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Sustainable synthesis of enantiopure fluorolactam derivatives by a selective direct fluorination – amidase strategy†

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Pharmaceutically important chiral fluorolactam derivatives bearing a fluorine atom at a stereogenic centre were synthesized by a route involving copper catalyzed selective direct fluorination using fluorine gas for the construction of the key C–F bond and a biochemical amidase process for the crucial asymmetric cyclisation stage. A comparison of process green metrics with reported palladium catalyzed enantioselective fluorination methodology shows the fluorination-amidase route to be very efficient and more suitable for scale-up.

Introduction

Enzyme catalysed reaction of functional fluoromalonate building blocks, prepared using fluorine gas, has been used for the first time for the enantioselective synthesis of a pharmaceutically important chiral fluorolactam derivative. An inexpensive, highly economically competitive, lower waste stream process that does not rely on precious metal catalysis and has been quantified by green metric analysis is described.

The synthesis of chemical intermediates bearing a fluorine atom at a stereogenic centre is becoming increasingly important for applications across the materials and life-science sectors.1 While fluoroaromatic derivatives appear as sub-units in many commercially valuable pharmaceutical products,2 there are far fewer fluorinated drugs on the market where a single fluorine atom is attached to an sp3 carbon, apart from several anti-inflammatory fluorosteroid derivatives.3 One reason for the relative lack of commercial products that bear fluorine at a stereogenic centre is the often very difficult synthesis, but much progress in the field of enantioselective chemical fluorination has been made in recent years.4 Fluorination of positions α to a carbonyl group by an electrophilic fluorination process is a common approach to the synthesis of enantiopure fluorinated building blocks and various Selectfluor™, cinchona alkaloid combinations,5 palladium or zinc catalysed processes using N-fluorobenzenesulfonyamide (NFSI),6 organocatalyst-fluorinating agent combinations7 and chiral fluorinating agents based upon Selectfluor™-type derivatives8 have been devised and successfully implemented to give a range of enantiopure fluorinated building blocks (Scheme 1). Whilst these chemical approaches can be very valuable at the discov-
ery stage of a medicinal chemistry process, the application of chemical enantioselective fluorination strategies at larger scale is severely hampered by the usually prohibitive expense of the reagent-ligand combinations and the large waste streams generated.

Pharmaceutical companies are increasingly concerned about the environmental impact of their commercial products and, for example, GSK recently announced an environmental strategy with the objective that the company’s operations become carbon neutral by 2050.9a Additionally, the European Federation of Pharmaceutical Industries and Associations (EFPIA) continues to develop the Eco-Pharmaco-Stewardship (EPS) proposal to develop methods to minimise the effect of pharmaceuticals within the environment including in the development and manufacturing stages.9b

Consequently, highly efficient low-waste synthetic processes for pharmaceutical manufacture are required to meet the industry’s ambitious environmental goals. Therefore, methods for assessing the efficiency and amount of waste generated by a synthetic strategy are used, in part, to identify a suitable final process for pharmaceutical manufacture. Green metrics packages allow a holistic comparison between potential synthetic reaction pathways using a mixture of quantitative and qualitative assessment criteria.10 Calculations of total process mass intensity (PMI) enables the synthetic chemist to simply compare the environmental effect of competing synthetic strategies from common starting materials, thus aiding the selection of the final preparative route.11

A series of pre-clinical candidate spleen tyrosine kinase (Syk) inhibitors12 1 have been synthesised from chiral fluoro-lactam building blocks 2 (Scheme 2). General synthetic procedures for the preparation of enantiopure 2-fluoro-1,3-amidoesters are relatively rare13 and are limited to enantio-selective fluorination of malonate esters using NFSI with Zn(OAc)2/DBFOX-Ph catalyst followed by amide formation,6c ligand catalysed chiral alkylation of fluoromalonate derivatives followed by amide formation14 or fluorination using NFSI with chiral palladium catalysis.12,15

The NFSI–palladium catalysis protocol reported by Sodeoka15 was adopted for scale up and 2a was synthesised on 100 g scale12 (Scheme 3). However, the route12a,15 requires a structurally complex palladium catalyst prepared by multi-step procedures and purification of the desired enantiomer by time-consuming chiral HPLC due to the relatively low 44% ee obtained for the fluorination stage when performed on the large scale.

