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Direct access to chiral aliphatic amines by catalytic enantioconvergent redox-neutral amination of alcohols

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Xiao Qian Ng[1,2,5], Ching Si Lim[1,5], Ming Wai Liaw[1,3], Thanh Truong Quach[1], Bin-Miao Yang[4], Valerio Isoni[2], Jie Wu[1] & Yu Zhao[1,4]

Chiral aliphatic amines are privileged functionalities in pharmaceutical molecules and play an essential role as ligands and catalysts in organic synthesis. It is therefore important to develop efficient catalytic strategies to access aliphatic amines in an enantiopure form. Despite great advancement in asymmetric amination methods, including reductive amination and C–N cross coupling, direct access to diverse enantioenriched aliphatic amines from readily available feedstocks is still lacking. Herein, we demonstrate direct enantioconvergent amination of racemic secondary alcohols using a variety of aliphatic primary amines, under the cooperative catalysis of a chiral iridium complex with a chiral phosphoric acid. This strategy realizes a challenging catalytic redox-neutral cascade without the need for any stoichiometric reagent, offering a one-step conversion of feedstock substrates to valuable chiral aliphatic secondary amines in high yield and enantioselectivity. The use of this atom-economical carbon–nitrogen bond-forming strategy is illustrated by the enantioselective synthesis of commercial drugs and their analogues. Futhermore, we discovered an intriguing racemization pathway for chiral aliphatic amines, which delivers important guiding principles for redox-related stereoselective control in chiral amine synthesis.

Amines play an essential role as key pharmacophores in life-saving pharmaceuticals and are ubiquitous in commercial small-molecule drugs (84% of >1,000 US Food and Drug Administration (FDA)-approved small-molecule pharmaceuticals in 2014)[1]. In particular, aliphatic amines bearing primary, secondary or tertiary alkyl amine units are often chiral and ubiquitously present in drugs as seen from highly valued examples in Fig. 1a. Accordingly, the development of efficient catalytic methods that allow access to diversely substituted aliphatic amines in high enantiopurity is highly desired and remains an actively explored area of research in synthetic chemistry[2].

Great advancements have been achieved towards efficient chiral amine synthesis using various approaches including enantioselective additions involving imines[3,4], hydroamination of alkenes[5] and the extensively used classical asymmetric hydrogenation of imines[6,7] and reductive amination of carbonyls[8]. The strategy of reductive amination in particular has found wide application in pharmaceutical industry due to its convenient use of simple ketone and amine substrates (strategy A in Fig. 1b). Yet, most successes for this strategy have been limited to the reactions of anilines and certain protected amines, with breakthroughs using ammonium salts[9,10] and benzylic amines[11] for reductive amination

[1]Department of Chemistry, National University of Singapore, Singapore, Singapore. [2]Institute of Sustainability for Chemicals, Energy and Environment (ISCE2), Singapore, Singapore. [3]Integrative Sciences and Engineering Programme, NUS Graduate School, National University of Singapore, Singapore, Singapore. [4]Joint School of National University of Singapore and Tianjin University, International Campus of Tianjin University, Fuzhou, China. [5]These authors contributed equally: Xiao Qian Ng, Ching Si Lim. e-mail: chmjie@nus.edu.sg; zhaoyu@nus.edu.sg

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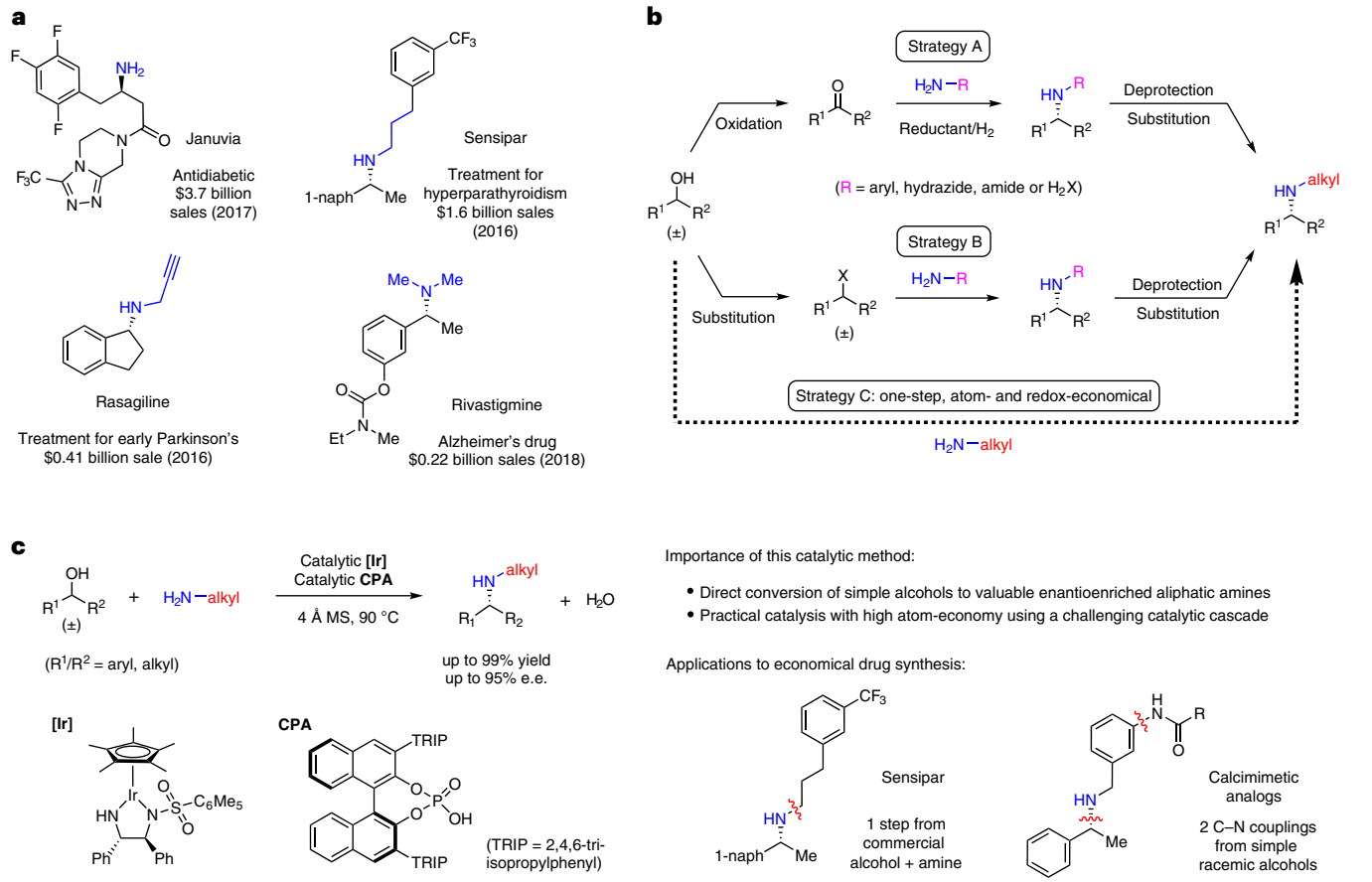

