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Xavier Bantreil, Nasreddine Kanfar, Nicolas Gehin, Ethan Golliard, Pauline Ohlmann, et al.. Iron-catalyzed benzamide formation. Application to the synthesis of moclobemide.. *Tetrahedron*, 2014, 70 (34), pp.5093-5099. 10.1016/j.tet.2014.06.001 . hal-01015316

HAL Id: hal-01015316

<https://hal.science/hal-01015316>

Submitted on 3 Mar 2021

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Iron-catalyzed benzamide formation. Application to the synthesis of moclobemide

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ABSTRACT

A convenient and user-friendly method to yield benzamides from primary and secondary amines and various benzylic alcohols in the presence of a cheap iron salt ($\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$) and *tert*-butylhydroperoxide (70% in water) as a stoichiometric oxidant is described. Control experiments indicated that this reaction might involve radical species. This method proved to be general, generating a family of 30 benzamides and was applied to the preparative synthesis of anti-anxiety drug moclobemide.

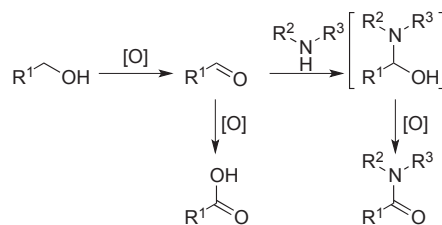
Keywords:

Iron
Homogeneous catalysis
Amides
Oxidation
Green chemistry

1. Introduction

Amides are highly important functional groups due to their preponderance in many natural products such as peptides and proteins, pharmaceutical agents or man-made polymers, such as Nylon 6,6.¹ In most cases, common techniques to generate an amide bond involve the use of toxic coupling agents and toxic solvents. On industrial scale, these drawbacks directly impact environment and economics. To circumvent such issues, organometallic methodologies to form amides directly from alcohols and amines have recently emerged.² The general mechanism for this type of reaction involves the oxidation of an alcohol to the corresponding aldehyde, which will react with the amine to form a hemiaminal intermediate that is converted to the amide upon oxidation. It is important to note that in a competitive pathway, the aldehyde could be oxidized to the carboxylic acid, an undesired side-product (Scheme 1).

Efficient approaches have been reported using transition metals such as ruthenium³ and rhodium,⁴ and heterogeneous catalysts,⁵ such as Au/TiO₂ systems,⁶ Au/DNA nanohybrids,⁷ and alumina-supported silver clusters.⁸ Such approaches are highly attractive

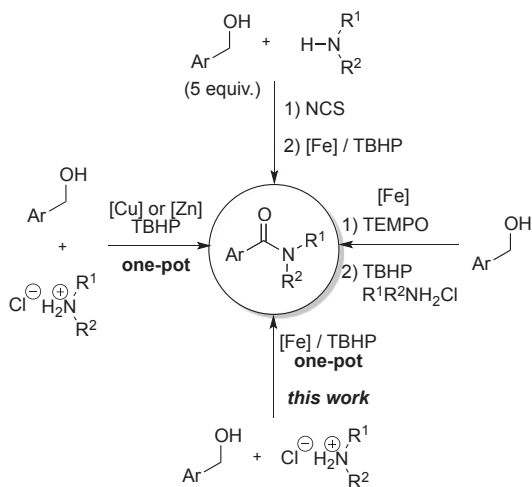


Scheme 1. General mechanism for amide formation.

as catalysis, step and atom economy are part of the 12 principles of green chemistry developed by Anastas and Warner.⁹

To compete with those techniques involving expensive metals, studies on copper- or iron-catalyzed formation of amides from aldehydes have been reported.¹⁰ As a part of our general interest in amide bonds,¹¹ we recently reported the copper-catalyzed amidation directly from benzylic alcohols and amines, which allowed to go one-step further and realize a one-pot double oxidation.¹² Similar approach using zinc was developed (Scheme 2, left).¹³ In 2013, Porcheddu et al. reported the iron-catalyzed amidation of *N*-chloramines, generated from toxic and non atom-economic *N*-chlorosuccinimide, which required the use of 5 equiv of alcohols to obtain good yields (Scheme 2, top).¹⁴ More recently, Ghosh et al. reported a stepwise iron-catalyzed synthesis of benzamides, requiring a first step of oxidation of alcohol into aldehyde prior to

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Scheme 2. Benzamide formation from alcohols in the literature.

addition of the amine and TBHP (*tert*-butylhydroperoxide) as final oxidant (Scheme 2, right).¹⁵ In here, we want to report a one-pot two-steps convenient and practical method using a cheap iron salt as catalyst and readily available hydrochloric salt of amines (TON < 8.9, TOF < 2.2 h⁻¹).

2. Results/discussion

Optimization of the reaction conditions was started using benzylic alcohol and cyclohexamine hydrochloric salt (1.5 equiv) in the presence of TBHP (70% in H₂O) as oxidant and an iron salt in refluxing acetonitrile. It is worth noting that initial attempts to perform the amidation directly from free amines failed, proving that masking of the nitrogen as its ammonium salt was compulsory to the reaction. As already stated for copper catalysis,¹² calcium carbonate gave the best results. Its weak basicity and poor solubility induce a slow and controlled release of free amine within the reaction media. In the meantime, the alcohol would be oxidized to aldehyde that could react with free amine to yield corresponding amide after a second oxidation. This choice of base proved to be the key point for the feasibility of a one-pot two-steps reaction.

