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Enantioselective isothiourea-catalysed *trans*-dihydropyridinone synthesis using saccharin-derived ketimines: scope and limitations†

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The catalytic enantioselective synthesis of a range of *trans*-dihydropyridinones from aryl-, heteroaryl- and alkenylacetic acids and saccharin-derived ketimines with good to excellent stereocontrol (15 examples, up to >95 : 5 dr, up to >99 : 1 er) is reported. After extensive optimisation, HyperBTM proved the optimal isothiourea catalyst for this transformation at −78 °C, giving *trans*-dihydropyridones with generally excellent levels of diastereo- and enantioselectivity.

Introduction

Saccharin (1,2-benzisothiazol-3-one-1,1-dioxide) **1** is a synthetic calorie-free additive, widely used as a sugar substitute in many food products and has proven an important discovery in the fight against diabetes.[1] The cyclic sulfonamide core motif embedded within saccharin has attracted much interest in recent decades from the medicinal chemistry community, with this motif a key constituent in many biologically active drugs (Fig. 1a). For example, saccharin-based sultams such as Ipsaspirone **2** are active agonists of 5-HT_{1A} receptors and have been applied as neuroprotectants and anxiolytics.[2] Current research within this area has led to the development of saccharin derivatives as inhibitors of carbonic anhydrase enzymes.[3] Similarly, related cyclic sulfonamides such as Ampiroxicam **3** are bioactive.[4]

A number of enantioselective organocatalytic strategies have been explored to access chiral sultam products that incorporate the saccharin motif. For example, in 2012 Bode and co-workers developed an NHC-catalysed enantioselective annulation process utilising sulfonyl imine **4** and enals **5**, giving tricylic sultams **7** in good to excellent yield (67–94%) and excellent enantioselectivity (90 : 10 to >99 : 1 er) using monosubstituted enals (Fig. 1b).[5] Alternatively, Chen and co-workers have investigated an aza Diels–Alder reaction using organocatalytically-generated trienamines. Cyclic sulfonyl imine **10**

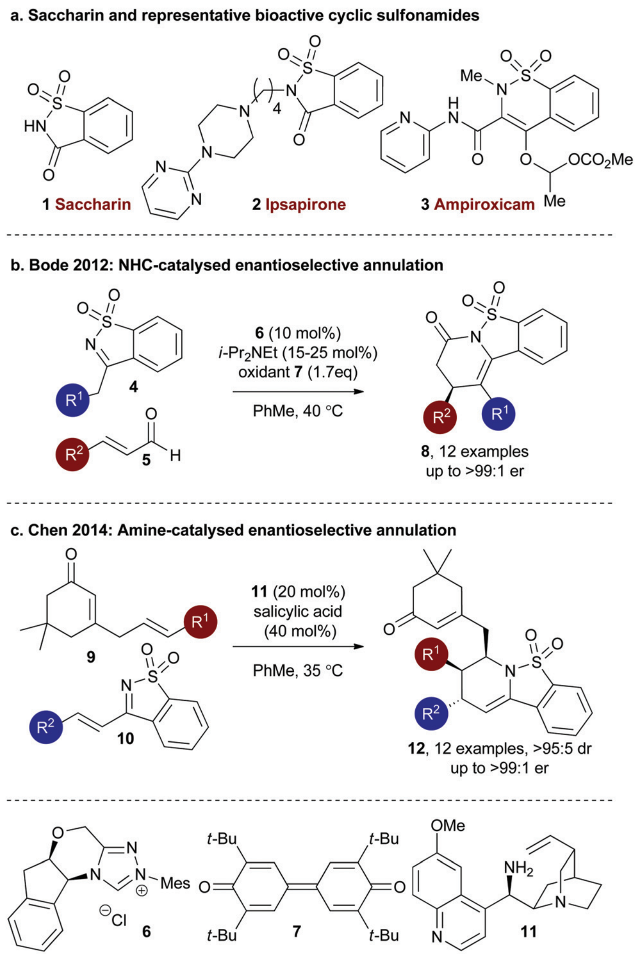

Fig. 1 Representative bioactive sultams and enantioselective organocatalytic strategies using saccharin derivatives to prepare cyclic sulfonamides.