Fig. 1 | Importance and synthesis of aliphatic amines. a, Representative drugs containing chiral aliphatic amines. **b**, Established strategies for chiral aliphatic amine synthesis. **c**, This work, showing direct enantioconvergent amination of racemic alcohols with applications to drug synthesis. naph, naphthyl; MS, molecular sieves.

made only recently. Application of these methods to the preparation of chiral aliphatic amines inevitably requires further stoichiometric derivatization (for example, deprotection followed by N-substitution), diminishing the overall efficiency of these methods. Notably, in many cases, the carbonyls are prepared from the corresponding readily available alcohols by oxidation (for example, in the patented synthesis of Sensipar)[12]. In these processes, the overall conversion of alcohols to chiral amine products proceeds through stepwise oxidation followed by reductive amination, which certainly leaves room for much improved atom and redox economy[13,14]. As an intriguing alternative approach, great advancement has been made in enantioconvergent C–N coupling of racemic organohalides with amines and amides in recent years, delivering chiral amines with high efficiency and enantiopurity (strategy B in Fig. 1b)[15,16]. Yet, application of this strategy to aliphatic amine synthesis also requires additional steps for the preconversion of alcohols into organohalide substrates and postconversion of protected chiral amines into the target *N*-alkyl amines. A one-step, enantioselective synthesis of diverse chiral aliphatic amines directly from feedstock alcohols and amines is still lacking.

Recognizing this notable gap in chiral aliphatic amine synthesis, we sought to achieve a one-step, redox-neutral access to a broad range of chiral aliphatic amines from the direct coupling of simple racemic alcohols and alkyl primary amines by the development of an efficient catalytic borrowing hydrogen methodology (strategy C in Fig. 1b). This strategy has attracted much attention in recent years as an atom- and redox-economical approach to promote sustainable chemical synthesis[17–21]. By adopting a catalytic oxidation-condensation-reduction cascade, borrowing hydrogen catalysis delivers the desired products using the alcohol substrate as an inherent hydrogen source, and thus avoids the use of oxidants or reductants and circumvents stoichiometric waste production. In particular, direct amination of alcohols in a redox-neutral fashion provides substantial practical advantages for amine synthesis over the traditional imine hydrogenation and reductive amination of ketones. Aimed towards chiral amine synthesis, our research group and others have reported catalytic enantioconvergent transformations of racemic alcohols to value-added enantioenriched amines[22–27] as well as *N*-containing heterocycles[28–33]. However, all these reports are exclusively limited to the use of anilines or protected amines. Deprotection and further substitution of these products are still needed to produce the target chiral aliphatic amines, hampering the wide use of these methods in drug synthesis.

Herein, we report our development of a general, enantioconvergent amination of racemic secondary alcohols using diverse aliphatic primary amines (Fig. 1c). Under the cooperative catalysis[34] of an iridium complex and a chiral phosphoric acid (CPA), this system successfully delivers a variety of enantioenriched aliphatic secondary amines from simple racemic alcohols and aliphatic primary amines. Notably, no external stoichiometric reagent is needed nor wasteful side product is generated for these redox-neutral transformations. Application of our method has also been showcased in the streamlined synthesis of chiral aliphatic amine-based drugs such as the blockbuster hyperparathyroidism drug Sensipar (R-Cinacalcet) and analogues of calcimimetic drugs for treating bowel disorders and epithelial injuries.

