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Flexible synthesis of polyfunctionalised 3-fluoropyrroles†

Thomas J. Cogswell,^a Craig S. Donald^b and Rodolfo Marquez^{*a,c}

An efficient and selective approach for the synthesis of polyfunctionalised 3-fluoropyrroles has been developed starting from commercial aldehydes. The methodology is concise, efficient and allows for the modular and systematic assembly of polysubstituted 3-fluoropyrroles. This synthesis provides an alternative and highly convergent strategy for the generation of these chemically and biologically important units.

Introduction

Polyfunctionalised pyrroles are an integral part of medicinal chemistry, forming the core unit of a number of biologically active compounds.^{1–4} Fluorinated polyfunctionalised pyrroles are particularly interesting due to their useful biological, metabolic, physical and pharmacokinetic properties. Key fluorinated pyrroles include compounds such as **1** and **2** which have been developed as anti-inflammatory and anti-hypertension agents respectively (Fig. 1).^{5,6}

Thus, it is not surprising that a significant amount of interest has been devoted to the synthesis of fluorinated pyrroles in recent years.^{7–9} As such, new flexible and efficient methods for their syntheses are desired.

Fluorinated α,β -unsaturated lactams were first synthesised *via* a ring-closing metathesis approach by Haufe and co-workers.¹⁰ The work was extended by the groups of Rutjes and Marquez to produce a number of novel fluorinated compounds (Scheme 1). To date, most work has been centred on the synthesis of 5 and 6-membered lactams with various degrees of functionalisation.^{11,12} We feel fluorinated α,β -unsaturated γ -lactams would be the ideal building block to provide access to polyfunctionalised fluorinated pyrroles.

Herein, we would like to report a quick, flexible and modular synthesis of polyfunctionalised fluorinated pyrroles. The methodology allows for the systematic introduction of substituents to produce novel polyfunctionalised fluorinated building blocks (Scheme 1).

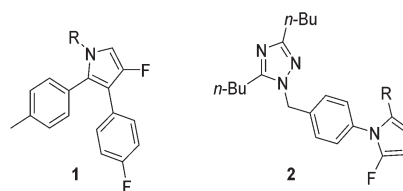
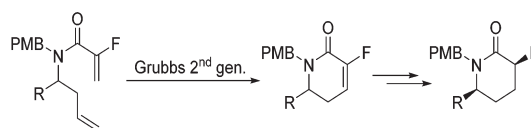
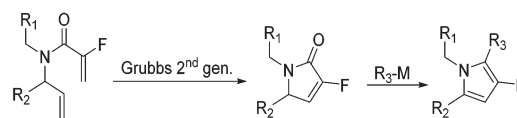


Fig. 1 Biologically active fluorinated pyrrole examples. Pyrrole **1** has anti-inflammatory activity, while pyrrole **2** is used to alleviate hypertension.^{1,2}

Previous work



This work



Scheme 1 Previous work to generate fluorinated δ -lactams *via* RCM approach.

Results and discussion

Our initial approach to the synthesis of the pyrrole core began with the condensation of benzaldehyde **3** with *t*-butylsulfinamide to generate the corresponding imine, which upon vinylation with vinylmagnesium bromide afforded the desired allylic amine **4** in excellent yield.¹³ Reductive amination of amine **4**

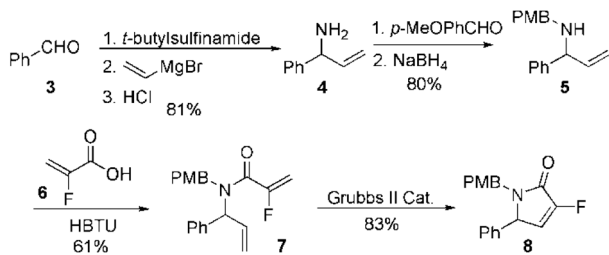
^aSchool of Chemistry, University of Glasgow, Glasgow, G12 8QQ, UK

^bOncology iMed, AstraZeneca, Alderley Park, Macclesfield, Cheshire SK10 4TG, UK

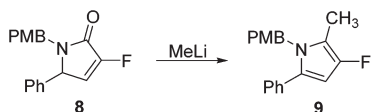
^cDepartment of Chemistry, Xi'an Jiaotong-Liverpool University, SIP Suzhou, 215123, China. E-mail: rudi.marquez@xjtlu.edu.cn; Tel: +86 (0)512 88161432

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Scheme 2 Synthesis of fluorinated α,β -unsaturated lactam **8**.



Scheme 3 Synthesis of fluorinated polysubstituted pyrrole **9**.

with *p*-anisaldehyde then produced the PMB protected amine **5** in high yield (Scheme 2).

Coupling of amine **5** with 2-fluoroacrylic acid **6** then proceeded to produce the desired amide unit **7** in reasonable yield. Subsequent treatment of diene **7** with Grubbs 2nd gen. catalyst then afforded the expected α,β -unsaturated lactam **8** in good yield.¹²

Rewardingly, alkylation of fluorolactam **8** with methyl-lithium proceeded cleanly to generate the desired pyrrole unit **9** in excellent yield (Scheme 3).^{14,15} Mechanistically, we believe that this aromatisation process takes place through hemiaminal formation followed by elimination of water and double bond isomerisation.^{15,16}

The alkylation–aromatisation methodology was then expanded by including an array of nucleophiles as to allow for the selective introduction of substituents at the C2 position of the C3 fluorinated-pyrrole ring. Thus, a collection of organometallic reagents including DIBAL-H, *n*-butyllithium, phenyllithium and allylmagnesium bromide were used to generate the desired substituted pyrroles **10–13** in high yields (Table 1).^{14–16}

Having demonstrated the ability to incorporate substituents at the pyrrole C2 position through an alkylation–aromatisation process, it was decided to explore the ability of our methodology to incorporate substituents in the other pyrrole positions.