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and cinchona alkaloid **11** (20 mol%) in the presence of salicylic acid generates a trienamine intermediate that can react through the δ,ε-alkene in an inverse electron demand Diels–Alder reaction with cyclic sulfonyl imines **9** to give products **12** in excellent diastereo- and enantioselectivity (>95 : 5 dr and 98 : 2 to >99 : 1 er, Fig. 1c).[6]

Following the pioneering nucleophile catalysed aldol lactonisation (NCAL) work of Romo and co-workers using carboxylic acids as ammonium enolate precursors,[8] we developed the use of isothioureas[9] for enantioselective Michael addition lactonisation processes directly from carboxylic acids.[10] The generality of this concept has been extended to a range of formal intermolecular [4 + 2],[11] [3 + 2][12] and [2 + 2][13] cycloaddition processes from carboxylic acids or anhydride starting materials (Fig. 2a).[14] Of particular relevance to this manuscript we have previously accessed the dihydropyridinone motif from arylacetic acids through enantioselective Michael addition lactamisation using acyclic ketimines derived from chalcones[15] and α,β-unsaturated γ-ketoesters.[16] Based upon this work, in this manuscript the use of saccharin-derived cyclic ketimines as suitable substrates for the enantioselective preparation of polycyclic dihydropyridinones from aryl-, heteroaryl-, and alkenylacetic acids is investigated (Fig. 2b).

During the course of this work elegant studies from Pericàs and co-workers reported a very similar reaction process. Using a polymer supported isothiourea catalyst (15 mol%), enantioselective annulation of a limited range of arylacetic acids as enolate precursors and saccharin-derived ketimines gave *trans*-dihydropyridinones in 86 : 14 to 96 : 4 dr and up to >99 : 1 er.[17] Notably, no heteroaryl or alkenyl acetic acids were evaluated as ammonium enolate precursors within this process, and only limited substitution patterns within the arylacetic acid component were included. Similarly, Ye and co-workers have recently reported a related NHC-catalysed process, utilising α-chloroaldehydes as azolium enolate precursors, giving *cis*-dihydropyridinones in >95 : 5 dr and >99 : 1 er upon reaction with saccharin-derived ketimines.[18] This effective methodology is however limited to the use of alkyl-α-chloroaldehydes.

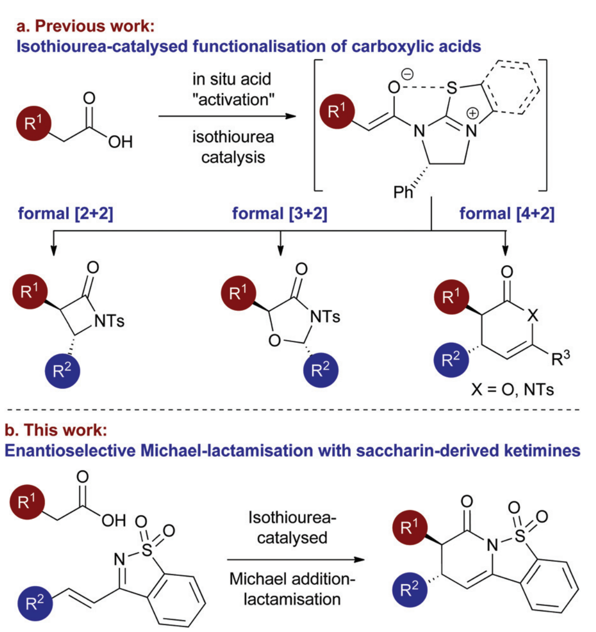


Fig. 2 Proposed Isothiourea-catalysed Michael addition-lactamisation using saccharin-derived ketimines.

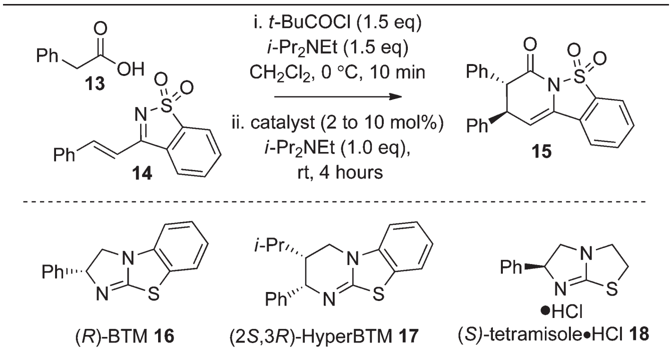
Results and discussion

Reaction optimisation

Optimisation studies began with evaluating a small range of isothioureas as catalysts for the synthesis of **15** using phenylacetic acid **13** and ketimine **14** as a model system. Using pivaloyl chloride to make an *in situ* mixed anhydride and (*R*)-BTM **16** (10 mol%) gave the desired product **15** in 71% yield, 85 : 15 dr and 92 : 8 er. Using (2*S*,3*R*)-HyperBTM **17** (10 mol%) at rt gave the desired product **15** in 64% yield, 84 : 16 dr and 90 : 10 er. The optimum catalyst, however, was (*S*)-tetramisole·HCl **18** (10 mol%) giving tricyclic sultam **15** in 73% yield, 85 : 15 dr and excellent 97.5 : 2.5 er. Attempts to lower the catalyst loading of (*S*)-tetramisole·HCl **18** to 5 mol% led to a reduced 56% isolated yield of **15** with 83 : 17 dr and 94 : 6 er. Alternative solvents such as EtOAc, THF and toluene were tested but gave poorer dr and er (entries 5–7), with poor solubility in toluene leading to a low product conversion (Table 1).