**Scheme 3 Process mass intensity (PMI), mass intensity (MI), atom economy (AE) and reaction mass efficiency (RME) calculations for the literature synthesis of 2a.**

Results and discussion

Our assessment of the reported synthesis of 2 (Scheme 3) using green metric analysis (SI-2†), shows that the single-step enantioselective fluorination reaction has an estimated calculated process mass intensity (PMI) value of 925 (SI-2†). Inspection of each stage of the synthetic route shows that most waste is generated in the key enantioselective fluorination stage because, of course, NFSI is synthesised by reaction of the corresponding sulfonamide with fluorine gas,16 which must be taken into account when calculating PMI measurements, and loss of material due to the low ee and subsequent resolution. We assumed that all solvent used in the HPLC resolution was recycled and the waste generated in the multi-step synthesis of the palladium catalyst was not included in the PMI calculation. Consequently, the PMI 925 is a low estimate and offers a reasonable benchmark for process development.

As an alternative synthetic strategy, initially we investigated the synthesis of related fluorolactam derivative 2b (R = Me) using a combined chemical and biochemical synthetic approach from fluoromalonate ester starting materials (Scheme 2). While enzyme catalysed asymmetric hydrolysis of various fluoromalonate derivatives have been developed,17 no asymmetric amidase reactions of fluoromalonate derivatives have been reported.
Fluoromalonate ester 4a is synthesised in the high yield direct fluorination reaction of dimethyl malonate ester using fluorine gas catalysed by copper nitrate in acetonitrile solution. Recently, we described the optimisation of this process which is routinely carried out on the 50 g scale and assessed to have a mass intensity MI = 9 (Scheme 4).18b

Initial unoptimised synthesis of a range of racemic monofluorinated functional precursors 4 for subsequent enzymatic transformation reactions were carried out. Michael addition of acrylonitrile to fluoromalonate 4a gave the desired nitrile 4b in 90% yield and subsequent reduction of the nitrile group of 4b by hydrogen over palladium enabled the isolation of salt 4c. Base catalysed ring closure gave racemic fluorolactam 4d (Scheme 4, SI-1.2). With products 4b–d in hand we began attempts to resolve each fluorinated intermediate by appropriate enzymatic methods to identify the most effective synthetic sequence for the large scale synthesis of the desired enantiopure chiral fluorolactam 2b.

Initially, hydrolase catalysed resolution of 4b was attempted adapting literature protocols. However, nitrile 4b was unstable in mildly basic aqueous media and so this approach was discounted as a viable starting material for desymmetrisation (SI-1.3†).

Attempted hydrolase promoted amidation in anhydrous tertiary amyl alcohol as the solvent21 gave only racemic product 4d from salt 4c using various enzyme catalysts (SI-1.4†). After determining that 4d does not hydrolyse in aqueous phosphate buffer (pH 7.3) to the corresponding acid at 20–25 °C over 16 hours (SI-1.4†), enzymatic transformations of 4c were explored in this aqueous buffered medium and, indeed, 4d could be resolved by a variety of hydrolases. Following an initial screening process of 56 enzymes (SI-1.5†), 25 promising hydrolases that afforded 10–60% hydrolysis of 4d in 8 hours were analysed further (SI-1.5†). A number of highly enantioselective processes were observed (Table 1) giving both acids 5a,b by hydrolysis (SI-1.6†) and the corresponding esters 2b,c as reaction products. Both 2b and 2c were isolated by preparative scale HPLC (SI-3†) and their structures and absolute stereochemistries confirmed by X-ray crystallography (Fig. 1, SI-4†).

CAL-B 10 000 is a recombinant Candida Antartica Lipase B that is commercially available from Fermase and used to catalyse a range of biotransformations on the large scale.22 Since inexpensive CAL-B 10 000 affords the desired fluorolactam (S)-2b (entry 4, Table 1), and is available for purchase on the multi-kilogram and tonne scale, this hydrolase was selected for further reaction optimisation. The possibility of telescoping the formation and resolution of 2b from salt 4c was explored to reduce the work-up process. Initially when 4c was added to buffer solution at room temperature to form a 25 mM solution, we observed that the pH reduced from 7.3 to 6.7 after 15 minutes and that no side-reactions or degradation could be detected. However, when the pH of the solution was readjusted to 7.3 by addition of 2 N NaOH (0.92 equiv.), 19F NMR spectroscopic and chiral HPLC (SI-3†) analysis of the crude reaction product detected 5a and 5b along with 5c (at 90% yield) and gave the desired fluorolactam 2b in 95% ee. Calibrated UPLC-MS conversion.

