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Solvent-controlled amidation of acid chlorides at room temperature: new route to access aromatic primary amides and imides amenable for late-stage functionalization†

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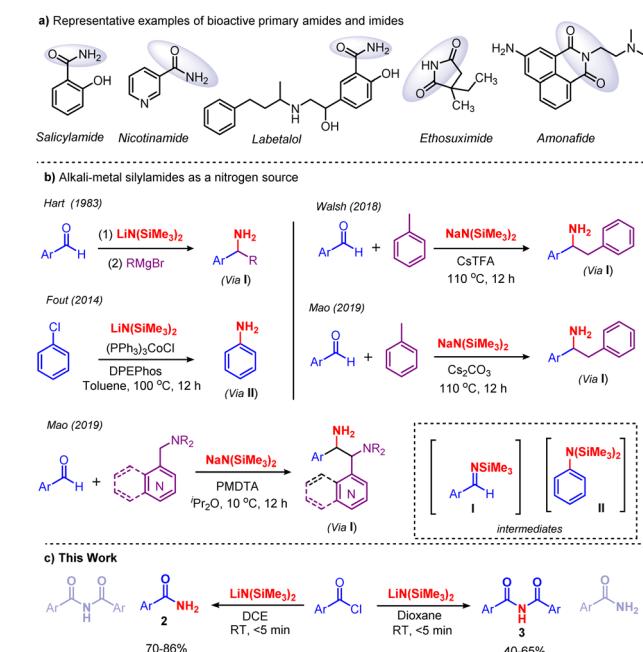
Herein, we report a solvent-controlled highly selective amidation and imidation of aryl chlorides using an alkali-metal silyl-amide reagent (LiHMDS), which serves as a nitrogen source at room temperature. A unique feature of this method lies in the sequential silyl amidation of aryl chlorides and nitrogen–silicon bond cleavage of the corresponding *N,N*-bis(trimethylsilyl)benzamide in a one-pot method in a very short reaction time. This effective strategy was extended to late-stage functionalization.

Introduction

Amides and imides are vital and appealing functionalities that are ubiquitous in biology, pharmaceutical intermediates, natural products, and materials science.¹ They are bestowed with remarkable properties which substantiate their existence in engineering plastics, lubricants, fertilizers, detergents, agrochemicals, proteins, *etc.*^{2,3} In particular, primary benzamides are found in various drugs, such as salicylamide, nicotinamide, labetalol, frovatriptan, niraparib, lenvatinib, ethosuximide and amonafide (Scheme 1a). Therefore, tremendous efforts have been made to develop synthetic methods for the preparation of primary amides. Classically, primary amides are accessed using carboxylic acid derivatives,⁴ aldehydes,⁵ alcohols,^{6,7} nitriles,⁸ and oximes.^{9–11} Later, various nonclassical strategies, such as oxidative-amidation,¹² hydroamination¹³ and C–N coupling reactions,¹⁴ were developed. Very recently, new methodologies for the synthesis of primary amides were established. Mechanochemical, transamidation, ring-opening selective cleavage and direct amidation were developed by Menéndez,¹⁵ Lee,¹⁶ Lin¹⁷ and Chen,¹⁸ respectively.

Traditionally, imides are prepared *via* two routes: (i) acylation of amides with acyl chlorides, carboxylic esters, and anhydrides,¹⁹ and (ii) a Mumm rearrangement of isoimides.²⁰ However, both of these methods suffer from limited substrate scope; furthermore, Mumm rearrangement demands pre-functionalization and results in moderate yields.²¹ Recently, considerable effort has been devoted to the synthesis of imides, and in this regard several methods have been developed, such

as the metal-catalyzed carbonylation of amides,²² the oxidation of amides,²³ and the oxidative decarboxylation of amino acids,²⁴ among others.^{25–33} Recently, the Liang group reported the synthesis of imides by the chemoselective acylation of *N*-acyl-glutarimides with *N*-acylpyrroles and aryl esters under transition-metal-free conditions.²¹ However, the reported imide synthesis displays certain drawbacks in terms of corrosive precursors, prefunctionalized substrates, specialized reagents, and excessive oxidants; besides, they are time-consuming with a limited substrate scope. The development of greener and



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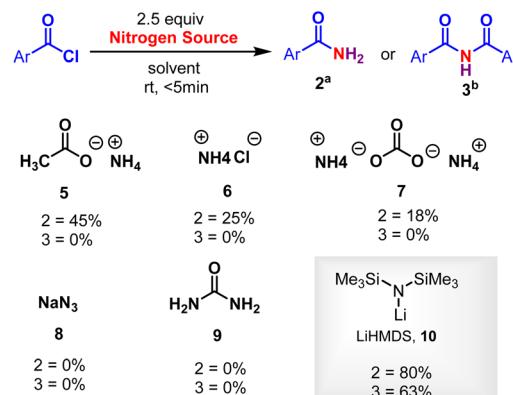
Table 1 Optimization of the reaction conditions