Further studies probed the generality of this enantioselective protocol using (*S*)-tetramisole·HCl **18** at rt through variation within the acid component, with arylacetic acids bearing both electron donating and withdrawing substituents,

Table 1 Enantioselective Michael addition–lactonisation optimisation



Entry	Catalyst (mol%)	Solvent	Yield[a] (%)	dr[b]	er[c]
1	**16** (10)	CH_2Cl_2	71	85 : 15	92 : 8 (*ent*)
2	**17** (10)	CH_2Cl_2	64	84 : 16	90 : 10 (*ent*)
3	**18** (10)	CH_2Cl_2	75	86 : 14	97.5 : 2.5
4	**18** (5)	CH_2Cl_2	65	85 : 15	97.5 : 2.5
5	**18** (2)	CH_2Cl_2	56	86 : 14	94 : 6
5	**18** (10)	EtOAc	65	85 : 15	92 : 8
6	**18** (10)	THF	61	85 : 15	92.5 : 7.5
7	**18** (10)	PhMe	16	85 : 15	92 : 8

[a] Isolated following column chromatography using Biotage® Isolera™ 4. [b] Determined by ^{1}H NMR spectroscopic analysis of crude reaction mixture. [c] Determined by chiral HPLC analysis.

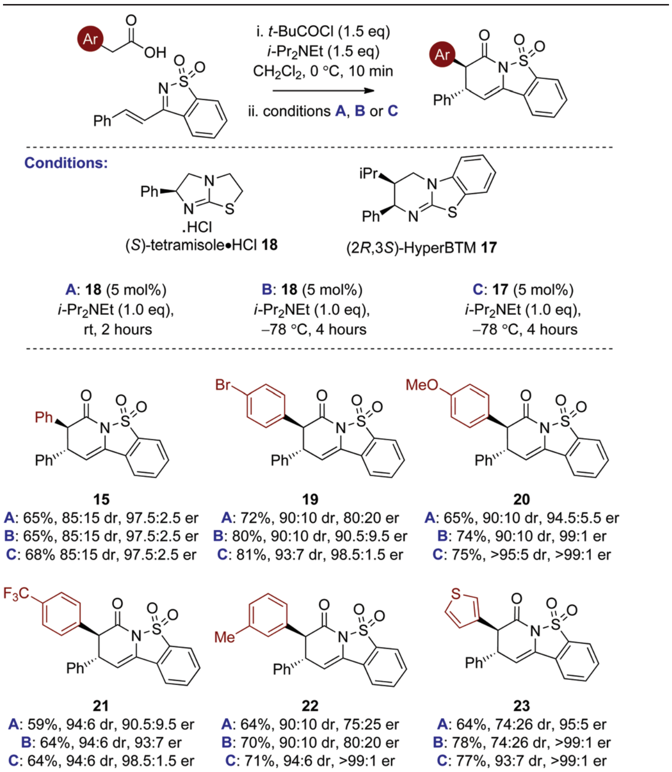
as well as heteroarylacetic acids targeted. Although good conversion to product was observed in all cases, significant variation in product diastereo- and enantioselectivity was observed using (*S*)-tetramisole·HCl **18** at rt (conditions A, Table 2). For example, reaction with 4-bromophenyl acetic acid and *m*-tolyl acetic acid gave sultams **19** and **22** in 90 : 10 dr but moderate 80 : 20 and 75 : 25 er respectively. Use of 3-thiophenylacetic acid yielded the thienyl sultam product **23** in good 95 : 5 er but in moderate 74 : 26 dr. While 4-methoxyphenyl acetic acid gave **20** in acceptable dr and er, incorporating an electron withdrawing substituent in 4-trifluoromethylphenyl acetic acid led to reduced enantioselectivity (**21**, 90.5 : 9.5 er). These moderate and variable results indicated that the initial conditions identified in the catalyst screen using (*S*)-tetramisole·HCl **18** at rt were not general and that further optimisation was required.