Thus, it was decided to showcase the methodology by generating a number of C3 fluorinated pyrrole analogues with different *N*-substituents. Synthetically, the generation of the new analogues was envisioned as originating through the incorporation of different aldehyde units during the reductive amination step.

Following this approach, different aromatic substitution patterns were initially explored with the benzyl and 4-bromobenzyl derivatives **14a** and **14b** being cleanly converted to the RCM precursors **15a** and **15b** in high yields (Table 2).

Table 1 Introduction of different nucleophiles (RM) in the synthesis of tetrasubstituted pyrroles (**9–13**)

RM	Yield		
DIBAL-H	78%		10
PhLi	93%		11
<i>n</i> BuLi	78%		12
AllylMgBr	75%		13

Table 2 Synthesis of fluorinated diene-amides **15a–d**

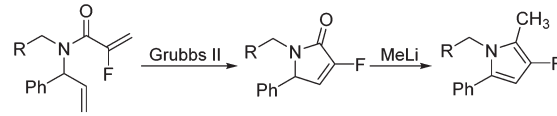
R	Yield		Yield
	74%	14a	74%
	81%	14b	71%
	82%	14c	86%
	71%	14d	58%
			15a
			15b
			15c
			15d

The non-aromatic derivative **15c**, bearing a cyclohexylmethyl group, worked well with yields upwards of 80% for both steps. *N*-Methylpyrrole-2-carboxaldehyde was also cleanly incorporated, yielding the desired diene **15d** in good yield over the sequence.

Ring-closing metathesis was then successfully carried out in all cases, with isolated yields higher than 80%.¹⁷



Table 3 Synthesis of fluorinated pyrroles 17a–d




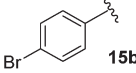

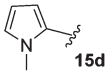
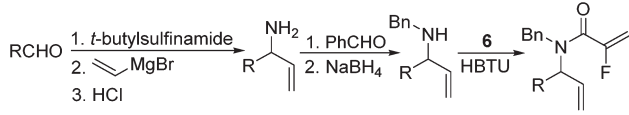
R	Yield	Yield		
 15a	98%	16a	86%	17a
 15b	96%	16b	83%	17b
 15c	92%	16c	84%	17c
 15d	81%	16d	75%	17d

Table 4 Synthesis of fluorinated amides 20a–e



R	Yield	Yield	Yield	
4-MeOC ₆ H ₄	71%	18a	79%	19a 60% 20a
4-CF ₃ C ₆ H ₄	61%	18b	80%	19b 45% 20b
4-BrC ₆ H ₄	75%	18c	84%	19c 62% 20c
Cyclohexyl	50%	18d	70%	19d 76% 20d
PhCH ₂ CH ₂	58%	18e	88%	19e 75% 20e

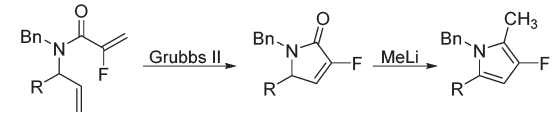
Gratifyingly, treatment of pyrrolidone compounds **16a–d** with methyllithium under our alkylation–aromatisation methodology afforded the desired *N*-substituted pyrrole derivatives **17a–d** in excellent isolated yields (Table 3).

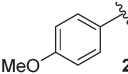
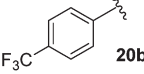
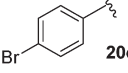

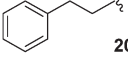
At this point, it was decided to now focus on exploring the nature and effect of the starting aldehyde on our pyrrole forming sequence. By changing the identity of the starting aldehyde, a range of functional groups could be efficiently installed at the C5 position (Table 4).

Electron donating and withdrawing aromatic analogues were investigated, resulting in good yields of the allylic amine intermediates **18a–c**. Aliphatic aldehydes could also be converted to the corresponding primary amines **18d–e** in reasonable yields.¹⁸ Treatment of the crude allylic amines **18a–e** under reductive amination conditions afforded the secondary amines **19a–e** which upon coupling with 2-fluoroacrylic acid **6** generated the desired fluorinated amides **20a–20e** in good yields.

Ring-closing metathesis in all cases proceeded in high yields (Table 5). However, examples with electron withdrawing

Table 5 Synthesis of fluorinated pyrroles 22a–d



R	Yield	Yield		
 20a	71%	21a	88%	22a
 20b	88%	21b	73%	22b
 20c	94%	21c	78%	22c
 20d	95%	21d	92%	22d
 20e	96%	21e	74%	22e

substituents required extended reaction times and higher catalyst loadings (15 mol%) to achieve high yields. Gratifyingly, treatment of all the pyrrolidone intermediates (**21a–21e**) under the methyllithium promoted alkylation–aromatisation conditions yielded the desired fluorinated tetrasubstituted pyrroles **22a–e** in good to excellent yield.

Conclusion

In conclusion, we have developed an efficient and selective approach for the synthesis of polyfunctionalised 3-fluorinated pyrroles. The methodology is concise and allows for the modular synthesis of chemically and biologically important units.