Entry	Nitrogen source	Solvent	Yield (%)	
			2	3
1	LiHMDS in THF	DCE	80	10
2	LiHMDS in toluene	DCE	0	0
3	NaHMDS in THF	DCE	60	5
4	KHMDS in toluene	DCE	0	0
5	LiHMDS in THF	CHCl ₃	10	0
6	LiHMDS in THF	TFE	5	0
7	LiHMDS in THF	DCM	4	45
8	LiHMDS in THF	Dioxane	10	63
9	LiHMDS in THF	DMF	0	38
10	LiHMDS in THF	THF	0	35
11	LiHMDS in THF	Et ₂ O	0	30
12	LiHMDS in THF	CH ₃ CN	0	25
13	LiHMDS in THF	Toluene	0	23
14	LiHMDS in THF	Acetone	0	10
15	LiHMDS in THF	DMSO	0	6
16	LiHMDS in THF	EtOAc	0	4
17	LiHMDS in THF	EtOH	0	0
18	LiHMDS in THF	MeOH	0	0

more practical methods for the synthesis of primary amides and imides remains in demand. Our group has a long-standing interest in Brønsted base [MN(SiMe₃)₂, M = Li, Na and K] promoted organic transformations, especially the cleavage of C-C and C-O bonds in C-acyl imidazolium salts and esters, respectively.³⁴ Recently, we have shown that KN(SiMe₃)₂ promotes the acylation of weakly acidic C-H bonds in toluene derivatives.³⁵ Along these lines, in 1983 Hart and co-workers reported for the first time that [MN(SiMe₃)₂, M = Li, Na and K] acts as a base and nitrogen source in converting aryl aldehydes to aryl amines. Likewise, Fout, Walsh, and Mao used [MN(SiMe₃)₂, M = Li, Na and K] as a nitrogen source for amination reactions (Scheme 1b).³⁶ To the best of our knowledge, the usage of [MN(SiMe₃)₂, M = Li, Na and K] as a nitrogen source for amination reactions at ambient temperature in a short reaction time is unknown. Herein, we report the solvent controlled metal-free, additive-free amidation and imidation of acid chlorides using LiN(SiMe₃)₂ as a nitrogen source in a very short reaction time at ambient temperature (Scheme 1c).

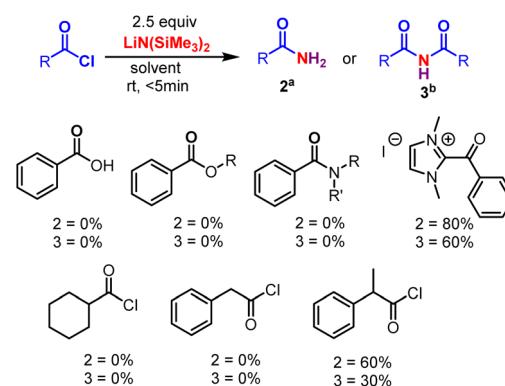
Results and discussion

Initially, the metal-free amidation of aryl chlorides with LiN(SiMe₃)₂ (in THF) was investigated. The reaction of 1.0 equiv. benzoyl chloride **1** with 2.5 equiv. LiN(SiMe₃)₂ at room temperature in DCE for 5 min resulted in the formation of the benzamide **2a** in 80% yield. An increment in LiN(SiMe₃)₂ (from 2.5 to 3.0 equiv.) reduced the yield of **2**, while decreasing it (from 2.5 to 1.0 equiv.) resulted in the appearance of unidentifiable products (without hampering the reaction progression). In the