Establishing efficient amination with aliphatic amines

Despite much effort in catalyst development for amination of alcohols through borrowing hydrogen, a truly general coupling of various

amines and alcohols (especially the less reactive secondary alcohols) with high catalytic efficiency was yet to be established. Towards this goal, we began our investigation with 1-phenylethanol **1a** and benzylamine **2a** as the model substrates. Various commercially available and well-established redox catalysts were examined at a low catalyst loading (0.25 mol%) in diethyl carbonate, which is a preferred green solvent (Fig. 2a)[35]. Our initial screening with the model substrates revealed that most of the known catalysts for redox chemistry did not yield the desired secondary amine product, except for a low yielding result with Shvo's complex and **Ir-1** (indicated by the two red columns). Following this, different additives were examined using these two catalysts. The use of strong bases such as *t*-BuOK that is known to facilitate the formation of metal hydride species in the catalytic cycle, only resulted in moderate improvement (roughly 0–30% yield, shown by the two blue columns). In contrast, the addition of a commercially available phosphoric acid led to dramatic enhancement, giving >80% yield for **3aa** (first two yellow columns). This acid presumably operates by providing activation of the relatively inactive ketone and ketoimine intermediates towards imine condensation and reduction[22,23]. The use of phosphoric acid was also examined at this stage with other Ru-, Rh- and Ir-based catalysts, yet most of them led to diminished efficiency. To further improve the reaction efficiency, we decided to examine the electronic tuning of complex **Ir-1**. While complex **Ir-3** with electron-withdrawing groups on the ligand resulted in a lower yield, complex **Ir-2** possessing electron-donating groups on the ligand resulted in improved yield (94% for **3aa**). **Ir-2** and diphenyl phosphate were then chosen for our subsequent studies.

The scope of this catalytic amination of alcohols turned out to be extremely broad (Fig. 2b). A wide range of substituted benzyl amines as well as branched or linear aliphatic amines underwent reaction with **1a** smoothly to deliver **3aa**–**3ar** in synthetically useful yields, with a good tolerance of a variety of functional groups such as OMe, CF_3 and halogens (Br, Cl). Also, the amination of different benzylic and aliphatic alcohols all proceeded with high efficiency to produce secondary amine products **3ba**–**3ts** of a broad range of substitution patterns. The strength of this catalytic alcohol amination approach emerged in the successful streamlined one-step synthesis of the blockbuster drug Sensipar (Fig. 2c). The patented synthesis of the active ingredient requires stepwise oxidation of alcohol **1u** followed by reductive amination of the aldehyde intermediate with **2t** using $NaBH(OAc)_3$, inevitably generating stoichiometric waste by-products[12]. In contrast, our gram-scale synthesis of Sensipar was realized using the same substrates in a single catalytic step in 97% yield, with water as the sole byproduct.

Enantioconvergent amination with aliphatic amines

We next turned to our goal of accessing enantioenriched aliphatic amines by an enantioconvergent amination of racemic alcohols. Our investigation focused on the reaction of model substrates **1a** and **2a** for the formation of enantioenriched **4aa**. Initial test of solvents quickly showed that *t*-amyl alcohol instead of diethyl carbonate was more promising for achieving high enantioselectivity. We then carried out systematic screening of CPAs in cooperation with **Ir-1** as the redox catalyst (Table 1). Notably, the presence of an acid cocatalyst was essential for both reactivity and selectivity of this catalytic system. As shown from entries 1–9, the steric bulk of the 3,3′-substituents proved to be crucial for the enantioselectivity. The 2,4,6-tri-isopropyl-substituted **CPA-6** and 2,6-di-isopropyl-4-adamantyl-substituted **CPA-7** provided the highest enantioselectivity, even compared to bulkier **CPA-8** and **CPA-9**.

To further improve the enantioselectivity of the process, we next evaluated various iridium-based redox catalysts **Ir-4** to **Ir-10** in combination with **CPA-6** that provided the optimal combination of efficiency and selectivity (Table 2). Using **Ir-4** (removal of HCl from **Ir-1**) did not lead to any improvement (entry 1). Using **Ir-5**, **Ir-6** or **Ir-7** that bear neutral oxime or pyridyl ligands resulted in a complete loss of reactivity or enantioselectivity (entries 2–4), highlighting the importance of the metal–amide complex for this catalytic system[36]. The use of chiral iridacycle complexes **Ir-8** and **Ir-9** led to improved efficiency but a lower enantioselectivity compared to **Ir-1** (entries 5 and 6). When (*S*,*S*)-**Ir-10** was tested, we observed good reactivity with a similar 74% enantiomeric excess (e.e.) (entry 7). To our delight, the use of (*R*,*R*)-**Ir-10** produced **4aa** with an improved 80% e.e. in 84% yield, demonstrating a clear match-and-mismatch relationship between these two chiral catalysts (entry 8). With this promising lead, further evaluation of reaction conditions was performed. Lowering the temperature from 110 to 90 °C improved the e.e. to 88% albeit with a lower 40% yield. Finally, higher catalyst loading with an extended reaction time of 48 h produced the desired chiral secondary amine **4aa** in 74% yield with 90% e.e. (entry 9).

With the optimal conditions in hand, we next studied the generality of this catalytic enantioconvergent amination (Fig. 3a). Different aliphatic primary amines were examined first. For the reactions using different substituted benzylamines, substituents at various positions could be well-tolerated (**4ab**–**4ad**). Chiral benzyl amine products bearing halogen substituents (X = Br, Cl) were delivered in high enantioselectivity (**4ae** or **4af**), which bode well for further functionalization and chiral drug synthesis. To our delight, this catalytic system is not limited to benzyl amines. A range of linear aliphatic amines underwent amination smoothly, producing **4ag**–**4ai** in high efficiency and enantioselectivity. Furthermore, a range of functionalities were also well-tolerated in the chiral amine structure, as exemplified by ether- and amine-containing products **4aj**–**4al**.