Experimental

All reactions were performed in oven-dried glassware under an inert argon atmosphere unless otherwise stated. Tetrahydrofuran (THF), diethyl ether, toluene and dichloromethane (DCM) were purified through a solvent purification system. Petroleum ether refers to the fraction boiling between 40–60 °C. All reagents were used as received, unless otherwise stated. Solvents were evaporated under reduced pressure at 40 °C unless otherwise stated. IR spectra were recorded as thin films on NaCl plates using a Fourier Transform spectrometer. Only significant absorptions (ν^{\max}) are reported in wavenumbers (cm^{−1}). Proton magnetic resonance spectra (¹H NMR) were recorded at either 400 or 500 MHz. Fluorine magnetic



resonance spectra (^{19}F NMR) were recorded at either 377 or 470 MHz. Carbon magnetic resonance spectra (^{13}C NMR) were recorded at either 100 or 125 MHz. Chemical shifts (δ) are reported in parts per million (ppm) and are referenced to the residual solvent peak. The order of citation in parentheses is (1) number of equivalent nuclei (by integration), (2) multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, quint = quintet, sext = sextet, sept = septet, m = multiplet, b = broad), (3) and coupling constant (J) quoted in Hertz to the nearest 0.1 Hz. High resolution mass spectra were obtained by electrospray (EI) chemical ionisation (CI) mass spectrometry operating at a resolution of 15 000 full widths at half height. Flash chromatography was performed using silica gel (40–63 micron) as the stationary phase. TLC was performed on aluminium sheets pre-coated with silica (Silica Gel 60 F254) unless otherwise stated. The plates were visualised by the quenching of UV fluorescence (λ_{max} 254 nm) and/or by staining with either anisaldehyde, potassium permanganate, iodine or cerium ammonium molybdate followed by heating.

General procedure I

A solution of the diene (1 eq.) in toluene (0.005 g ml^{-1}) and was heated to $100\text{ }^{\circ}\text{C}$. Grubbs 2nd generation catalyst was added in portions and the reaction was stirred until completion as indicated by TLC analysis. The reaction was cooled down to room temperature, the solvent was removed under reduced pressure and the crude material was purified by flash column chromatography.

General procedure II

α,β -Unsaturated lactam (1 eq.) was dissolved in diethyl ether (5 mL) and cooled to $0\text{ }^{\circ}\text{C}$. Methyl lithium (1.1 eq.) was added dropwise and the mixture was stirred for 1 h. Following this time, the reaction was quenched with H_2O (10 mL), extracted with diethyl ether ($3 \times 10\text{ mL}$), dried (Na_2SO_4) and evaporated *in vacuo*. The crude residue was purified by flash column chromatography.

3-Fluoro-1-[(4'-methoxyphenyl)methyl]-5-phenyl-2,5-dihydro-1H-pyrrol-2-one, 8. Dialkene **7** (270 mg, 0.84 mmol) was treated with 7.5 mol% Grubbs 2nd generation catalyst as described in General procedure I. The crude product was purified by flash column chromatography (0–15% EtOAc in petroleum ether) to yield the desired α,β -unsaturated lactam **8** (210 mg, 0.71 mmol, 83%) as a pale yellow oil. ^1H NMR (CDCl_3 , 400 MHz) δ : 7.50–7.33 (3H, m), 7.20–7.09 (2H, m), 7.06 (2H, $J_{\text{H}} = 8.6\text{ Hz}$), 6.85 (2H, d, $J_{\text{H}} = 8.6\text{ Hz}$), 6.26 (1H, d, $J_{\text{H}} = 1.6\text{ Hz}$), 5.12 (1H, d, $J_{\text{H}} = 14.8\text{ Hz}$), 4.78 (1H, dd, $J_{\text{F}} = 6.0\text{ Hz}$, $J_{\text{H}} = 2.4\text{ Hz}$), 3.82 (3H, m), 3.58 (1H, $J_{\text{H}} = 14.8\text{ Hz}$). ^{19}F NMR (CDCl_3 , 470 MHz) δ : -138.5 . ^{13}C NMR (CDCl_3 , 125 MHz) δ : 163.0 (d, $J_{\text{F}} = 31.2\text{ Hz}$), 159.2, 152.3 (d, $J_{\text{F}} = 279.6\text{ Hz}$), 133.9 (d, $J_{\text{F}} = 2.1\text{ Hz}$), 129.8 (2C), 129.3 (2C), 129.2, 128.6, 127.6 (2C), 118.4 (d, $J_{\text{F}} = 4.4\text{ Hz}$), 114.2 (2C), 59.1 (d, $J_{\text{F}} = 5.7\text{ Hz}$), 55.3, 43.5. m/z [EI (+ve)] 297.2 $[\text{M}]^+$, HRMS found $[\text{M}]^+$ 297.1164, $\text{C}_{18}\text{H}_{16}\text{FNO}_2$ requires 297.1165. IR (thin film) $\nu_{\text{max}} = 2355$, 1710, 1666, 1514, 1247 cm^{-1} .

3-Fluoro-1-[(4'-methoxyphenyl)methyl]-2-methyl-5-phenyl-1H-pyrrole, 9. α,β -Unsaturated lactam **8** (36 mg, 0.12 mmol) was reacted with methyl lithium (83 μL , 0.13 mmol, 1.6 M in diethyl ether) following General procedure II. The product was purified by flash column chromatography (0–2.5% diethyl ether in petroleum ether) to yield the pyrrole **9** (30 mg, 0.1 mmol, 86%) as a white solid. ^1H NMR (CDCl_3 , 400 MHz) δ : 7.35–7.13 (5H, m), 6.78–6.76 (4H, m), 5.96 (1H, s), 4.93 (2H, s), 3.72 (3H, s), 1.98 (3H, d, $J_{\text{F}} = 1.6\text{ Hz}$). ^{19}F NMR (CDCl_3 , 470 MHz) δ : -169.4 . ^{13}C NMR (CDCl_3 , 125 MHz) δ : 158.7, 149.2 (d, $J_{\text{F}} = 235.6\text{ Hz}$), 132.9, 130.6, 130.1 (d, $J_{\text{F}} = 6.9\text{ Hz}$), 128.8 (2C), 128.5 (2C), 127.1, 126.7 (2C), 114.2 (2C), 112.5 (d, $J_{\text{F}} = 24.3\text{ Hz}$), 96.4 (d, $J_{\text{F}} = 16.4\text{ Hz}$), 55.3, 47.2, 8.2. m/z [EI (+ve)] 295.2 $[\text{M}]^+$, HRMS found $[\text{M}]^+$ 295.1373 $\text{C}_{19}\text{H}_{18}\text{FNO}$ requires 295.1372. IR (thin film) $\nu_{\text{max}} = 2928$, 2359, 1614, 1599, 1512, 1352, 1249, 1174 cm^{-1} . m.p. $73\text{--}75\text{ }^{\circ}\text{C}$.