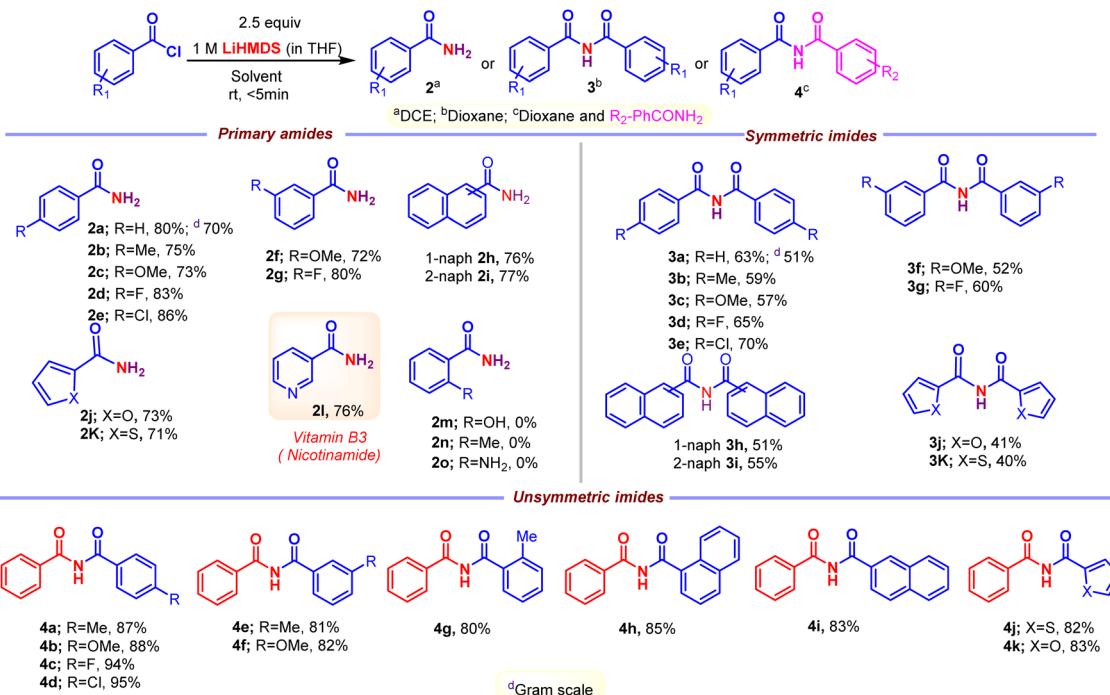
Scheme 2 Other nitrogen sources. Reaction conditions were as follows: aryl chloride **1** (0.2 mmol), LiHMDS (2.5 equiv.), ^aDCE (3 mL) and ^bdioxane (3 mL), RT, <5 min.

absence of LiN(SiMe₃)₂ (in THF) no product was observed, suggesting that LiN(SiMe₃)₂ promotes the process. Other silyl amides like NaHMDS (in THF) and KHMDS (in Toluene) were tried. No reaction was observed in case of KHMDS in toluene (Table 1, entry 4), whereas reduction in the yield of **2** was observed when NaHMDS in THF was used (Table 1, entry 3). We next tested various nitrogen sources (ammonium salts, azide and urea). Among these, ammonium salts gave the desired primary amides, whereas LiHMDS were the best (Scheme 2). The relative importance of various solvents on the reaction, such as CHCl₃, TFE, DCM, dioxane, DMF, THF, diethyl ether, acetonitrile, toluene, acetone, DMSO, ethyl acetate, ethanol and methanol, was examined (Table 1, entries 5–18). Among these, halogenated solvents showed a trace amount of **2** (Table 1, entries 5–7), and, surprisingly, non-halogenated solvents showed the formation of imide **3** devoid of **2** (Table 1, entries 9–18). Thus, dioxane was found to be the best solvent to give **3** in a higher yield (63%) (Table 1, entry 8). This investigation reveals that the solvents play a crucial role in the formation of **2** and **3**. Furthermore, various acyl sources, such as acids, esters, amides, C-acyl imidazolium salts, aliphatic acid chlorides,



Scheme 3 Other acyl sources. Reaction conditions were as follows: aryl chloride **1** (0.2 mmol), LiHMDS (2.5 equiv.), ^aDCE (3 mL) and ^bdioxane (3 mL), RT, <5 min.

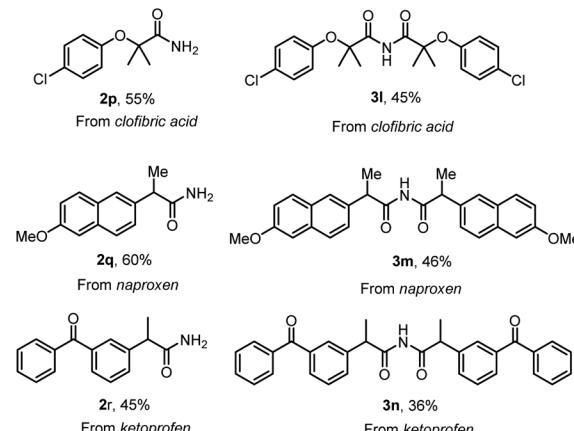




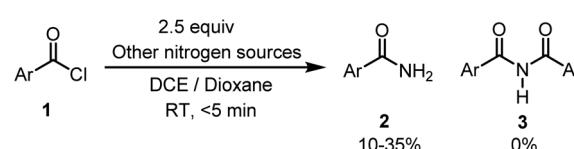
Scheme 4 Synthesis of primary amides, symmetric and unsymmetric imides. Reaction conditions were as follows: aryl chloride 1 (0.2 mmol), LiHMDS (2.5 equiv.), DCE (3 mL) and dioxane (3 mL), RT, <5 min.