We then went on to explore the scope of alcohols, first by using 3-bromobenzylamine as the primary amine substrate since the corresponding chiral amine products can be further derivatized through cross-coupling chemistry. A range of benzylic alcohols bearing various substituents including electron-donating methoxy group and electron-withdrawing chloro and bromo groups all underwent this transformation smoothly, furnishing **4bf**–**4gf** in high yield and enantioselectivity. Heteroaryl-containing alcohols also participated this reaction to deliver **4hf** in a useful level of selectivity. In addition to the use of benzyl amines, *n*-octylamine was subsequently investigated for the scope of alcohol partners. Similarly, good to high level of efficiency and enantioselectivity were achieved for chiral amines **4bg**–**4hg**. When aliphatic alcohols such as 1-cyclohexylethanol **1i** was tested with *n*-octylamine, the corresponding chiral amine **4ig** was also obtained with a good enantioselectivity of 80% e.e. However, extension of this set of conditions to other aliphatic primary amines met with limited success (for example, the reaction of **1i** and **2a** produced the amine product in roughly 20% e.e.).

Considering the value of this class of chiral secondary amines with all alkyl substituents, we decided to further optimize the reaction conditions for amination of alkyl-substituted alcohols, using the bulky diphenylmethamine **2n** that may be beneficial for enantiocontrol and is known to be a convenient protecting group for amines. On further screening of catalysts including further CPAs for the reaction between **1i** and **2n**, we were able to identify **CPA-10** bearing a dimeric binaphthyl backbone[37] and **Ir-4** as the optimal catalysts (Fig. 3b). Under this new set of conditions, **4in** was produced in a high yield (80%) and excellent e.e. (92%). For other aliphatic alcohols, good to high enantioselectivities were also obtained for cyclopentyl- or isopropyl-substituted **4jn** and **4kn**, due to sufficiently large steric difference between the substituents in the ketoimine intermediates. Yet, the enantioselectivity decreased significantly in the case of **4ln** associated with a more linear aliphatic chain, highlighting the difficulty of this class of enantioselective transformations.

Our catalytic methodology establishes direct access to valuable chiral aliphatic amines that can be derivatized in various ways. First, deprotection of the benzyl or diphenylmethyl groups allows efficient access to enantioenriched primary amines. As shown in Fig. 3c, both the removal of the *N*-benzyl group on **4aa** and deprotection of **4in** were

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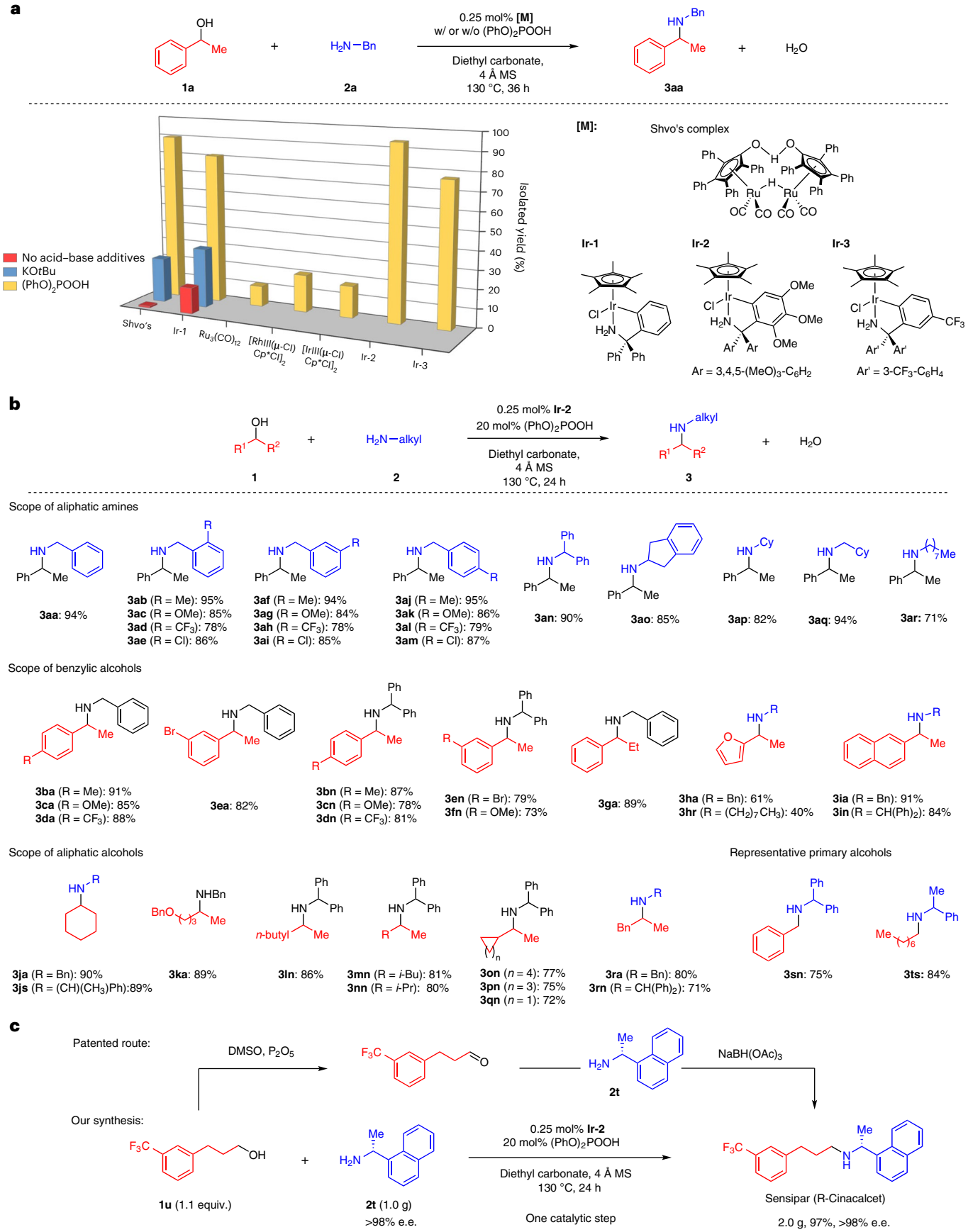