4-Fluoro-1-[(4'-methoxyphenyl)methyl]-2-phenyl-1H-pyrrole, 10. α,β -Unsaturated lactam **8** (40 mg, 0.13 mmol) was dissolved in CH_2Cl_2 (4 mL) and cooled to $-78\text{ }^{\circ}\text{C}$. Diisobutyl-aluminium hydride (0.41 mL, 0.41 mmol, 1 M in hexanes) was added dropwise and the mixture was stirred for 16 h. Following this time, the reaction was quenched with H_2O (10 mL), extracted with diethyl ether ($3 \times 10\text{ mL}$), dried (Na_2SO_4) and evaporated *in vacuo*. The crude residue was purified by flash column chromatography (0–2.5% diethyl ether in petroleum ether) to yield the pyrrole **10** (30 mg, 0.11 mmol, 85%) as a yellow oil. ^1H NMR (CDCl_3 , 400 MHz) δ : 7.40–7.32 (5H, m), 6.98 (2H, d, $J_{\text{H}} = 8.7\text{ Hz}$), 6.86 (2H, d, $J_{\text{H}} = 8.7\text{ Hz}$), 6.46 (1H, dd, $J_{\text{F}} = 3.2\text{ Hz}$, $J_{\text{H}} = 2.0\text{ Hz}$), 6.04 (1H, d, $J_{\text{F}} = 2.4\text{ Hz}$), 4.99 (2H, s), 3.82 (3H, s). ^{19}F NMR (CDCl_3 , 470 MHz) δ : -165.4 . ^{13}C NMR (CDCl_3 , 125 MHz) δ : 159.0, 152.0 (d, $J_{\text{F}} = 239.1\text{ Hz}$), 132.5 (d, $J_{\text{F}} = 1.6\text{ Hz}$), 131.8 (d, $J_{\text{F}} = 6.4\text{ Hz}$), 130.2, 129.0 (2C), 128.5 (2C), 127.9 (2C), 127.5, 114.1 (2C) 105.5 (d, $J_{\text{F}} = 27.3\text{ Hz}$), 97.1 (d, $J_{\text{F}} = 16.4\text{ Hz}$), 55.3, 50.2. m/z [EI (+ve)] 281.1 $[\text{M}]^+$, HRMS found $[\text{M}]^+$ 281.1215, $\text{C}_{18}\text{H}_{16}\text{FNO}$ requires 281.1216. IR (thin film) $\nu_{\text{max}} = 2956$, 2837, 1701, 1612, 1512, 1247, 1176 cm^{-1} .

3-Fluoro-1-[(4'-methoxyphenyl)methyl]-2,5-diphenyl-1H-pyrrole, 11. α,β -Unsaturated lactam **8** (45 mg, 0.15 mmol) was dissolved in diethyl ether (5 mL) and cooled to $0\text{ }^{\circ}\text{C}$. Phenyl-lithium (87 μL , 0.16 mmol, 1.9 M in di-*n*-butyl ether) was added dropwise and the mixture was stirred for 1 h. Following this time, the reaction was quenched with H_2O (10 mL), extracted with diethyl ether ($3 \times 10\text{ mL}$), dried (Na_2SO_4) and evaporated *in vacuo*. The crude residue was purified by flash column chromatography (0–2.5% diethyl ether in petroleum ether) to yield the pyrrole **11** (50 mg, 0.14 mmol, 93%) as a white solid. ^1H NMR (CDCl_3 , 400 MHz) δ : 7.39–7.36 (7H, m), 7.35–7.37 (3H, m), 6.66 (2H, d, $J_{\text{H}} = 8.8\text{ Hz}$), 6.55 (2H, d, $J_{\text{H}} = 8.8\text{ Hz}$), 6.17 (1H, br s), 5.10 (2H, s), 3.74 (3H, s). ^{19}F NMR (CDCl_3 , 470 MHz) δ : -165.3 . ^{13}C NMR (CDCl_3 , 125 MHz) δ : 158.5, 149.6 (d, $J_{\text{F}} = 242.5\text{ Hz}$), 133.0 (d, $J_{\text{F}} = 7.1\text{ Hz}$), 132.9 (d, $J_{\text{F}} = 1.8\text{ Hz}$), 130.8, 129.9 (d, $J_{\text{F}} = 3.3\text{ Hz}$), 129.5, 129.1 (2C), 128.5 (2C), 128.5 (2C), 127.5, 127.3 (2C), 127.2, 119.1 (d, $J_{\text{F}} = 21.0\text{ Hz}$), 113.7 (2C), 98.4 (d, $J_{\text{F}} = 16.6\text{ Hz}$), 55.2, 48.3. m/z [EI (+ve)] 357.0 $[\text{M}]^+$, HRMS found $[\text{M}]^+$ 357.1531, $\text{C}_{24}\text{H}_{20}\text{FNO}$ requires 357.1529. IR (thin film) $\nu_{\text{max}} = 3063$,



2955, 2835, 1610, 1512, 1492, 1435, 1247, 1176 cm⁻¹. m.p. 84–86 °C.