Screening of iron salts was realized. Apart from K₄Fe(CN)₆·3H₂O that gave only 53% conversion, all sources of iron tested gave around 80–85% conversion independently of the oxidation state of the metal (Table 1, entries 1–6). The best results were obtained using FeCl₂·4H₂O and FeCl₃, giving 87% conversion of amide **3aa**. As FeCl₂·4H₂O is less corrosive than FeCl₃, the optimization was continued with this salt. Replacement of TBHP (70% in H₂O) by TBHP (5.5 M in nonane) or hydrogen peroxide induced a decrease to, respectively, 45% and 5% conversion (entries 7–8).

As explained above (Scheme 1), the main side-product formed during the amidation is carboxylic acid. During our previous study on copper-catalyzed amidation, we realized that alcohols featuring electron-donating groups were prone to convert quickly to corresponding benzoic acids. Thus, in view to develop the most general conditions and increase the isolated yield of this reaction, a reverse of the amine/alcohol stoichiometry was envisioned (Table 2). While the use of 1.3 equiv of alcohols in the presence of 5 equiv of TBHP and 5 mol % of FeCl₂·4H₂O gave a 72% yield (entry 1), increasing the quantity of iron salt to 10 mol % induced a satisfactory 89% yield (entry 2). Decreasing the excess of TBHP to 4 equiv did not affect the isolated yield (89%, entry 3). As commercially available iron salts are often contaminated with other metals, the reaction was performed using extra pure iron source and base. Resulting amide was isolated in 82% (entry 4), indicating that traces of metals were not

Table 1
Optimization of reaction conditions^a

Entry	[Fe] (mol%)	[Ox] (equiv.)	Conversion (%) ^b
1	FeSO ₄ ·7H ₂ O (5)	TBHP (4)	84
2	FeCl ₂ ·4H ₂ O (5)	TBHP (4)	87
3	K ₄ Fe(CN) ₆ ·3H ₂ O (5)	TBHP (4)	53
4	Fe(acac) ₃ (5)	TBHP (4)	78
5	Fe(NO ₃) ₃ ·9H ₂ O (5)	TBHP (4)	84
6	FeCl ₃ (5)	TBHP (4)	87
7	FeCl ₂ ·4H ₂ O (5)	TBHP (4) ^c	45
8	FeCl ₂ ·4H ₂ O (5)	H ₂ O ₂ (4)	<5

^a Reaction conditions: benzylic alcohol (0.5 mmol), cyclohexamine hydrochloride (0.75 mmol), CaCO₃ (0.75 mmol), TBHP (70% in H₂O, 270 μL, 4 equiv.), CH₃CN (1 mL), 80°C, 4h.

^b Conversion was determined by HPLC, based on **1a**.

^c *tert*-butylhydroperoxide, 5.5M in nonane.

Table 2
Optimization of the reaction conditions with a reverse stoichiometry^a

Entry	[Fe] (mol %)	[Ox] (equiv)	Ratio 2a/1a	Yield (%) ^b
1	FeCl ₂ ·4H ₂ O (5)	TBHP (5)	1:1.3	72
2	FeCl ₂ ·4H ₂ O (10)	TBHP (5)	1:1.3	89
3	FeCl ₂ ·4H ₂ O (10)	TBHP (4)	1:1.3	89
4	FeCl ₂ ·4H ₂ O (10) ^c	TBHP (4)	1:1.3	82
5	—	TBHP (4)	1:1.3	27

^a Reaction conditions: Benzylic alcohol (0.65 mmol), cyclohexamine hydrochloride (0.5 mmol), CaCO₃ (0.5 mmol), TBHP (70% in H₂O, 270 μL, 4 equiv.), CH₃CN (1 mL), 80 °C, 4 h.

^b Isolated yield, based on **2a**.

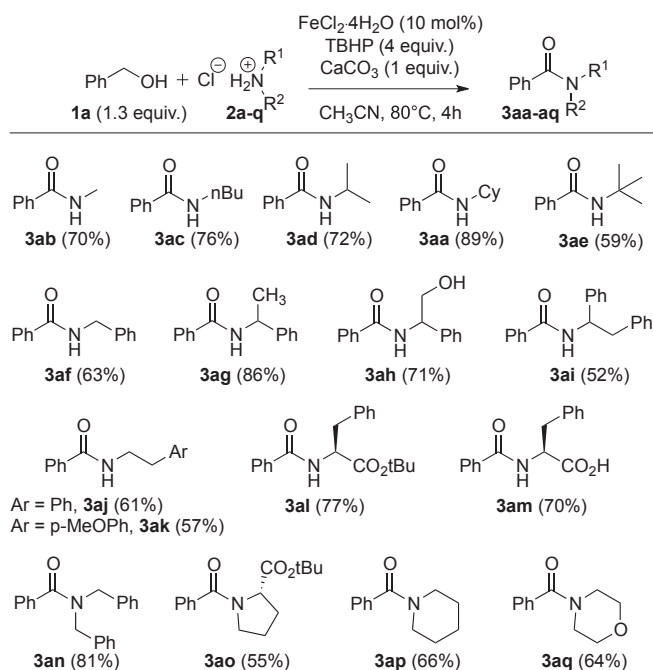
^c FeCl₂·4H₂O 99.99% and CaCO₃ 99.995% pure were used.

responsible for the amidation reaction. Finally, a control experiment in the absence of iron salt indicated that the transition metal was necessary to the reaction (27% without FeCl₂·4H₂O, entry 5).