Fig. 2 | A general amination of alcohols using aliphatic amines with high catalytic efficiency. a, Reaction optimization for amination of secondary alcohols using benzyl amines. **b**, Substrate scope for amination using aliphatic amines via borrowing hydrogen. **c**, Application to one-step synthesis of Sensipar. General reaction conditions for substrate scope evaluation were: **1** (0.3 mmol), **2** (0.1 mmol), **Ir-2** (0.00025 mmol), $(PhO)_2POOH$ (0.02 mmol) and 4 Å MS (40 mg) in toluene (0.5 ml) at 130 °C under N_2 for 24 h. Bn, benzyl; Cp, cyclopentadienyl; Cy, cyclohexyl; DMSO, dimethyl sulfoxide; w/, with; w/o, without.

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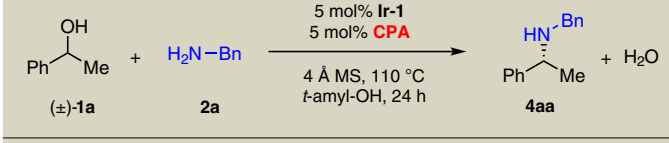
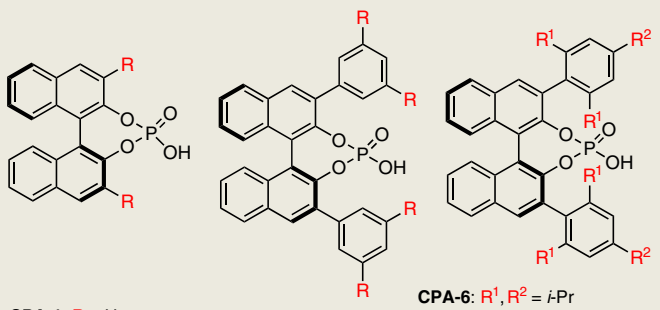
Table 1 | Optimization of CPAs for enantioconvergent amination of 1-phenylethanol with benzyl amine

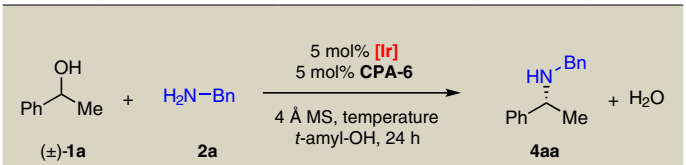


Entry	CPA	Yield (%)	e.e. (%)
1	**CPA-1**	61	40
2	**CPA-2**	61	8
3	**CPA-3**	31	22
4	**CPA-4**	46	0
5	**CPA-5**	71	0
6	**CPA-6**	60	73
7	**CPA-7**	43	75
8	**CPA-8**	60	71
9	**CPA-9**	47	53

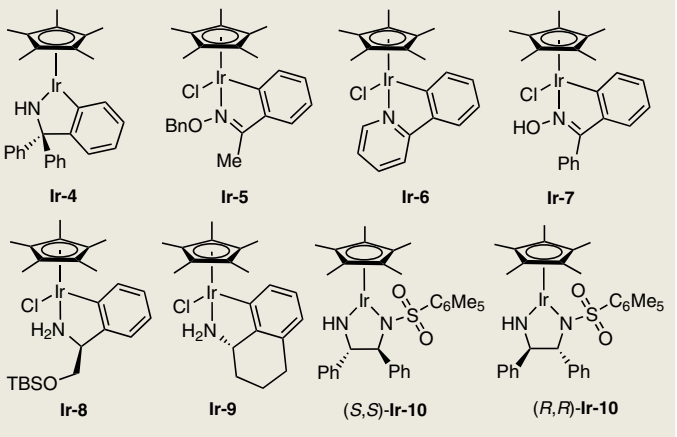


Reaction conditions: **1a** (0.30 mmol), **2a** (0.10 mmol), **Ir** (0.005 mmol), **CPA** (0.005 mmol) and 4 Å MS (40 mg) in toluene (0.5 ml) at 110 °C under N_2 for 24 h. See Supplementary Information for details. *t*-amyl-OH, *tert*-Amyl alcohol; Adm, adamantyl; TRIP, 2,4,6-triisopropylphenyl.

Table 2 | Optimization of iridium catalysts for enantioconvergent amination of 1-phenylethanol with benzyl amine



Entry	[Ir]	Temperature (°C)	Yield (%)	e.e. (%)
1	**Ir-4**	110	43	75
2	**Ir-5**	110	0	-
3	**Ir-6**	110	0	-
4	**Ir-7**	110	60	0
5	**Ir-8**	110	99	51
6	**Ir-9**	110	80	63
7	(*S*,*S*)-**Ir-10**	110	78	74
8	(*R*,*R*)-**Ir-10**	110	84	80
9[a,b]	(*R*,*R*)-**Ir-10**	90	74	90



For reaction conditions, see Table 1. [a]Reaction performed at 90 °C and 48 h. [b]Reaction performed with Ir (0.01 mmol) and CPA (0.01 mmol). TBS, *t*-butyldimethylsilyl.

successfully achieved in the presence of Pd/C under acidic conditions to deliver the desired primary amines in high yield with complete retention of chirality.