![Scheme 4](image-url) Initial unoptimised synthesis of racemic 4a–d.

![Table 1](image-url) Initial hydrolase resolution screening of 4d

<table>
<thead>
<tr>
<th>Entry</th>
<th>Hydrolase</th>
<th>Conv. %†</th>
<th>ee %</th>
<th>Ester 2</th>
<th>Acid 5</th>
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<tbody>
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<td>1</td>
<td>JM X14</td>
<td>30</td>
<td>&gt;95</td>
<td>(S)-5a</td>
<td>62 (R)-2c</td>
</tr>
<tr>
<td>2</td>
<td>JM X33</td>
<td>19</td>
<td>&gt;95</td>
<td>(S)-5a</td>
<td>19 (R)-2c</td>
</tr>
<tr>
<td>3</td>
<td>JM X50</td>
<td>28</td>
<td>&gt;95</td>
<td>(S)-5a</td>
<td>37 (R)-2c</td>
</tr>
<tr>
<td>4</td>
<td>CAL-B 10 000</td>
<td>51</td>
<td>&gt;95</td>
<td>(R)-5b</td>
<td>95 (S)-2b</td>
</tr>
</tbody>
</table>

† Calibrated UPLC-MS conversion.

![Fig. 1](image-url) Molecular structures of (S)-2b (above) and (R)-2c (below).
mixture indicated full conversion to the desired enantiopure lactam 2b in 47% yield and 98% ee (Scheme 5, SI-1.7†).

The most operationally simple experimental protocol for the transformation of 4c to 2b would be to add 4c in one portion to the reaction mixture and then adjust the pH to 7.3. Unfortunately, at 250 mM concentrations, the solution became too acidic (pH 4.9) and hydrolysis by-products were formed. This issue was, however, resolved by slow addition of the salt and base, such that the pH was maintained between 6.8 and 7.3. Consequently, the desymmetrization reaction could be telescoped very successfully at 257 mM concentration and the desired fluorolactam 2b was separated efficiently by solid phase extraction. CAL-B enzyme was recovered quantitatively and recycled three times without any observed loss of reactivity profile in subsequent cyclisation processes.

With basic operational parameters for the synthesis of enantiopure 2b using inexpensive reagents and solvents in place, we carried out studies to optimise the multistep synthesis in order to assess the green metrics of the chemo-enzymatic process in comparison to the published enantioselective chemical synthesis strategy used previously.15

In order to reduce the solvent use in reaction work-up, the possibility of carrying out the subsequent Michael addition reaction of 4a with acrylonitrile in a one-pot process without any work-up after the fluorination stage was explored. Firstly, the Michael addition reaction between the crude direct fluorination product mixture and acrylonitrile was assessed but no alkylation reaction occurred due to problems associated with the presence of copper nitrate and HF in the reaction mixture. Consequently, reactions in which a short series of environmentally benign bases including DBU, potassium phosphate and 2-methyl pyridine, were added to the crude direct fluorination product mixture were screened. Addition of 0.5 equivalents of potassium phosphate to the reaction mixture allowed the Michael reaction to proceed to full conversion at room temperature. Scale-up of the one-pot process on 100 mmol scale, where the acrylonitrile was added to the crude direct fluorination reaction mixture via syringe pump over 30 minutes, gave 4b in 60% yield after 1.5 hours.

Reduction of the nitrile group of 4b was carried out in a Parr hydrogenator with palladium/carbon in methanol and conc. hydrochloric acid. Upon completion of the hydrogenation, a white precipitate formed upon washing the crude reaction mixture with ethanol which allowed simple filtration of the ammonium hydrochloride salt 4c. After process optimisation, the solvent volume used for the reduction could be reduced significantly, providing 4c in 84% yield after recrystallisation. The telescoped cyclisation and resolution process was carried out on 10 g scale to obtain realistic metrics data, generating 2b in 43% isolated yield, 99% ee from 4c (Scheme 6, SI-1.9–11†).