Further optimisation probed the effect of lowering the reaction temperature to −78 °C as this was predicted to minimise any competitive racemic background reaction over the range of substrates.[19] Using (*S*)-tetramisole·HCl **18** (5 mol%) at −78 °C (conditions B, Table 2) led to generally improved enantioselectivity. However, moderate er was observed for the formation of 3-MeC_6H_4-substituted derivative **22** (80 : 20 er), and poor diastereoselectivity for 3-thiophenyl substituted **23** (74 : 26 dr). Pleasingly, however, (2*R*,3*S*)-HyperBTM **17** (5 mol%) proved significantly more successful. 4-BrC_6H_4 substituted sultam **19** was produced in 81% yield, 93 : 7 dr and excellent 98.5 : 1.5 er. Sultams **20** and **21** incorporating the electron rich 4-$MeOC_6H_4$ and the electron withdrawing 4-$CF_3C_6H_4$ substituents were isolated in good yield, and excellent diastereo- and enantioselectivity. A dramatic improvement in enantioselectivity was observed for 3-MeC_6H_4-substituted derivative **22** (>99 : 1 er), while improved diastereoselectivity was observed for 3-thiophenyl derivative **23** (93 : 7 dr, >99 : 1 er).

Further substrate scope

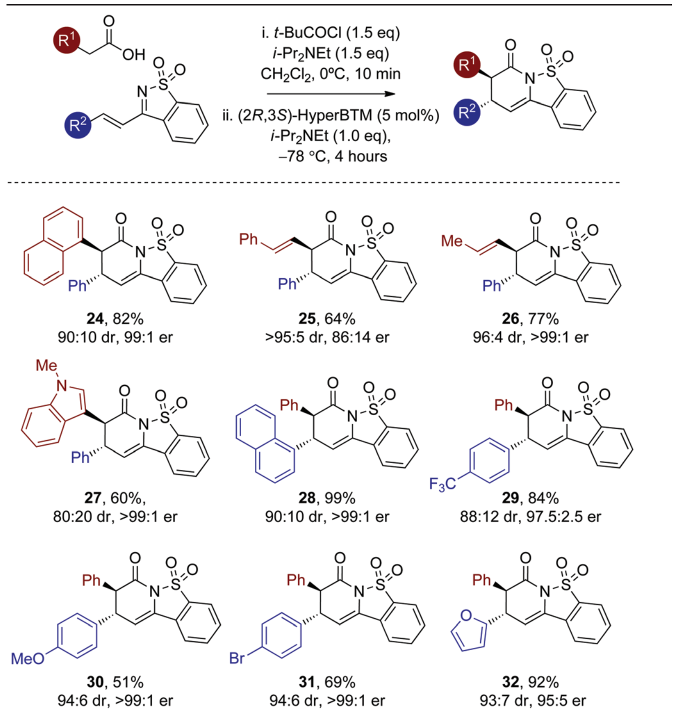
With a reliable enantioselective process in hand using (2*R*,3*S*)-HyperBTM **17** at −78 °C, the scope and limitations of this protocol was further investigated, with the extension to alternative heteroaryl and alkenylacetic acids targeted (Table 3). Variation of the carboxylic acid group showed that extended aromatic substituents are readily tolerated, with the 1-naphthyl unit incorporated to give **24** in 82% yield and 99 : 1 er. The incorporation of alkenyl substituents from the corresponding acids worked well, giving **25** and **26** in excellent dr. Consistent with our previous work the incorporation of the styrenyl unit within **25** led to reduced enantioselectivity (86 : 14 er) in comparison to **26** (>99 : 1 er).[12b] The 3-indolyl unit was also readily included albeit with reduced diastereoselectivity (**27**, 80 : 20 dr) but excellent er (>99 : 1 er). Variation within the β-substituent of the saccharin-derived ketimine was next evaluated (products **28–32**). The 1-naphthyl unit was readily incorporated, as were electron-donating and -withdrawing 4-substituents, as well as

Table 2 Probing the Michael addition–lactamisation process[a,b,c]



[a] Isolated yield. [b] dr determined by ^1H NMR of the crude reaction product. [c] er determined by chiral HPLC.

Table 3 Probing the generality of the Michael addition–lactamisation process[a,b,c]



[a] Isolated yield. [b] dr determined by ^1H NMR of the crude reaction product. [c] er determined by chiral HPLC.

