz, 1H). ¹³C NMR (CDCl₃, 100 MHz) δ 155.09, 143.34, 141.09, 139.47, 134.09, 131.97, 130.83, 129.17, 122.25, 121.87, 120.72, 114.26, 112.92, 112.25, 109.32. HRMS (ESI) m/z calcld for C₁₇H₁₃N₂O₃ [M + H]⁺: 235.0871, found: 235.0872.

**Methyl-1-(furan-2-yl)-1,2,3,4-tetrahydro-9H-pyrido[3,4-b]indole-3-carboxylate 6.** Compound 6 was prepared from tryptophan methyl ester and 2-furaldehyde according to the same procedure as above for compound 5. Compound 6 was obtained as an epimeric mixture of cis and trans isomers (cis/trans = 3 : 5) in a combined yield of 83% as offwhite solid. Two epimers can be separated by chromatography, but herein the epimeric mixture was used as such for the next step. Data for cis epimer: white solid, mp 141–142 °C. ¹H NMR (CDCl₃, 400 MHz) δ 7.98 (s, 1H, NH in indole), 7.50 (d, J = 7.6 Hz, 1H), 7.41 (d, J = 3.5 Hz, 1H), 7.25 (d, J = 7.8 Hz, 1H), 7.15 (dd, J₁ = 7.6 Hz, J₂ = 7.7 Hz, 1H), 7.11 (dd, J₁ = 7.7 Hz, J₂ = 7.8 Hz, 1H), 6.32–6.36 (m, 2H), 5.38 (s, 1H), 3.91 (dd, J₁ = 9.8 Hz, J₂ = 4.5 Hz, 1H), 3.79 (s, 3H), 3.17 (dd, J₁ = 15.0 Hz, J₂ = 4.5 Hz, 1H), 2.95 (dd, J₁ = 15.0 Hz, J₂ = 9.8 Hz, 1H), 2.44 (s, 1H, NH). ¹³C NMR (CDCl₃, 100 MHz) δ 173.06, 153.02, 142.85, 136.03, 131.79, 129.01, 122.18, 119.68, 118.28, 111.07, 110.48, 108.61, 107.78, 56.51, 52.33, 51.64, 25.46. HRMS (ESI) m/z calcld for C₁₇H₁₄N₂O₃Na [M + Na]⁺: 319.1059, found: 319.1057.

**Compound 8.** Compound 8 was prepared from compound 6 according to the same procedure as above for compound 7. Compound 8 was obtained in 90% yield as white solid, mp 168–169 °C. ¹H NMR (DMSO-d₆, 400 MHz) δ 11.93 (s, 1H, NH in indole), 8.90 (s, 1H), 8.44 (d, J = 8.0 Hz, 1H), 8.06 (d, J = 3.3 Hz, 1H), 7.84 (d, J = 8.2 Hz, 1H), 7.65 (dd, J₁ = 8.0 Hz, J₂ = 8.1 Hz, 1H), 7.32–7.40 (m, 2H), 6.85 (dd, J₁ = 3.3 Hz, J₂ = 3.7 Hz, 1H), 3.96 (s, 3H). ¹³C NMR
ethyl acetate (25 mL) and water (20 mL) were added. The reaction was complete (checked by TLC, eluent: EtOAc/CH2Cl2 15:85) and was removed by vacuum distillation to give a viscous residue, which was partitioned between ethyl acetate (30 mL) and an aqueous solution of potassium carbonate (10% w/v, 20 mL). Two phases were separated, and aqueous phase was extracted again with ethyl acetate (20 mL). The organic extracts were combined and washed twice with brine (2 × 10 mL). After having been dried over anhydrous MgSO4, the organic solution was concentrated under vacuum to give crude solid product, which was purified by flash chromatography (eluent: MeOH/CH2Cl2 = 1 : 10) to give pure perolyrine 3 (0.457 g, 1.729 mmol) in 86% yield as pale yellow solid, mp 165–166 °C. 

\[ ^1H \text{ NMR (DMSO-d}_6, 400 MHz) \delta 11.24 (s, 1H, NH in indole), 8.38 (d, J = 5.1 Hz, 1H), 8.27 (d, J = 7.8 Hz, 1H), 8.08 (d, J = 5.1 Hz, 1H), 7.78 (d, J = 8.2 Hz, 1H), 7.61 (dd, J1 = 7.8 Hz, J2 = 8.0 Hz, 1H), 7.29 (dd, J1 = 8.0 Hz, J2 = 8.2 Hz, 1H), 7.23 (d, J = 3.3 Hz, 1H), 6.60 (d, J = 3.3 Hz, 1H), 5.50 (t, J = 6.0 Hz, 1H), 4.68 (d, J = 6.0 Hz, 2H). \]

\[ ^13C \text{ NMR (DMSO-d}_6, 100 MHz) \delta 156.73, 152.14, 140.92, 138.16, 133.14, 130.47, 129.42, 128.39, 121.59, 120.61, 119.68, 113.60, 112.40, 109.62, 109.04, 55.95. \]

HRMS (ESI) calcd for C16H11NO2 [M + H]+: 265.0977, found: 265.0974. IR (KBr) 3406, 3297, 2922, 1727, 1565, 1435, 1351, 1251, 1118, 1005, 746 cm⁻¹.

### Conflicts of interest

There are no conflicts to declare.

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