The scope of the reaction was then examined. First, variation of the amine was investigated (Table 3). For convenience, even if not specified, the amine hydrochloride salts were used throughout this study. Methyl and butyl amine reacted efficiently yielding **3ab** and **3ac** in 70% and 76%, respectively. Increasing the bulkiness with *iso*-propyl and cyclohexamine did not affect the amidation reaction (**3ad**, 72%; **3aa**, 89%). Even bulkier *tert*-butyl amine gave **3ae** in 59% yield. Benzyl amine, which was shown to yield easily benzamide in the presence of iron and TBHP,¹⁶ was found to produce amide **3af** in 63% yield. Substituted benzylamines **2g–i** furnished corresponding amides in yields spanning from 52% to 86%. Phenethyl and *p*-methoxyphenethyl amines **2j** and **2k** gave corresponding amides in moderate yields (≈ 60%). Phenylalanine *tert*-butyl ester gave 77% of corresponding benzoylated amino acid **3al**. To our delight, the use of unprotected phenylalanine hydrochloric salt allowed the coupling in 70% yield (**3am**), indicating the tolerance of the conditions toward the carboxylic acid functionality. To the best of our knowledge, such reaction with substrate featuring a free acid had never been accomplished in previous reports. The iron-catalyzed amidation was also performed in the presence of more nucleophilic but also more hindered secondary amines. Although bearing two benzylic oxidable positions, dibenzylamine gave a good 81% yield of **3an**. Cyclic amines reacted correctly, HCl-Pro-^tBu (**2o**), piperidine (**2p**) and morpholine (**2q**) yielding the corresponding amides in, respectively, 55% (**3ao**), 65% (**3ap**) and 64% (**3aq**).

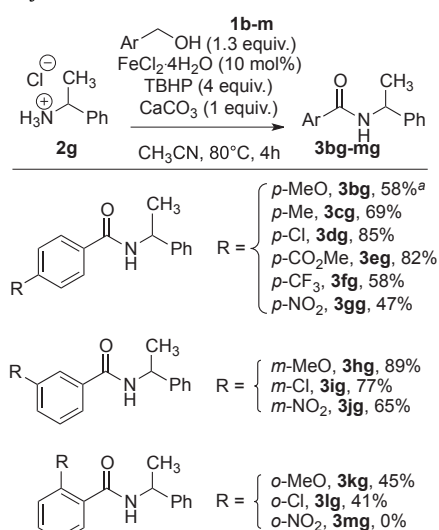
The diversification was continued using various benzylic alcohols in the presence of (α)-methylbenzyl amine **2g** (Table 4).

Table 3
Variation of primary and secondary amines in the amidation conditions



Reaction conditions: benzyl alcohol (0.65 mmol), amine hydrochloride **2a-q** (0.5 mmol), $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ (0.05 mmol), CaCO_3 (0.5 mmol), TBHP (70% in H_2O , 270 μL , 4 equiv.), CH_3CN (1 mL), 80°C , 4h.

Table 4
Variation of benzylic alcohols in the amidation conditions



Reaction conditions: benzylic alcohol **1b-m** (0.65 mmol), amine hydrochloride **2g** (0.5 mmol), $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ (0.05 mmol), CaCO_3 (0.5 mmol), T-Hydro (270 μL , 4 equiv.), CH_3CN (1 mL), 80°C , 4h. ^a 2 equiv. of *p*-methoxybenzylalcohol were used.

Electron-donating substituents in *para* position gave a slight decrease in yield with 58% and 69% for, respectively, **3bg** and **3cg**. *p*-Chlorobenzyl alcohol was efficiently converted to amide **3dg** (85%). Introducing electron-withdrawing groups led to, respectively, 82% and 58% yield for *p*-CO₂Me and *p*-CF₃ groups. Surprisingly, *p*-NO₂ substitution, which accounted for the best yield in copper-catalyzed amidation, gave a poor 47% of corresponding amide **3gg**. When *meta*-substituted benzylic alcohols were used, yields

from 65% to 89% were obtained, with methoxy (**3hg**), chloro (**3ig**) and nitro (**3jg**) substituents. Finally, *ortho* substitution, which combined steric and electronic influence, gave lower yields of amides **3kg** and **3lg**, bearing, respectively, methoxy (45%) and chloro groups (41%). *ortho*-Nitrobenzyl alcohol did not react as expected and amide **3mg** was not observed.

In order to compare this catalytic reaction with literature, TON (turnover number) and TOF (turnover frequency) were calculated using the best results reported in previous works and herein (Table 5). The copper-catalyzed reaction¹² was by far the most efficient regarding TON (up to 44) and TOF (up to 11 h⁻¹), as only 2 mol % of CuO and 4 h of reaction were necessary to obtain good yields. Apart from copper, considering TOF, the use of $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$ as catalyst (TOF up to 2.2 h⁻¹) gave better results than other catalytic systems involving zinc or iron (TOF up to 1.1 h⁻¹), therefore attesting that these reaction conditions represent a good alternative to reported procedures.