2-Butyl-3-fluoro-1-[(4'-methoxyphenyl)methyl]-5-phenyl-1H-pyrrole, 12. α,β -Unsaturated lactam **8** (38 mg, 0.13 mmol) was dissolved in diethyl ether (5 mL) and cooled to 0 °C. *n*-Butyllithium (54 μ L, 0.13 mmol, 2.5 M in hexanes) was added dropwise and the mixture was stirred for 1 h. Following this time, the reaction was quenched with H₂O (10 mL), extracted with diethyl ether (3 \times 10 mL), dried (Na₂SO₄) and evaporated *in vacuo*. The crude residue was purified by flash column chromatography (0–2.5% diethyl ether in petroleum ether) to yield the pyrrole **12** (34 mg, 0.10 mmol, 78%) as a white solid. ¹H NMR (CDCl₃, 400 MHz) δ : 7.22–7.14 (5H, m), 6.74 (4H, m), 5.95 (1H, s), 4.94 (2H, s), 3.71 (3H, s), 2.37 (2H, t, J_H = 7.6 Hz), 1.43–1.34 (2H, m), 1.25–1.18 (2H, m), 0.78 (3H, t, J_H = 7.3 Hz). ¹⁹F NMR (CDCl₃, 470 MHz) δ : –168.0. ¹³C NMR (CDCl₃, 125 MHz) δ : 158.7, 149.5 (d, J_F = 236.1 Hz), 133.0, 131.0, 130.0 (d, J_F = 7.0 Hz), 128.9 (2C), 128.4 (2C), 127.1, 126.7 (2C), 117.0 (d, J_F = 23.5 Hz), 114.1 (2C), 96.7 (d, J_F = 16.6 Hz), 55.3, 47.1, 31.3 (d, J_F = 2.0 Hz), 23.1 (d, J_F = 2.6 Hz), 22.4, 13.8. *m/z* [EI (+ve)] 337.2 [M]⁺, HRMS found [M]⁺ 337.1840, C₂₂H₂₄FNO requires 337.1842. IR (thin film) ν_{\max} = 2956, 2929, 2858, 1612, 1595, 1512, 1464, 1249 cm⁻¹. m.p. 32–34 °C.

3-Fluoro-1-[(4"-methoxyphenyl)methyl]-5-phenyl-2-(prop-2'-en-1'-yl)-1H-pyrrole, 13. α,β -Unsaturated lactam **8** (41 mg, 0.14 mmol) was dissolved in diethyl ether (5 mL) and cooled to 0 °C. Allylmagnesium bromide (0.21 mL, 0.21 mmol, 1 M in Et₂O) was added dropwise and the mixture was stirred for 1.5 h. Following this time, the reaction was quenched with H₂O (10 mL), extracted with diethyl ether (3 \times 10 mL), dried (Na₂SO₄) and evaporated *in vacuo*. The crude residue was purified by flash column chromatography (0–2.5% diethyl ether in petroleum ether) to yield the pyrrole **13** (34 mg, 0.11 mmol, 75%) as a white solid. ¹H NMR (CDCl₃, 400 MHz) δ : 7.30–7.12 (5H, m), 6.75 (4H, m), 5.98 (1H, s), 5.76 (1H, ddt, J_H = 16.1, 10.1, 6.0 Hz), 5.00–4.84 (4H, m), 3.71 (3H, s, OCH₃), 3.12 (2H, dd, J_H = 5.9, 0.8 Hz). ¹⁹F NMR (CDCl₃, 470 MHz) δ : –168.0. ¹³C NMR (CDCl₃, 125 MHz) δ : 158.7, 149.5 (d, J_F = 237.3 Hz), 135.3, 132.8, 130.8, 130.7, 128.9 (2C), 128.5 (2C), 127.2, 126.7 (2C), 115.4, 114.2 (2C), 113.9 (d, J_F = 23.5 Hz), 96.6 (d, J_F = 16.3 Hz), 55.3, 47.1, 27.5 (d, J_F = 2.1 Hz). *m/z* [EI (+ve)] 321.1 [M]⁺, HRMS found [M]⁺ 321.1526, C₂₁H₂₀FNO requires 321.1529. IR (thin film) ν_{\max} = 2931, 1612, 1595, 1512, 1354, 1247, 1174 cm⁻¹. m.p. 30–32 °C.

1-Benzyl-3-fluoro-5-phenyl-2,5-dihydro-1H-pyrrol-2-one, 16a. Dialkene **15a** (110 mg, 0.36 mmol) was treated with 7.5 mol% Grubbs 2nd generation catalyst as described in General procedure I. The crude product was purified by flash column chromatography (0–10% EtOAc in petroleum ether) to yield the desired α,β -unsaturated lactam **16a** (100 mg, 0.35 mmol, 98%) as a pale yellow oil. ¹H NMR (CDCl₃, 400 MHz) δ : 7.35–7.29 (3H, m), 7.26–7.20 (3H, m), 7.05–7.01 (4H, m), 6.19 (1H, d, J_H = 1.9 Hz), 5.08 (1H, d, J_H = 15.0 Hz), 4.70 (1H, dd, J_F = 5.8 Hz, J_H = 2.3 Hz), 3.53 (1H, d, J_H = 15.0 Hz). ¹⁹F NMR (CDCl₃, 470 MHz) δ : –138.6. ¹³C NMR (CDCl₃, 125 MHz) δ : 163.0 (d, J_F = 31.3 Hz), 152.4 (d, J_F = 279.5 Hz), 136.5, 133.8, 129.3 (2C),

129.2, 128.8 (2C), 128.4 (2C), 127.8, 127.6 (2C), 118.5 (d, J_F = 4.4 Hz), 59.3 (d, J_F = 5.7 Hz), 44.1. *m/z* [ESI (+ve)] 290.1 [M + Na]⁺, HRMS found [M + Na]⁺ 290.0943, C₁₇H₁₄FNONa requires 290.0940. IR (thin film) ν_{\max} = 3063, 1710, 1666, 1456, 1220, 1186 cm⁻¹.