Our catalytic method also opens up new possibilities for direct access to chiral aliphatic amine-based drugs and analogues from simple racemic alcohols and amines. To exemplify the strength of the approach we chose the class of calcimimetic agents that bear chiral amines with a meta-substituted benzyl unit as the target (Fig. 3c, right). The first step consisted of our gram-scale enantioconvergent amination of **1a** with **2f**, which delivered **4af** with high efficiency and enantioselectivity comparable with the small-scale reaction in Fig. 3a. Then, a challenging copper-catalysed amidation of the aryl bromide moiety in **4af** with different amides was carried out by the use of a diamine ligand[38], resulting in an overall two-step synthesis of calcimimetic agent analogues **7a** and **7b** from simple racemic substrates. Notably previous synthesis of the same class of drug candidates required an alternative sequence of amide coupling followed by reductive amination using the enantiopure chiral amine[39]. In comparison, our synthetic procedure uses inexpensive racemic alcohol as the starting material, and involves two catalytic transformations with much higher atom economy and less waste production. Application of this catalytic enantioconvergent amination to the preparation of various classes of chiral aliphatic amine-based drugs is under investigation in our laboratory.

Mechanistic studies

An important observation was made during our development of this methodology: the chiral amine products underwent an undesired partial racemization with prolonged reaction time. The comparison of enantiopurity for representative products **4** after 24 versus 48 h reactions is summarized in Fig. 4a. The racemization of the chiral amine products clearly accumulates with the build-up in concentration of the amine product over time. This key observation highlighted the additional challenges for achieving enantioenriched aliphatic amine synthesis using this catalytic redox cascade strategy.

To shed light on the underlying causes for the racemization, we first subjected enantioenriched **4gg** (94% e.e.) to the standard catalytic amination conditions with both or only one of the two catalysts present (Fig. 4b). In the presence of both iridium and acid catalysts, a drastic decrease of enantiopurity for **4gg** to only 15% e.e. was observed (column 1, Fig. 4b). The use of an iridium catalyst alone in the absence of CPA reduced the enantiopurity of **4gg** to a lower extent (52% e.e., column 2), while the use of the acid catalyst alone resulted in no racemization of **4gg** at all (column 3). Notably, in all cases, >98% recovery of **4gg** was indicated by ^{1}H NMR spectroscopic analysis. These data clearly indicate that the racemization requires the iridium catalyst for a redox process to take place, and it is also facilitated by the acid cocatalyst. When the same experiment using both iridium and acid catalysts was

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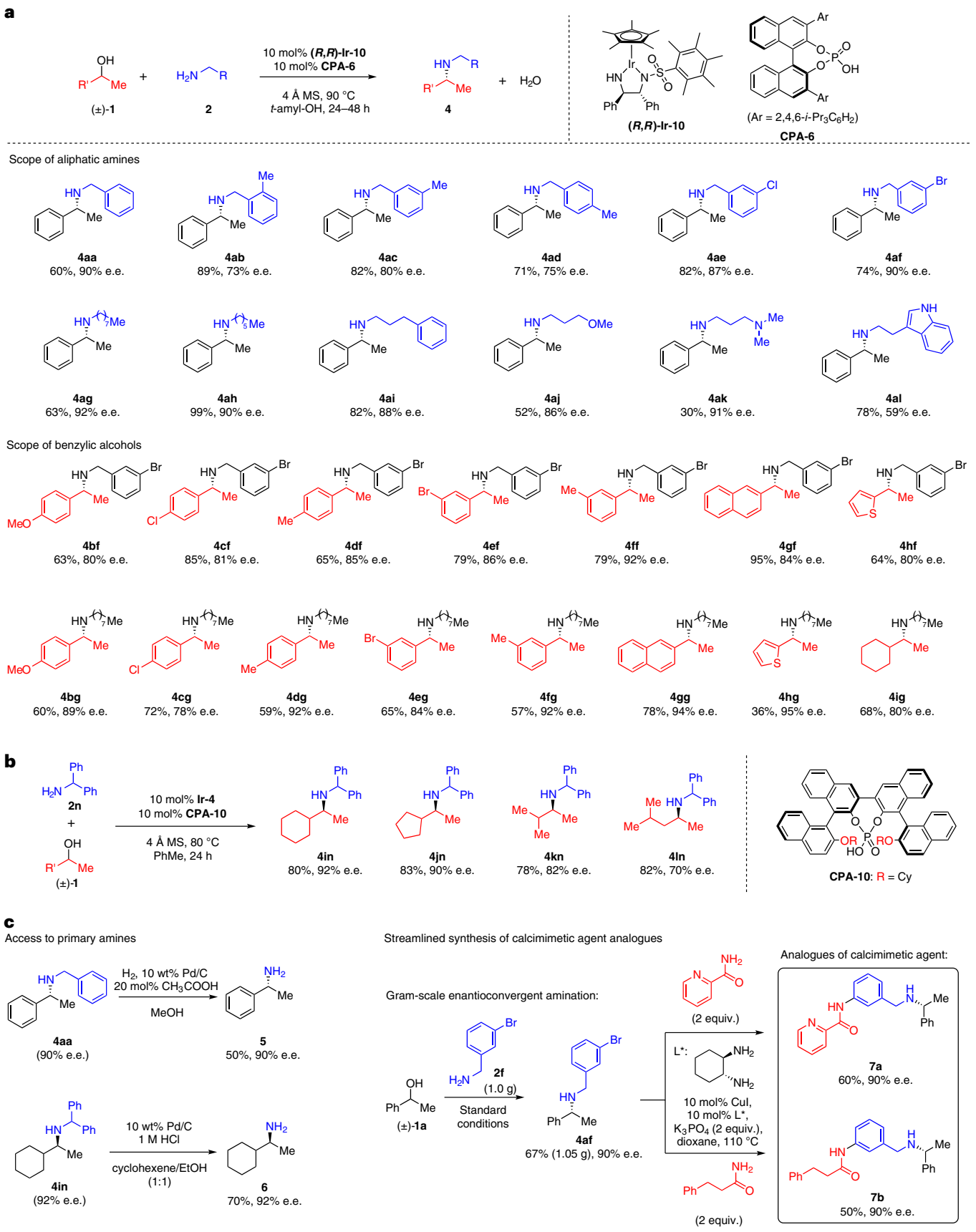