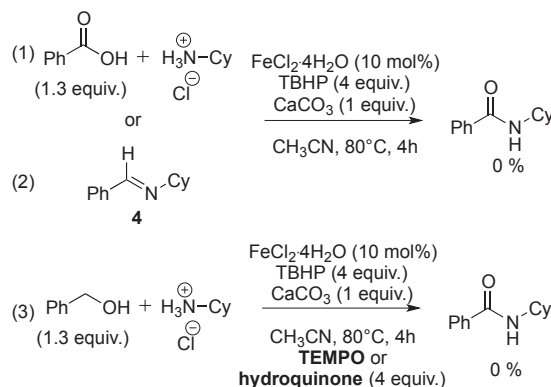
Table 5
Comparison of TON and TOF with literature^a

	TON	TOF (h ⁻¹)
$\text{FeCl}_2 \cdot 4\text{H}_2\text{O}/\text{TBHP}$	<8.9	<2.2
CuO/TBHP (Lamaty) ¹²	<44	<11
ZnI_2/TBHP (Beller) ¹³	<17	<1.1
$\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}/\text{TEMPO}/\text{TBHP}$ (Chen) ¹⁵	<16.2	<0.9
$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}/\text{NCS}/\text{TBHP}$ (De Luca) ¹⁴	<7	n.d. ^b

^a TON=(mmol of product)/(mmol of catalyst). TOF=TON/(reaction time). TON and TOF were calculated using literature data.

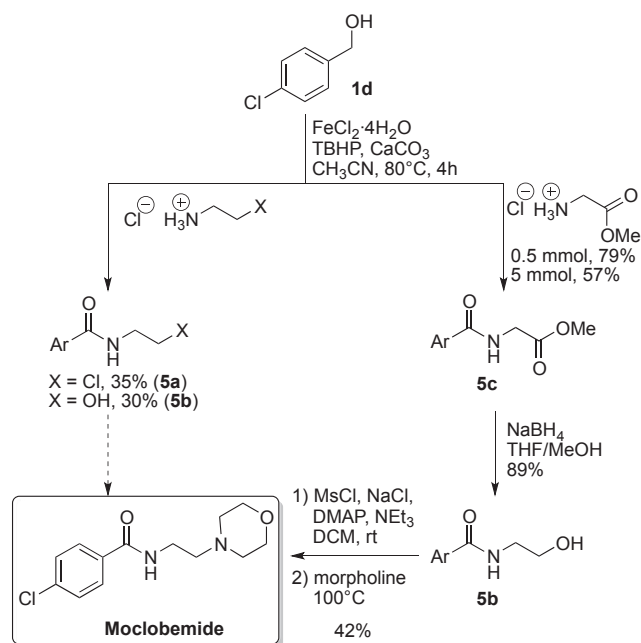
^b Reaction time was not specified in the publication.

Control experiments were then run to assess if the iron-catalyzed amidation was indeed going through the general mechanism depicted in Scheme 1. First, when benzoic acid was used instead of benzylic alcohol in the presence of cyclohexylamine and under the exact optimized conditions used above, no reaction occurred, proving that no direct thermal condensation between acid and amine happened as described elsewhere (Scheme 3, Eq. 1).¹⁷ In addition, when aldimine **4** was reacted under the amidation conditions, no expected amide was observed, proving that formation of amide bond might result from oxidation of the hemiaminal rather than from corresponding aldimine (Scheme 3, Eq. 2). Finally, reaction between benzylic alcohol and cyclohexylamine was performed in the presence of TEMPO or hydroquinone as radical scavengers (Scheme 3, Eq. 3). Expected amide **3aa** could not be observed under those conditions, indicating that the iron-catalyzed amidation might certainly involve the formation of radical species during the oxidation process. However, no trapping intermediate could be isolated.



Scheme 3. Control experiments for amidation reaction.

To prove that this methodology could be efficiently applied to the synthesis of compounds of interest, the synthesis of moclobemide was envisioned using an iron-catalyzed amidation as a first synthetic step (Scheme 4). Moclobemide, an Hoffmann-La Roche drug used against depression and social anxiety, could be readily obtained from 4-chloro-*N*-(2-chloroethyl)benzamide **5a**. Thus, *p*-chlorobenzyl alcohol **1d** was reacted with commercially available 2-chloroethylamine hydrochloride. The isolated yield of amide **5a** being only 35%, the synthesis of synthetic intermediates **5b** and **5c** was intended. While reacting **1d** with ethanolamine hydrochloride gave also a poor yield (**5b**, 30%), the use of glycine methyl ester yielded amide **5c** in 79% yield on a 0.5 mmol scale. On a 10-fold scale (5 mmol) under the exact same conditions, amide **5c** could be isolated with a slight depletion of the yield (57%). The final steps of the synthesis were achieved according to literature procedures. Reacting NaBH₄ in a mixture THF/MeOH¹⁸ allowed the reduction of **5c** to alcohol **5b** in 89% yield. Quantitative substitution of the hydroxyl group by a chlorine atom and reaction with morpholine directly yielded moclobemide, with a 42% yield over two-steps. This modest yield was consistent with the reported one (33%),¹⁹ and moclobemide could be obtained from easily available substrates and in a more sustainable manner to generate the amide functionality.



Scheme 4. Synthesis of moclobemide using iron-catalyzed amidation.

3. Conclusions

In conclusion, we described a new protocol of iron-catalyzed direct formation of benzamides from alcohols and amines. This system required the use of a cheap iron salt and TBHP as a non-toxic stoichiometric oxidant, which decomposes only to form *tert*-butanol and water. Ammonium salts of amines, which are easily accessible, user-friendly and stable, were used in this study. Primary, secondary aliphatic and benzylic amines were well tolerated, as well as benzylic alcohols featuring electron-withdrawing and -donating groups. To validate the usefulness of this methodology, the synthesis of the anti-anxiety drug moclobemide was performed starting from easily available substrates.