3-Fluoro-1-[(4'-bromophenyl)methyl]-5-phenyl-2,5-dihydro-1H-pyrrol-2-one, 16b. Dialkene **15b** (120 mg, 0.31 mmol) was treated with 7.5 mol% Grubbs 2nd generation catalyst as described in General procedure I. The crude product was purified by flash column chromatography (0–5% EtOAc in petroleum ether) to yield the desired α,β -unsaturated lactam **16b** (100 mg, 0.29 mmol, 96%) as a pale yellow oil. ¹H NMR (CDCl₃, 400 MHz) δ : 7.36 (2H, d, J_H = 8.3 Hz), 7.34–7.28 (3H, m), 7.03–7.00 (2H, m), 6.91 (2H, d, J_H = 8.3 Hz), 6.21 (1H, d, J_H = 2.0 Hz), 4.98 (1H, J_H = 15.0 Hz), 4.69 (1H, dd, J_F = 5.8 Hz, J_H = 2.2 Hz), 3.54 (1H, J_H = 15.0 Hz). ¹⁹F NMR (CDCl₃, 470 MHz) δ : –138.5. ¹³C NMR (CDCl₃, 125 MHz) δ : 163.0 (d, J_F = 31.3 Hz), 152.3 (d, J_F = 279.8 Hz), 135.5, 133.6 (d, J_F = 2.2 Hz), 132.0 (2C), 130.1 (2C), 129.4 (2C), 129.3, 127.5 (2C), 121.9, 118.6 (d, J_F = 4.4 Hz), 59.4 (d, J_F = 5.6 Hz), 43.6. *m/z* [EI (+ve)] 344.9 [M]⁺, HRMS found [M]⁺ 345.0167, C₁₇H₁₃BrFNO requires 345.0165. IR (thin film) ν_{\max} = 2960, 1708, 1666, 1489, 1404, 1220, 1012 cm⁻¹.

3-Fluoro-1-(cyclohexylmethyl)-5-phenyl-2,5-dihydro-1H-pyrrol-2-one, 16c. Dialkene **15c** (150 mg, 0.5 mmol) was treated with 7.5 mol% Grubbs 2nd generation catalyst as described in General procedure I. The crude product was purified by flash column chromatography (0–7.5% EtOAc in petroleum ether) to yield the desired α,β -unsaturated lactam **16c** (130 mg, 0.46 mmol, 92%) as a pale yellow oil. ¹H NMR (CDCl₃, 500 MHz) δ : 7.37–7.22 (3H, m), 7.09–7.07 (2H, m), 6.20 (1H, d, J_H = 1.5 Hz), 4.90 (1H, dd, J_F = 5.5 Hz, J_H = 2.0 Hz), 3.48 (1H, dd, J_H = 14.0, 8.7 Hz), 2.46 (1H, dd, J_H = 14.0, 6.0 Hz), 1.63–1.58 (2H, m), 1.40–1.43 (3H, m), 1.09–1.04 (3H, m), 0.87–0.79 (3H, m). ¹⁹F NMR (CDCl₃, 470 MHz) δ : –138.4. ¹³C NMR (CDCl₃, 125 MHz) δ : 163.3 (d, J_F = 31.0 Hz), 152.6 (d, J_F = 279.3 Hz), 134.2, 129.3 (2C), 129.1, 127.4 (2C), 117.9 (d, J_F = 4.4 Hz), 60.7 (d, J_F = 5.9 Hz), 46.6, 37.0, 30.9, 30.4, 26.3, 25.7, 25.6. *m/z* [EI (+ve)] 273.2 [M]⁺, HRMS found [M]⁺ 273.1528, C₁₇H₂₀FNO requires 273.1529. IR (thin film) ν_{\max} = 2922, 2852, 1703, 1666, 1448, 1220, 1116 cm⁻¹.

3-Fluoro-1-[(1'-methyl-1H-pyrrol-2'-yl)methyl]-5-phenyl-2,5-dihydro-1H-pyrrol-2-one, 16d. Dialkene **15d** (80 mg, 0.27 mmol) was treated with 7.5 mol% Grubbs 2nd generation catalyst as described in General procedure I. The crude product was purified by flash column chromatography (0–5% EtOAc in petroleum ether) to yield the desired α,β -unsaturated lactam **16d** (60 mg, 0.22 mmol, 81%) as a pale yellow solid. ¹H NMR (CDCl₃, 400 MHz) δ : 7.45–7.27 (3H, m), 7.09–7.06 (2H, m), 6.51 (1H, appt t, J_H = 2.4 Hz), 6.18 (1H, d, J_H = 2.0 Hz), 5.95 (1H, dd, J_H = 3.6, 2.8 Hz), 5.78 (1H, dd, J_H = 3.6, 2.0 Hz), 4.99 (1H, d, J_H = 15.5 Hz), 4.74 (1H, dd, J_F = 5.9 Hz, J_H = 2.3 Hz), 3.60 (1H, d, J_H = 15.5 Hz), 3.48 (3H, s). ¹⁹F NMR (CDCl₃, 470 MHz) δ : –138.7. ¹³C NMR (CDCl₃, 125 MHz) δ : 162.4 (d, J_F = 31.3 Hz), 151.9 (d, J_F = 279.8 Hz), 133.7, 129.3 (2C), 129.1, 127.6 (2C), 126.8, 123.3, 118.8 (d, J_F = 4.2 Hz), 110.3, 106.9,



58.9 (d, $J_F = 5.5$ Hz), 35.4, 34.1. m/z [EI (+ve)] 270.1 $[M]^+$, HRMS found $[M]^+$ 270.1170, $C_{16}H_{15}FN_2O$ requires 270.1168. IR (thin film) $\nu_{max} = 2960, 2359, 1716, 1666, 1417, 1217$ cm^{-1} . m.p. 92–94 °C.