The three stage, enhanced synthesis of (S)-2b from dimethyl malonate ester gave a calculated PMI = 201, over four times lower than the corresponding enantioselective chemical synthesis strategy used previously.15

![Scheme 5 Synthesis of fluorolactam 6 from 4c.](image)

![Scheme 6 Optimised synthesis of 2b.](image)

**Experimental**

Optimised synthesis of 2b (Scheme 6)

Telescoped fluorination-Michael addition: synthesis of dimethyl (2-cyanoethyl)-2-fluoromalonate 4b. Dimethyl malonate 4a (26.40 g, 200 mmol) and copper(n) nitrate hemi(pentahydrate) (4.65 g, 20 mmol) were dissolved in acetonitrile (100 mL) and the mixture was cooled to 0–5 °C and stirred at 650 rpm using an overhead stirrer. After purging the system with N₂ for 5 minutes, fluorine gas (20% v/v in N₂, 100 mL min⁻¹, 220 mmol) was introduced into the reaction mixture for 4 h 25 min. After purging with nitrogen for 5 min, potassium phosphate tribasic (anhydrous) (4.65 g, 20 mmol) were dissolved in acetonitrile (2 × 20 mL) before a further portion of potassium phosphate (42.45 g, 200 mmol) was added to the reaction mixture and stirred. After 1 h the potassium phosphate was removed by filtration and washed with acetonitrile (2 × 20 mL) before a further portion of potassium phosphate (42.45 g, 200 mmol) was added to the solution which was heated to 55 °C. Acrylonitrile (12.73 g, 240 mmol) in acetonitrile (10 mL) was added over 30 min and the solution stirred. After a further 3.25 h the potassium phosphate was removed by filtration and washed with acetonitrile (3 × 20 mL) and the filtrate was concentrated in vacuo. Vacuum distillation (140–141 °C, 6 mbar) of the crude product yielded dimethyl(2-cyanoethyl)-2-fluoromalonate 4b (24.45 g, 60%) as a clear oil; ([MH]+, 204.0652. C₉H₁₃FNO₄ requires: [MH]+, 204.0672); IR (neat, cm⁻¹) 2962, 2253, 1748, 1438; ¹H NMR (400 MHz, CDCl₃) δ 3.85 (6H, s, OCH₃), 2.60–2.49 (4H, m, CH₂); ¹³C NMR (101 MHz, CDCl₃) δ 167.85 (CF 201.0, C-F), 53.86 (s, CH₂O), 30.16 (d, JCF 21.5, CH₂), 11.48 (d, JCF 5.5, CH₃); m/z (ASAP) 204.1 (100%, [MH]+), 162.1 (25);
Reduction: synthesis of dimethyl 2-(3-aminopropyl)-2-fluoromalonate, hydrochloride salt 4c. 10% Pd/C (2.62 g, 5 mol%) and conc. HCl (4.85 mL) were added into a Hastelloy autoclave. A solution of dimethyl(2-cyanoethyl)-2-fluoromalonate 4b (10 g, 49.2 mmol) in methanol (43.3 mL) was added and the vessel sealed. The vessel was pressurized with H2 (4 bar) and the contents were stirred at 600 rpm. After 16 h the solution was filtered through celite (2 g) with methanol (20 mL) and evaporated to give crude 4c. The solid was washed with methanol (2 × 20 mL) and acetone (2 × 15 mL) to give dimethyl(2-aminopropyl)-2-fluoromalonate, hydrochloride salt 4c (10.43 g, 84%) as white crystals; mp 147–148 °C; ([M – Cl]−, 208.9798. C8H13FNO3 requires: [MH]+, 176.0723); IR (neat, CCl4) ν 2942, 1748, 1580, 1437, 1249, 1033; 1H NMR (400 MHz, methanol-d4) δ 3.87 (6H, s, OCH3), 3.08–2.98 (2H, m, CH2), 2.32 (2H, ddd, JHF 23.1, JHH 9.2, JHH 6.9, CH3), 1.89–1.77 (2H, m, CH2); 19F NMR (376 MHz, methanol-d4) δ −167.20 (t, JHF 23.1); 13C NMR (101 MHz, methanol-d4) δ 167.60 (d, JCF 25.8, C=O), 95.57 (d, JCF 197.4, C=F), 54.10 (s, s, CH2O), 40.21 (s, CH2NMe2), 32.18 (d, JCF 21.6, CH2CF), 22.38 (d, JCF 3.2, CH2); m/z (ASAP) 208.1 (100%, [M – Cl]−), 191 (14), 176 (8).