4. Experimental section

4.1. General

In a sealed tube were added FeCl₂·4H₂O (9.9 mg, 0.05 mmol, 10 mol %), cyclohexylamine·HCl (67.8 mg, 0.5 mmol, 1 equiv) and CaCO₃ (50.1 mg, 0.5 mmol, 1 equiv). 1 mL of CH₃CN, benzyl alcohol (67 μL, 0.65 mmol, 1.3 equiv) and *tert*-butylhydroperoxide (70% in H₂O, 140 μL, 2 equiv) were then added. After 2 h of stirring at 80 °C, another 2 equiv of *tert*-butylhydroperoxide (70% in H₂O) were added, and the mixture was further stirred for 2 h. After cooling to rt, HCl 1 N (5 mL) and AcOEt (5 mL) were added. The mixture was extracted with AcOEt (2×5 mL), and the combined organic phases were washed with saturated aqueous NaHCO₃ solution (10 mL), brine (10 mL), dried over magnesium sulfate and concentrated under reduced pressure. The crude mixture was purified by chromatography on silica gel using mixtures of cyclohexane and ethyl acetate as eluant.

4.1.1. *N*-Cyclohexylbenzamide **3aa.**²⁰ 89% yield (90.2 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.85–7.64 (m, 2H), 7.53–7.30 (m, 3H), 6.17 (d, 1H, *J*=6.6 Hz), 3.95 (ttd, 1H, *J*=11.9, 8.0, 3.8 Hz), 2.09–1.91 (m, 2H), 1.84–1.55 (m, 3H), 1.50–1.10 (m, 5H). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=166.8, 135.2, 134.3, 128.6, 127.0, 48.8, 33.3, 25.7, 25.0.

4.1.2. *N*-Methylbenzamide **3ab.** 70% yield (48.7 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.84–7.67 (m, 2H), 7.52–7.30 (m, 3H), 6.71 (s, 1H), 2.96 (d, *J*=4.8 Hz, 3H). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=168.5, 134.7, 131.4, 128.6, 127.0, 26.9.

4.1.3. *N*-*n*-Butylbenzamide **3ac.**²¹ 76% yield (67.4 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.78–7.73 (m, 2H), 7.46–7.34 (m, 3H), 6.42 (br s, 1H), 3.42 (q, 2H, *J*=6.5 Hz), 1.65–1.47 (m, 2H), 1.43–1.24 (m, 2H), 0.93 (t, 3H, *J*=7.2 Hz). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=167.7, 134.9, 131.3, 128.6, 127.0, 39.9, 31.8, 20.2, 13.9.

4.1.4. *N*-*iso*-propylbenzamide **3ad.**²² 72% yield (58.6 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.84–7.68 (m, 1H), 7.53–7.30 (m, 2H), 6.18 (s, 1H), 4.40–4.11 (m, 1H), 1.23 (d, *J*=6.6 Hz, 3H). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=166.8, 135.1, 131.3, 128.5, 126.9, 41.9, 22.9.

4.1.5. *N*-*tert*-Butylbenzamide **3ae.**^{10d} 59% yield (52.0 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.93–7.60 (m, 2H), 7.42 (m, 3H), 5.99 (s, 1H), 1.46 (s, 9H). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=167.0, 136.0, 131.2, 128.6, 126.8, 51.7, 20.0.

4.1.6. *N*-Benzylbenzamide **3af.**²³ 63% yield (66.6 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.75–7.70 (m, 2H), 7.47–7.17 (m, 8H), 6.62 (br s, 1H), 4.55 (d, 2H, *J*=5.7 Hz). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=167.6, 138.4, 134.4, 131.5, 128.8, 128.6, 127.9, 127.5, 127.1, 44.1.

4.1.7. *N*-(α -Methylbenzyl)benzamide **3ag.**²⁴ 77% yield (86.2 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.89–7.65 (m, 2H), 7.59–7.20 (m, 8H), 6.56 (d, *J*=7.1 Hz, 1H), 5.33 (p, *J*=7.0 Hz, 1H), 1.59 (d, *J*=6.9 Hz, 3H). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=166.7, 143.3, 134.7, 131.5, 128.8, 128.6, 127.5, 127.1, 126.3, 49.3, 21.8.

4.1.8. *N*-Benzoyl-phenylglycinol **3ah.**²⁵ 71% yield (85.9 mg) as a white solid. ¹H NMR (DMSO-*d*₆, 200 MHz): δ (ppm)=8.70 (d, *J*=8.1 Hz, 1H), 7.90 (d, *J*=6.3 Hz, 2H), 7.64–7.11 (m, 8H), 5.07 (dd, *J*=13.8, 8.1 Hz, 1H), 4.94 (t, *J*=5.8 Hz, 1H), 3.80–3.55 (m, 2H). ¹³C

NMR (DMSO-*d*₆, 75 MHz): δ (ppm)=166.3, 141.4, 134.7, 131.2, 128.3, 128.2, 127.4, 127.0, 126.9, 64.6, 56.1.

4.1.9. *N*-(1,2-Diphenylethyl)benzamide **3ai**.²⁶ 52% yield (78.4 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.75–7.55 (m, 2H), 7.51–7.13 (m, 11H), 7.08 (d, *J*=5.9 Hz, 2H), 6.56 (d, *J*=7.4 Hz, 1H), 5.45 (q, *J*=7.2 Hz, 1H), 3.19 (d, *J*=7.0 Hz, 2H). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=166.9, 141.6, 137.35, 134.7, 131.55, 129.5, 128.7, 128.6, 128.5, 127.6, 127.0, 126.8, 54.9, 42.7.