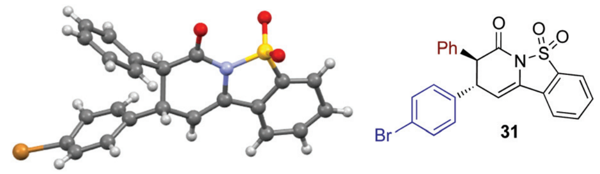
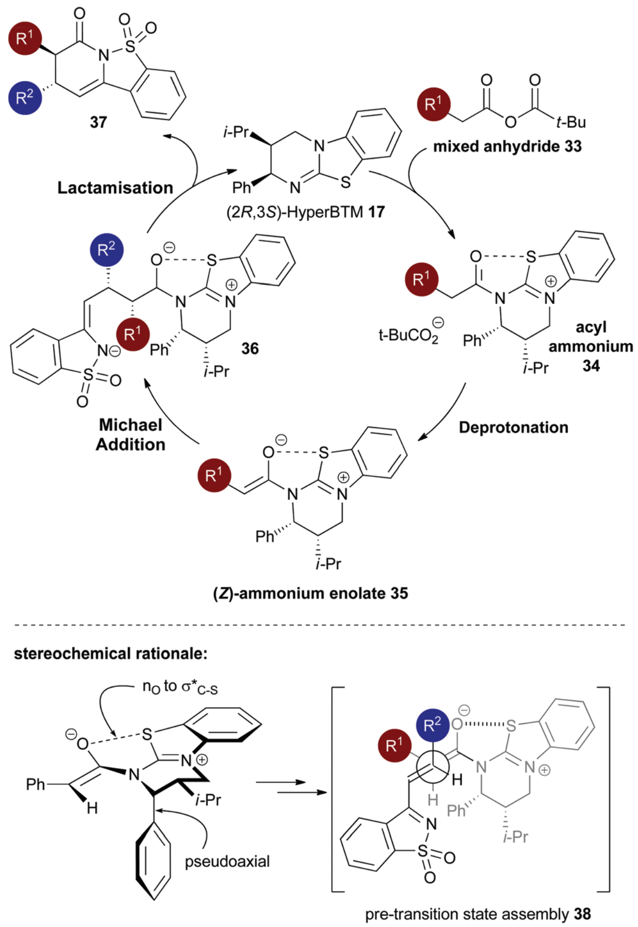


Fig. 3 Molecular representation of the X-ray structure of **31**.



Scheme 1 Proposed mechanism and stereochemical rationale of the isothiourea-catalysed Michael addition–lactamisation.

the 2-furyl motif with good to excellent diastereo- and enantioselectivity.[20]

The relative and absolute configuration within **31** was assigned by X-ray crystallography analysis, with the configuration within all other products assigned by analogy (Fig. 3).[21]

Proposed mechanism

Consistent with our previous studies, a proposed catalytic cycle for the synthesis of these saccharin-derived dihydropyridones is shown in Scheme 1. Initial *in situ* formation of the mixed anhydride **33** from pivaloyl chloride and the carboxylic acid, followed by subsequent nucleophilic attack from the (2*R*,2*S*)-HyperBTM catalyst **17** generates acyl ammonium ion **34**. Deprotonation to form the corresponding (*Z*)-ammonium enolate **35**, followed by stereoselective Michael addition gives **36**, with lactonisation releasing catalyst **17** and the polycyclic dihydropyranone product **37**. A stabilising n_O to σ^*_{C-S} interaction between the enolate oxygen and the sulfur of the isothiouronium ion is proposed to lock the conformation of the enolate species,[22] forcing the adjacent stereodirecting phenyl substituent to adopt a pseudoaxial orientation to minimise 1,2-strain.[23] Subsequent Michael addition occurs preferentially *anti*- to this stereodirecting group, with the two prostereogenic centres adopting an approximately staggered array to minimise unfavourable non-bonding interactions. By analogy to Heathcock's model[24] a pre-transition state assembly **38** is consistent with the observed sense of diastereo- and enantioselectivity.

Conclusions

In conclusion, the catalytic enantioselective synthesis of a range of saccharin-derived *trans*-dihydropyridinones (15 examples, up to >95 : 5 dr, up to >99 : 1 er) using both aryl-, heteroaryl-, and alkenylacetic acids as ammonium enolate precursors using (2*R*,3*S*)-HyperBTM has been developed. Further work from this laboratory is directed toward developing alternative uses of isothioureas and other Lewis bases in enantioselective catalysis.

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19 Treatment of 4-bromophenyl acetic acid with pivalolyl chloride, i-Pr_2NEt and ketimine **14**, gave 24% conversion into corresponding product **19** (as determined by ^1H NMR spectroscopic analysis). This confirms the presence of a base-catalysed racemic background reaction at room temperature.

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