Cyclisation: synthesis of (S)-methyl 3-fluoro-2-oxopiperidine-3-carboxylate 2b. To a 500 mL round bottomed flask was added 0.06 M Na2HPO4: 0.06 M KH2PO4 buffer (164 mL, 3 : 1, pH 7.3) followed by 4c (10.00 g, 41.0 mmol) in small portions using 0.5 M NaOH to buffer the solution to pH 7.3. The solution was filled to 328 mL total volume with further 0.06 M Na2HPO4: 0.06 M KH2PO4 buffer (3 : 1, pH 7.3) to give a 257 mM solution Fermase immobilised CAL-B 10 000 (7.2 g). The solution was concentrated to pH 7.3 followed by 4c (10.00 g, 41.0 mmol) in small portions using 0.5 M NaOH to buffer the solution to pH 7.3. The solution was concentrated under reduced pressure and water (30 mL) was added to the cartridge such that the acid was fully eluted (ca. 1 mL per min). The washed enzyme was removed and the ester was eluted with 20% formic acid (30 mL). The solution was concentrated under reduced pressure at RT to give a solid, which was recrystallised from acetone (10 mL) to give (S)-methyl 3-fluoro-2-oxopiperidine-3-carboxylate 2b (3.15 g, 44%, >99% ee) as white crystals; mp 115–116 °C; [α]D +14.393° ([c]D +14.393° (1.00, MeCN); [MH]+, 176.0718. C7H13FNO3 requires: [MH]+, 176.0723); IR (neat, cm−1) 3200, 3074, 2968, 2888, 1760, 1668, 1435; 1H NMR (400 MHz, CDCl3) δ 7.49 (1H, s, NH), 3.85 (3H, s, OCH3), 3.45–3.37 (2H, m, CH2), 2.42–2.20 (2H, m, CH2), 2.04–1.89 (2H, m, CH2); 19F NMR (376 MHz, CDCl3) δ −156.07 (dd, JHF 28.2, JHF 20.0); 13C NMR (101 MHz, CDCl3) δ 168.68 (d, JCF 26.2, NH−CH3), 165.13 (d, JCF 22.4, CO3), 90.87 (s, CH2), 84.09 (s, CH2OH), 42.22 (s, CH2-NH), 31.25 (d, JCF 22.4, CH2-CF), 18.26 (d, JCF 2.6, CH3); m/z (ASAP) 176 (100%, [MH]+), 162 (9).

Conclusions

In conclusion, the combined three stage chemo-enzymatic synthesis of enantiopure fluorolactam 2b using fluorine gas for the construction of the C-F bond and amidase CAL-B 10 000 for the key desymmetrization step has been optimised on a reasonable scale and is suitable for scale-up. The PMI of the fluorination-amidase route is PMI = 201 compared to PMI = 925 for the enantioselective fluorination literature synthesis. Clearly, the fluorination-amidase route established here has a PMI that is highly competitive with the corresponding chemical synthesis and demonstrates the very effective use of amidase enzymes for larger scale synthesis of challenging pharmaceutically relevant enantiopure fluorinated systems. However, the still relatively high PMI for the three step synthetic process is largely due to the final resolution step which, by definition, leads to the loss of half the product material.

Perhaps of more importance for synthesis on the large scale is that the cost of the overall fluorination-amidase process is several orders of magnitude less expensive than the use of enantioselective fluorination strategies that require the utilisation of relatively expensive N–F electrophilic fluorinating agents prepared from fluorine gas and the use of structurally complex precious metal catalysts. Simple recycling of the enzyme catalyst by filtration, recycling of solvents and a high yielding inexpensive, copper catalysed fluorination step make the strategy very attractive for scale-up.

The use of the fluorine-enzyme multi-step approach complements existing chemical enantioselective fluorination procedures that are more applicable to discovery scale synthesis. Here, we have demonstrated that the development of new fluorinated sub-units within drug structures bearing fluorine at a chiral sp3 centre assessed in the discovery phase by chemical enantioselective fluorination on the small scale can, when required, be scaled up by a combined inexpensive fluorination-enzyme catalysed approach thus extending the chemical space for fluorinated aliphatic units within the structures of drug candidates.

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2 For reviews on fluorinated pharmaceuticals, see: (a) K. Muller, C. Faeh and F. Diedrich, Science, 2007, 317, 1881–1886; (b) Fluorine in Medicinal Chemistry and Chemical