4.1.10. *N*-Phenethylbenzamide **3aj**.^{10a,27} 61% yield (69.0 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.77–7.60 (m, 2H), 7.54–7.16 (m, 8H), 6.23 (s, 1H), 3.72 (q, 2H, *J*=6.9 Hz), 2.94 (t, 2H, *J*=6.9 Hz). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=167.6, 139.0, 134.7, 131.5, 128.9, 128.8, 128.6, 126.9, 126.7, 41.3, 35.8.

4.1.11. *N*-*p*-Methoxyphenethylbenzamide **3ak**.²⁸ 58% yield (73.8 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.72–7.68 (m, 2H), 7.51–7.34 (m, 3H), 7.16–7.12 (m, 2H), 6.87–6.83 (m, 2H), 6.36 (br s, 1H), 3.78 (s, 3H), 3.66 (q, 2H, *J*=7.0 Hz), 2.86 (t, 2H, *J*=7.0 Hz). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=167.6, 158.4, 134.8, 131.4, 131.0, 129.8, 128.6, 127.9, 126.9, 114.2, 55.3, 41.4, 34.9.

4.1.12. *N*-Benzoylphenylalanine *tert*-butyl ester **3al**.²⁹ 77% yield (124.8 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.72–7.55 (m, 2H), 7.46–7.23 (m, 3H), 7.23–7.05 (m, 5H), 6.67 (d, 1H, *J*=7.3 Hz), 4.88 (dt, 1H, *J*=7.4, 5.8 Hz), 3.14 (d, 2H, *J*=5.7 Hz), 1.34 (s, 9H). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=170.8, 166.8, 136.3, 134.1, 131.7, 129.6, 128.6, 128.4, 127.0, 82.6, 54.0, 38.1, 28.0.

4.1.13. *N*-Benzoylphenylalanine·½H₂O **3am**. 70% yield (97.6 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.73 (d, *J*=6.8 Hz, 2H), 7.64–7.28 (m, 8H), 6.87 (s, 1H, NH), 5.81 (s, 1H, CO₂H), 5.41 (s, 1H, ½ H₂O), 4.90 (s, 1H), 3.40–3.01 (m, 2H). ¹³C NMR (CD₃OD, 75 MHz): δ (ppm)=176.3, 170.1, 138.7, 135.3, 132.8, 130.3, 129.5, 129.4, 128.4, 127.8, 56.3, 38.9.

4.1.14. *N,N*-Dibenzylbenzamide **3an**.²⁹ 69% yield (104.0 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.65–7.29 (m, 7H), 7.18 (s, 1H), 4.73 (s, 1H), 4.42 (s, 1H). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=172.3, 137.0, 136.5, 136.2, 129.7, 128.9, 128.6, 128.5, 127.6, 127.1, 126.8, 51.6, 46.9.

4.1.15. *N*-Benzoyl proline *tert*-butyl ester **3ao**. 55% yield (76.4 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.56–7.51 (m, 2H), 7.42–7.29 (m, 3H), 4.52 (dd, *J*=8.0, 5.5 Hz, 1H, 70%), 4.26–4.13 (m, 1H, 30%), 3.79–3.41 (m, 2H), 2.34–2.14 (m, 1H), 2.01–1.79 (m, 3H), 1.47 (s, 9H, 70%), 1.29 (s, 9H, 30%). ¹³C NMR (CDCl₃, 100 MHz): δ (ppm)=171.5, 169.6, 136.6, 130.1, 128.3, 127.3, 126.8, 81.3, 60.0, 50.0, 29.5, 28.1, 27.8, 25.4 (major rotamer). δ (ppm)=171.5, 170.5, 137.2, 129.7, 81.8, 62.1, 46.7, 31.6, 29.8, 22.7 (minor rotamer).

4.1.16. *N*-Benzoyl piperidine **3ap**.⁷ 66% yield (62.2 mg) as a translucent oil. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.36 (s, 5H), 3.68 (s, 2H), 3.31 (s, 2H), 1.64–1.51 (m, 6H). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=170.3, 136.6, 129.4, 128.4, 126.8, 48.8, 43.1, 26.6, 25.7, 24.6.

4.1.17. *N*-Benzoyl morpholine **3aq**.^{10c} 64% yield (61.2 mg) as a white oil. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.39 (s, 5H), 3.69 (br s, 6H), 3.45 (br s, 2H). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=170.5, 135.4, 129.9, 128.6, 127.1, 67.0.

4.1.18. *N*-(*p*-Methoxybenzoyl)- α -methylbenzyl amine **3bg**.³⁰ 58% yield (74.4 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.71 (d, 2H, *J*=8.9 Hz), 7.47–7.08 (m, 6H), 6.95–6.79 (m, 2H), 6.45 (d, 1H, *J*=7.5 Hz), 5.28 (p, 1H, *J*=7.0 Hz), 3.78 (s, 3H), 1.54

(d, 3H, *J*=6.9 Hz). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=166.3, 162.2, 143.5, 128.9, 128.8, 127.4, 126.9, 126.3, 113.8, 55.5, 49.2, 21.9.

4.1.19. *N*-(*p*-Methylbenzoyl)- α -methylbenzyl amine **3cg**.³¹ 69% yield (83.8 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.65 (d, 2H, *J*=8.2 Hz), 7.44–7.11 (m, 7H), 6.37 (d, 1H, *J*=7.0 Hz), 5.31 (p, 1H, *J*=7.0 Hz), 2.36 (s, 3H), 1.57 (d, 3H, *J*=6.9 Hz). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=166.7, 143.4, 142.0, 131.8, 129.3, 128.8, 127.5, 127.1, 126.4, 49.2, 21.9, 21.5.