Fig. 3 | Asymmetric amination of racemic alcohols using aliphatic amines with product functionalization. a, Enantioconvergent synthesis of chiral aliphatic amines. **b**, Enantioconvergent amination of aliphatic alcohols catalysed by **Ir-4** and **CPA-10**. **c**, Synthetic application of chiral aliphatic amine products. L*, chiral ligand.

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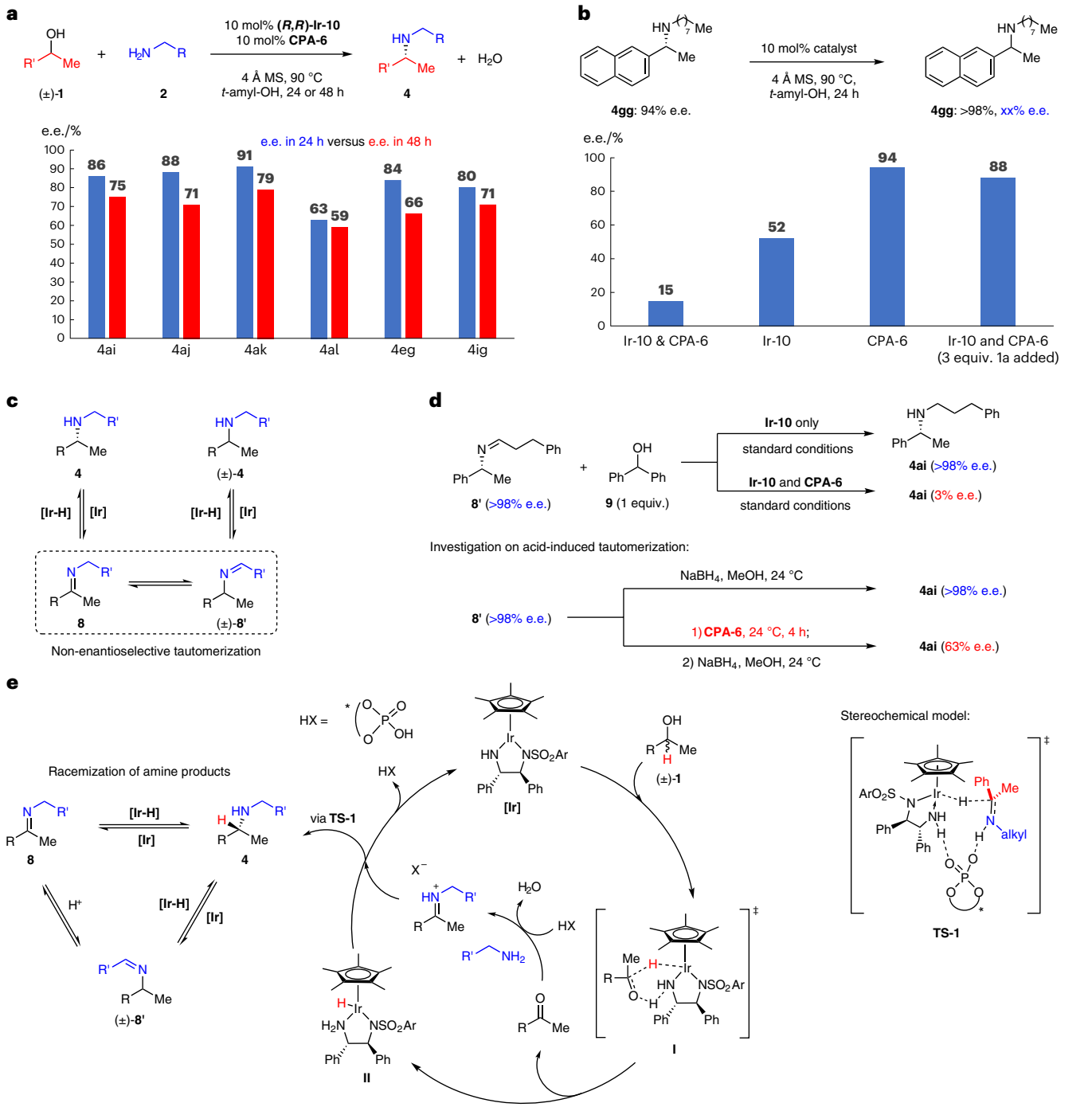

Fig. 4 | Mechanistic aspects of asymmetric amination with concomitant racemization of the chiral amine product. a, Observation of product racemization with extended reaction time. **b**, Evaluation of product racemization by different catalysts with or without alcohol. **c**, Hypothesis for racemization of aliphatic amines. **d**, Investigation on tautomerization-induced racemization. **e**, Proposed pathways for enantioconvergent amination and racemization of the amine product.

carried out in the presence of excess alcohol **1a**, racemization of **4gg** took place to a much lower extent (88% e.e., column 4, Fig. 4b). Possibly, the redox chemistry of the excess alcohols is more facile than the redox of the amine product **4gg**, effectively slowing down the undesirable racemization of chiral amine products.