1-Benzyl-3-fluoro-2-methyl-5-phenyl-1H-pyrrole, 17a. α,β -Unsaturated lactam **16a** (33 mg, 0.13 mmol) was reacted with methyllithium (100 μ L, 0.14 mmol, 1.4 M in diethyl ether) following General procedure II. The product was purified by flash column chromatography (0–2.5% diethyl ether in petroleum ether) to yield the pyrrole **17a** (29 mg, 0.11 mmol, 86%) as a white solid. 1H NMR ($CDCl_3$, 400 MHz) δ : 7.30–7.09 (8H, m), 6.87–6.84 (2H, m), 5.98 (1H, s), 4.99 (2H, s), 1.97 (3H, d, $J_F = 1.6$ Hz). ^{19}F NMR ($CDCl_3$, 470 MHz) δ : –169.3. ^{13}C NMR ($CDCl_3$, 125 MHz) δ : 149.2 (d, $J_F = 235.6$ Hz), 138.6, 132.8, 130.2 (d, $J_F = 3.3$ Hz), 128.8 (2C), 128.5 (2C), 127.2, 127.1, 125.6 (2C), 112.6 (d, $J_F = 24.4$ Hz), 96.5 (d, $J_F = 16.5$ Hz), 47.8, 8.2. m/z [EI (+ve)] 265.1 $[M]^+$, HRMS found $[M]^+$ 265.1269, $C_{18}H_{16}FN$ requires 265.1267. IR (thin film) $\nu_{max} = 2924, 1662, 1599, 1452, 1352, 1118$ cm^{-1} . m.p. 44–46 °C.

1-[(4'-Bromophenyl)methyl]-3-fluoro-2-methyl-5-phenyl-1H-pyrrole, 17b. α,β -Unsaturated lactam **16b** (38 mg, 0.11 mmol) was reacted with methyllithium (74 μ L, 0.12 mmol, 1.6 M in diethyl ether) following General procedure II. The product was purified by flash column chromatography (0–2.5% diethyl ether in petroleum ether) to yield the pyrrole **17b** (31 mg, 0.09 mmol, 83%) as a white solid. 1H NMR ($CDCl_3$, 400 MHz) δ : 7.36 (2H, d, $J_H = 8.6$ Hz), 7.27–7.14 (5H, m), 6.72 (2H, d, $J_H = 8.6$ Hz), 5.98 (1H, s), 4.93 (2H, s), 1.97 (3H, d, $J_F = 1.6$ Hz). ^{19}F NMR ($CDCl_3$, 470 MHz) δ : –168.8. ^{13}C NMR ($CDCl_3$, 125 MHz) δ : 149.3 (d, $J_F = 236.2$ Hz), 137.7, 132.6, 131.9 (2C), 130.2 (d, $J_F = 6.8$ Hz), 128.8 (2C), 128.6 (2C), 127.3 (2C), 127.3, 121.0, 112.4 (d, $J_F = 24.4$ Hz), 96.8 (d, $J_F = 16.5$ Hz), 47.2, 8.1 (d, $J_F = 2.1$ Hz). m/z [EI (+ve)] 343.1 $[M]^+$, HRMS found $[M]^+$ 343.0367, $C_{18}H_{15}FNBr$ requires 343.0372. IR (thin film) $\nu_{max} = 2924, 1680, 1599, 1489, 1363, 1072, 1010$ cm^{-1} . m.p. 98–100 °C.

1-(Cyclohexylmethyl)-3-fluoro-2-methyl-5-phenyl-1H-pyrrole, 17c. α,β -Unsaturated lactam **16c** (36 mg, 0.13 mmol) was reacted with methyllithium (91 μ L, 0.15 mmol, 1.6 M in diethyl ether) following General procedure II. The product was purified by flash column chromatography (0–2.5% diethyl ether in petroleum ether) to yield the pyrrole **17c** (29 mg, 0.11 mmol, 84%) as a white solid. 1H NMR ($CDCl_3$, 500 MHz) δ : 7.31–7.28 (2H, m), 7.25–7.20 (3H, m), 5.81 (1H, s), 3.66 (2H, d, $J_H = 7.0$ Hz), 2.17 (3H, d, $J_F = 1.6$ Hz), 1.50–1.45 (3H, m), 1.28–1.23 (3H, m), 0.98–0.88 (3H, m), 0.56–0.49 (2H, m). ^{19}F NMR ($CDCl_3$, 470 MHz) δ : –170.1. ^{13}C NMR ($CDCl_3$, 125 MHz) δ : 149.1 (d, $J_F = 235.0$ Hz), 133.9, 130.0 (d, $J_F = 7.2$ Hz), 128.3 (2C), 128.3 (2C), 126.8, 112.2 (d, $J_F = 23.8$ Hz), 96.3 (d, $J_F = 16.3$ Hz), 50.2, 39.2, 30.4 (2C), 26.2, 25.7 (2C), 8.5 (d, $J_F = 1.9$ Hz). m/z [EI (+ve)] 271.1 $[M]^+$, HRMS found $[M]^+$ 271.1733, $C_{18}H_{22}FN$ requires 271.1736. IR (thin film) $\nu_{max} = 2926, 2852, 1597, 1450, 1348, 1112$ cm^{-1} . m.p. 73–75 °C.