4.1.20. *N*-(*p*-Chlorobenzoyl)- α -methylbenzyl amine **3dg**.³² 85% yield (114.4 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.61 (dd, 2H, *J*=8.2, 1.2 Hz), 7.34–7.13 (m, 7H), 6.59 (d, 1H, *J*=7.2 Hz), 5.21 (p, 1H, *J*=7.0 Hz), 1.50 (dd, 3H, *J*=6.9, 1.0 Hz). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=165.7, 143.1, 137.7, 133.0, 128.8, 128.8, 128.6, 127.6, 126.3, 49.5, 21.8.

4.1.21. *N*-(*p*-(Methoxycarbonyl)benzoyl)- α -methylbenzyl amine **3eg**.³¹ 82% yield (115.5 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=8.09 (d, *J*=8.6 Hz, 2H), 7.82 (d, *J*=8.6 Hz, 2H), 7.45–7.28 (m, 5H), 6.34 (d, *J*=6.7 Hz, 1H), 5.35 (p, *J*=6.8 Hz, 1H), 1.63 (d, *J*=6.9 Hz, 3H). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=166.4, 165.9, 143.0, 138.6, 132.6, 129.8, 128.8, 127.6, 127.2, 126.3, 52.4, 49.5, 21.7.

4.1.22. *N*-(*p*-Trifluorobenzoyl)- α -methylbenzyl amine **3fg**. 58% yield (85.2 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.83 (d, *J*=8.2 Hz, 2H), 7.60 (d, *J*=8.3 Hz, 2H), 7.42–7.26 (m, 5H), 6.85 (d, *J*=7.6 Hz, 1H), 5.30 (p, *J*=7.0 Hz, 1H), 1.59 (d, *J*=6.9 Hz, 3H). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=165.6, 142.9, 138.0, 133.2 (q, *J*=32.5 Hz), 128.9, 127.7, 127.6, 126.3, 125.7, 125.6, 123.8 (q, *J*=271 Hz), 49.6, 21.7. ¹⁹F NMR (CDCl₃, 282 MHz): δ (ppm)=–62.9. HRMS(ESI⁺) *m/z* calculated for (MH⁺): 294.1106. Found: 294.1107.

4.1.23. *N*-(*p*-Trifluorobenzoyl)- α -methylbenzyl amine **3gg**.³³ 53% yield (71.8 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=8.31–8.12 (m, 2H), 7.98–7.83 (m, 2H), 7.44–7.27 (m, 5H), 6.70 (d, 1H, *J*=7.3 Hz), 5.30 (p, 1H, *J*=7.0 Hz), 1.61 (d, 3H, *J*=6.9 Hz). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=164.8, 149.5, 142.7, 140.2, 128.9, 128.3, 127.8, 126.3, 123.7, 49.8, 21.7.

4.1.24. *N*-(*m*-Methoxybenzoyl)- α -methylbenzyl amine **3hg**.¹² 89% yield (114.5 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.43–7.34 (m, 8H), 7.21–6.92 (m, 1H), 6.65 (d, *J*=6.6 Hz, 1H), 5.56–5.23 (p, 1H, *J*=7.0 Hz), 3.86 (s, 3H), 1.64 (d, 3H, *J*=6.9 Hz). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=166.5, 159.9, 143.3, 136.1, 129.6, 128.8, 127.5, 126.3, 118.8, 117.7, 112.5, 55.5, 49.4, 21.8.

4.1.25. *N*-(*m*-Chloro)- α -methylbenzyl amine **3ig**.³⁴ 77% yield (100.2 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=7.72 (t, *J*=1.8 Hz, 1H), 7.64–7.54 (m, 1H), 7.45–7.17 (m, 7H), 6.74 (d, *J*=7.5 Hz, 1H), 5.26 (p, *J*=7.0 Hz, 1H), 1.54 (d, *J*=6.9 Hz, 3H). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=165.5, 143.0, 136.5, 134.7, 131.5, 129.9, 128.8, 127.6, 127.4, 126.3, 125.2, 49.5, 21.7.

4.1.26. *N*-(*m*-Nitro)- α -methylbenzyl amine **3jg**.³⁵ 65% yield (88.0 mg) as a white solid. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=8.55 (s, 1H), 8.25 (d, *J*=8.1 Hz, 1H), 8.10 (d, *J*=7.7 Hz, 1H), 7.52 (t, *J*=8.0 Hz, 1H), 7.35–7.21 (m, 4H), 7.12 (d, *J*=7.1 Hz, 1H), 5.28 (p, *J*=6.9 Hz, 1H), 1.58 (d, *J*=6.9 Hz, 3H). ¹³C NMR (CDCl₃, 75 MHz): δ (ppm)=164.4, 148.1, 142.8, 136.2, 133.5, 129.8, 128.8, 127.6, 126.3, 126.0, 122.0, 49.9, 21.7.

4.1.27. *N*-(*o*-Methoxybenzoyl)- α -methylbenzyl amine **3kg**.¹² 45% yield (57.4 mg) as a slurry. ¹H NMR (CDCl₃, 200 MHz): δ (ppm)=8.27 (d, 1H, *J*=6.7 Hz), 8.20 (dd, 1H, *J*=7.8, 1.8 Hz), 7.55–7.18 (m, 6H), 7.08

(dt, 1H, $J=7.5$, 0.8 Hz), 6.97 (d, 1H, $J=8.3$ Hz), 5.35 (p, 1H, $J=6.9$ Hz), 3.94 (s, 3H), 1.59 (d, $J=6.9$ Hz, 3H). ^{13}C NMR (CDCl_3 , 75 MHz): δ (ppm)=164.7, 157.6, 143.8, 133.0, 132.4, 128.8, 127.3, 126.2, 121.5, 111.5, 56.1, 49.3, 22.6.