We reasoned that a simple redox process between enantioenriched **4** and its corresponding ketoimine **8** should not result in pronounced racemization of **4**, considering the microscopic reversibility of the dehydrogenation and hydrogenation processes under the influence of the same chiral catalysts (Fig. 4c)[40]. Instead, we proposed that the racemization probably proceeds through an alternative pathway involving a non-enantioselective imine tautomerization between ketoimine **8** and aldimine **8'** (generated in a nearly racemic form). Reduction of aldimine **8'** by the iridium hydride should be facile and produce amine product **4** in low enantioselectivity, thus resulting in the overall net partial racemization of **4**. To validate this hypothesis, we synthesized a representative enantiopure imine **8'**, and attempted a transfer hydrogenation of **8'** using alcohol **9** catalysed by **Ir-10** with

or without cocatalyst **CPA-6**, mimicking the catalytic conditions in our catalytic amination of alcohols. As shown in Fig. 4d, the use of iridium catalyst alone for transfer hydrogenation produced **4ai** in high yield with preservation of the enantiopurity (>98% e.e.), suggesting a facile direct imine reduction. In contrast, the use of both iridium and acid catalysts yielded the amine product **4ai** with complete loss of the enantiopurity (3% e.e.). This result can only be rationalized by racemization through an acid-promoted imine isomerization[41] followed by reduction of rac-**8′** to the amine product. To provide further support for this, we subjected imine **8′** to reduction using $NaBH_4$. Similarly, while using $NaBH_4$ alone led to reduction with complete retention of enantiopurity, acid treatment followed by $NaBH_4$ reduction led to the formation of **4ai** with much reduced 63% e.e. All these control experiment provided strong support for our hypothesis that in our catalytic amination of alcohols, the isomerization of ketimine **8** to aldimine intermediate **8′** was responsible for racemization of the chiral aliphatic amine. In addition, the acid cocatalyst facilitated this racemization by promoting a more efficient aldimine to ketoimine tautomerization.

On the basis of the experimental results as well as our previous mechanistic studies of enantioselective amination of alcohols by borrowing hydrogen using closely related catalysts[42], we propose the reaction pathways for amination of alcohols using aliphatic primary amines and partial racemization of the chiral amine products as shown in Fig. 4e. Ir-catalysed dehydrogenation of the alcohol substrate produces the ketone intermediate and iridium hydride **II** through a concerted transition state **I**. Imine condensation promoted by CPA produces an activated iminium intermediate, which undergoes subsequent reduction by iridium hydride **II** to produce the desired chiral amine product and regenerate the iridium catalyst. Notably the enantioselectivity obtained in this amination using alkyl amines was consistent with our previous studies using anilines[22]. On the basis of our previous stereochemical model based on density functional theory calculations[42], we propose an analogous transition state model **TS-1** in Fig. 4e for the stereochemical outcome of the current system. In conjunction, the enantioenriched aliphatic amine can undergo Ir-catalysed dehydrogenation to the ketoimine intermediate **8**, which undergoes non-enantioselective tautomerization to yield racemic aldimine **8′** that probably undergoes hydrogenation to produce amine **4** with lower enantiopurity. Such a phenomenon will take place to a more notable extent with prolonged reaction duration when higher concentration of the amine product is accumulated.

Conclusions

We have achieved a highly efficient and general coupling of aliphatic primary amines and simple secondary alcohols through a borrowing hydrogen process by adopting a cooperative catalysis strategy using a redox-active metal complex and an acid cocatalyst. More importantly, an unprecedented direct enantioconvergent amination of racemic secondary alcohols using diverse aliphatic primary amines was achieved. Using a chiral iridium complex with a CPA, a wide range of valuable chiral aliphatic secondary amines are obtained in high yield and enantioselectivity from feedstock alcohols and primary amines. The use of this atom- and step-economical carbon–nitrogen bond formation is illustrated by the streamlined, enantioselective synthesis of important commercial drugs and analogues. An intriguing racemization pathway for chiral aliphatic amines under redox conditions was also discovered, which provides important guiding principles for redox-related stereoselective control in chiral amine synthesis.

Methods

The general procedure for the enantioconvergent amination of alcohols was as follows. To a 10-ml glass reaction tube containing a mini stir bar was added 10 mol% of CPA-6, 10 mol% of iridium complex (*R*,*R*)-Ir-10, 0.3 mmol of alcohol 1, 0.1 mmol of aliphatic amine 2, 20 mg of 4 Å molecular sieves and 0.5 ml of *t*-amyl alcohol in the glovebox. The vial was capped and sealed tightly using the screw cap and paraffin film. The reaction mixture was then taken outside the glovebox, heated to 90 °C and allowed to stir for 24–48 h. The reaction mixture was allowed to cool to room temperature and the solvent was then evaporated using a rotary evaporator. The crude mixture was directly purified through flash-column chromatography using silica gel and eluent containing hexane/ethyl acetate to obtain the desired products.

Data availability

The data supporting the findings of this study are available within the paper and its Supplementary Information.

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Author contributions

X.Q.N. and C.S.L. performed most of the experiments, with support from M.W.L., T.T.Q. and B.-M.Y. on the catalyst and substrate preparation. Y.Z., J.W. and V.I. directed the project. Y.Z., X.Q.N. and C.S.L. cowrote the paper. All authors discussed the results and commented on the paper.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Jie Wu or Yu Zhao.

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