3-Fluoro-2-methyl-1-[(1'-methyl-1H-pyrrole-2'-yl)methyl]-5-phenyl-1H-pyrrole, 17d. α,β -Unsaturated lactam **16d** (31 mg, 0.12 mmol) was reacted with methyllithium (79 μ L, 0.13 mmol, 1.6 M in diethyl ether) following General pro-

cedure II. The product was purified by flash column chromatography (0–2.5% diethyl ether in petroleum ether) to yield the pyrrole **17d** (23 mg, 0.09 mmol, 75%) as a white solid. 1H NMR ($CDCl_3$, 400 MHz) δ : 7.28–7.23 (2H, m), 7.23–7.19 (3H, m), 6.46 (1H, appt t, $J_H = 2.5$ Hz), 5.95 (1H, appt t, $J_H = 3.5$ Hz), 5.92 (1H, s), 5.70–5.69 (1H, m), 4.88 (2H, s), 3.26 (3H, s), 2.03 (3H, d, $J_F = 1.6$ Hz). ^{19}F NMR ($CDCl_3$, 470 MHz) δ : –169.5. ^{13}C NMR ($CDCl_3$, 125 MHz) δ : 149.2 (d, $J_F = 235.4$ Hz), 133.0, 129.9 (d, $J_F = 6.9$ Hz), 128.8 (3C), 128.5 (2C), 127.1, 122.3, 112.9 (d, $J_F = 24.6$ Hz), 107.9, 107.1, 96.4 (d, $J_F = 16.5$ Hz), 41.6, 33.7, 8.2. m/z [EI (+ve)] 268.1 $[M]^+$, HRMS found $[M]^+$ 268.1380, $C_{17}H_{17}FN_2$ requires 268.1376. IR (thin film) $\nu_{max} = 2922, 1705, 1599, 1469, 1361, 1301, 1089$ cm^{-1} . m.p. 69–71 °C.

1-Benzyl-3-fluoro-5-(4'-methoxyphenyl)-2,5-dihydro-1H-pyrrol-2-one, 21a. Dialkene **20a** (100 mg, 0.31 mmol) was treated with 7.5 mol% Grubbs 2nd generation catalyst as described in General procedure I. The crude product was purified by flash column chromatography (0–10% EtOAc in petroleum ether) to yield the desired α,β -unsaturated lactam **21a** (70 mg, 0.22 mmol, 71%) as a white solid. 1H NMR ($CDCl_3$, 400 MHz) δ : 7.35–7.29 (3H, m), 7.14–7.13 (2H, m), 7.03 (2H, d, $J_H = 8.7$ Hz), 6.93 (2H, d, $J_H = 8.7$ Hz), 6.25 (1H, d, $J_H = 1.6$ Hz), 5.15 (1H, d, $J_H = 15.0$ Hz), 4.75 (1H, dd, $J_F = 5.8$ Hz, $J_H = 2.1$ Hz), 3.85 (3H, s), 3.61 (1H, d, $J_H = 15.0$ Hz). ^{19}F NMR ($CDCl_3$, 470 MHz) δ : –138.7. ^{13}C NMR ($CDCl_3$, 125 MHz) δ : 162.9 (d, $J_F = 31.3$ Hz), 160.3, 152.3 (d, $J_F = 279.3$ Hz), 136.7, 128.9 (2C), 128.8 (2C), 128.4 (2C), 127.8, 125.4 (d, $J_F = 2.1$ Hz), 118.5 (d, $J_F = 4.0$ Hz), 114.6 (2C), 58.7 (d, $J_F = 5.8$ Hz), 55.4, 43.9. m/z [EI (+ve)] 297.1 $[M]^+$, HRMS found $[M]^+$ 297.1169, $C_{18}H_{16}FNO_2$ requires 297.1165. IR (thin film) $\nu_{max} = 2933, 1707, 1666, 1512, 1247, 1174, 1030$ cm^{-1} . m.p. 101–103 °C.

1-Benzyl-3-fluoro-5-[(4'-trifluoromethyl)phenyl]-2,5-dihydro-1H-pyrrol-2-one, 21b. Dialkene **20b** (80 mg, 0.22 mmol) was treated with 15 mol% Grubbs 2nd generation catalyst as described in General procedure I. The crude product was purified by flash column chromatography (0–15% EtOAc in petroleum ether) to yield the desired α,β -unsaturated lactam **21b** (70 mg, 0.20 mmol, 88%) as a pale yellow oil. 1H NMR ($CDCl_3$, 400 MHz) δ : 7.58 (2H, d, $J_H = 8.1$ Hz), 7.26–7.21 (3H, m), 7.16 (2H, d, $J_H = 8.1$ Hz), 7.03–7.01 (2H, m), 6.19 (1H, d, $J_H = 1.2$ Hz), 5.09 (1H, d, $J_H = 15.0$ Hz), 4.77 (1H, dd, $J_F = 4.8$ Hz, $J_H = 2.0$ Hz), 3.57 (1H, d, $J_H = 15.0$ Hz). ^{19}F NMR ($CDCl_3$, 470 MHz) δ : –62.9, –137.2. ^{13}C NMR ($CDCl_3$, 125 MHz) δ : 162.9 (d, $J_F = 31.2$ Hz), 152.7 (d, $J_F = 280.9$ Hz), 138.1, 136.1, 131.7, 131.4, 129.0 (2C), 128.4 (2C), 128.1, 128.0 (2C), 126.3 (2C, q, $J_F = 3.7$ Hz), 118.0 (d, $J_F = 5.0$ Hz), 58.7 (d, $J_F = 5.7$ Hz), 44.4. m/z [EI (+ve)] 335.0 $[M]^+$, HRMS found $[M]^+$ 335.0932, $C_{18}H_{13}F_4NO$ requires 335.0933. IR (thin film) $\nu_{max} = 2362, 2332, 1718, 1670, 1421, 1325, 1166, 1126, 1066$ cm^{-1} .

1-Benzyl-3-fluoro-5-(4'-bromophenyl)-2,5-dihydro-1H-pyrrol-2-one, 21c. Dialkene **20c** (100 mg, 0.3 mmol) was treated with 10 mol% Grubbs 2nd generation catalyst as described in General procedure I. The crude product was purified by flash column chromatography (0–10% EtOAc in petroleum ether) to yield the desired α,β -unsaturated lactam **21c** (90 mg, 0.3 mmol, 94%) as a pale yellow oil. 1H NMR ($CDCl_3$, 400 MHz) δ : 7.54



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