4.1.28. *N*-(*o*-Chlorobenzoyl)- α -methylbenzyl amine **3lg**.³⁶ 41% yield (53.4 mg) as a white solid. ^1H NMR (CDCl_3 , 200 MHz): δ (ppm)=7.65 (dd, $J=6.0$, 3.1 Hz, 1H), 7.45–7.26 (m, 8H), 6.46 (s, 1H), 5.34 (p, $J=7.0$ Hz, 1H), 1.62 (d, $J=6.9$ Hz, 3H). ^{13}C NMR (CDCl_3 , 75 MHz): δ (ppm)=165.6, 142.9, 135.2, 131.4, 130.8, 130.4, 130.3, 128.9, 127.6, 127.2, 126.4, 49.8, 21.9.

4.1.29. *N*-(*p*-Chlorobenzoyl)-glycine methylester **5c**.^{10e} 79% yield (90.2 mg) as a white solid. ^1H NMR (CDCl_3 , 200 MHz): δ (ppm)=7.82–7.68 (m, 2H), 7.48–7.36 (m, 2H), 6.64 (s, 1H), 4.24 (d, $J=5.0$ Hz, 2H), 3.81 (s, 3H). ^{13}C NMR (CDCl_3 , 75 MHz): δ (ppm)=170.6, 166.5, 138.3, 132.2, 129.1, 128.7, 52.7, 41.9.

4.1.30. *N*-(*p*-Chlorobenzoyl)-glycinol **5b**.³⁷ Following a literature procedure,¹⁸ ester **5c** (488.2 mg, 2.15 mmol), NaBH_4 (408.8 mg, 10.75 mmol) and THF (1.8 mL) were stirred at 65 °C for 15 min. Then MeOH (1.2 mL) was added and the resulting mixture was stirred for another 15 min at 65 °C. The mixture was then cooled to room temperature, quenched with HCl 1 M and extracted with CH_2Cl_2 . The combined organic layers were dried over MgSO_4 , filtered and concentrated under reduced pressure to afford the expected alcohol **5b** as a white solid in 89% yield (384.4 mg). The crude compound was found pure enough for further reactions. ^1H NMR (CDCl_3 , 200 MHz): δ (ppm)=7.73–7.60 (m, 2H), 7.39–7.27 (m, 2H), 7.01 (s, 1H), 3.84–3.71 (m, 2H), 3.55 (dd, $J=10.2$, 5.2 Hz, 2H), 3.46 (s, 1H). ^{13}C NMR (CDCl_3 , 75 MHz): δ (ppm)=167.7, 138.1, 132.6, 128.9, 128.6, 62.0, 42.9.

4.1.31. Moclobemide.³⁸ Alcohol **5b** (350 mg, 1.97 mmol), triethylamine (826 μL , 5.93 mmol) DMAP (24.1 mg, 0.20 mmol), and sodium chloride (346.6 mg, 5.93 mmol) were stirred in CH_2Cl_2 (9.9 mL) and methanesulfonyl chloride (460 μL , 5.93 mmol) was added dropwise. The mixture was stirred overnight and completion of the reaction was assessed by HPLC. Reaction was quenched using a saturated solution of NH_4Cl and extracted with CH_2Cl_2 . The combined organic layers were washed with a saturated solution of NaHCO_3 , brine, dried over MgSO_4 filtered and concentrated under reduced pressure. The crude chloride was filtered through a pad of silica using CH_2Cl_2 as eluant. Filtered compound (white solid, 450 mg) was found pure enough for further reaction. ^1H NMR (CDCl_3 , 200 MHz): δ (ppm)=7.81–7.62 (m, 2H), 7.47–7.33 (m, 2H), 6.69 (s, 1H), 3.87–3.64 (m, 4H). ^{13}C NMR (CDCl_3 , 75 MHz): δ (ppm)=166.7, 138.2, 132.6, 129.1, 128.6, 44.2, 41.9. A mixture of compound **5a** (109.0 mg, 0.5 mmol) and morpholine (348 μL , 4 mmol) was then stirred at 100 °C for 2 h. After cooling to room temperature, 5 mL of H_2O and then a 10% ammonia solution were added. The solution was extracted with CH_2Cl_2 . The organic layers were combined, dried over MgSO_4 , filtered and evaporated under reduced pressure. Purification on silica gel using a mixture $\text{CH}_2\text{Cl}_2/\text{MeOH}$ 95:5 afforded 56.6 mg of moclobemide as a white solid (42% yield). ^1H NMR (CDCl_3 , 200 MHz): δ (ppm)=7.72 (dd, $J=8.9$, 2.2 Hz, 2H), 7.41 (dd, $J=8.9$, 2.2 Hz, 2H), 6.78 (s, 1H), 3.78–3.69 (m, 4H), 3.54 (dd, $J=11.4$, 5.4 Hz, 2H), 2.67–2.56 (m, 2H), 2.56–2.46 (m, 4H). ^{13}C NMR (CDCl_3 , 75 MHz): δ (ppm)=166.4, 137.6, 133.0, 128.8, 128.4, 66.9, 56.9, 53.4, 36.2.

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