aromatic side chain carboxyl chlorides and α -substituted aromatic side chain carboxyl chlorides were examined (Scheme 3). Among these *C*-acyl imidazolium salts and α -substituted aromatic side chain carboxyl chlorides gave products 2 and 3, which reveals that this protocol is a substrate selective reaction.

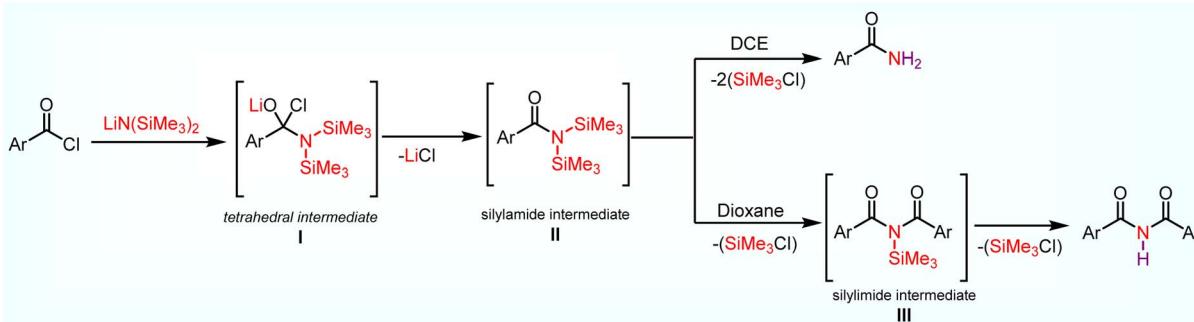
With the optimized conditions in hand, the substrate scope was first surveyed for the reaction of primary amides and symmetric imides (Scheme 4). Various examples of acid chlorides were subjected to the synthesis of corresponding products. The substrates with electron-withdrawing groups, 2d, 2e, 2g, 3d, 3e and 3g, were well tolerated compared with that to electron-releasing groups, 2b, 2c, 2f, 3b, 3c and 3f, in amidation and imidation reactions. Importantly, the amidation reaction does not progress with substrates possessing *ortho* substituents, 2m–2o. Successively, our intent was to explore unsymmetrical imides 4 (Scheme 4) by adopting this approach. The reaction of acid chloride 1 with primary amide 2a in the presence LiHMDS in dioxane at room temperature afforded unsymmetrical imides 4. There were no significant changes in yield with respect to electron-releasing or electron-withdrawing groups, 4a–4g. Additionally, poly- and heterocyclic substrates were compatible to give amides 2h–2k, symmetric imides 3h–3k, and unsymmetrical imides 4h–4k in moderate to good yields. This protocol could be extended to the synthesis of drug nicotinamide 2l from its corresponding acid chloride. Scale-up experiments were performed in order to put forth the practicality of the solvent-controlled amidation and imidation methodology by using aryl chloride (1 g, 7.14 mmol) as a test molecule under the optimized reaction conditions. As can be clearly seen from Scheme 4, the isolated yields of 2a (70% yield) and 3a (51%) are



Scheme 5 Late-stage functionalization of drugs. Reaction conditions were as follows: acid chloride 1 (0.2 mmol), LiHMDS (2.5 equiv.), DCE (3 mL) and dioxane (3 mL), RT, <5 min.



Scheme 6 Control experiment. Reaction conditions were as follows: acid chloride 1 (0.2 mmol), LiHMDS (2.5 equiv.), DCE (3 mL) and dioxane (3 mL), RT, <5 min.



Scheme 7 Plausible mechanistic pathways.

quite satisfactory. Late-stage functionalization strategies are currently receiving great interest in both the drug discovery and chemical biology, and in this regard, solvent controlled amidation and imidation studies were carried out on three different drug molecules, clofibric acids **2p** and **3l**, naproxens **2q** and **3m**, and ketoprofens **2r** and **3n** (Scheme 5).

Further, to understand this methodology, a control experiment was carried out (Scheme 6). Precursor **1** reacted with other nitrogen sources (ammonium salts, azide and urea) under the optimal reaction conditions resulted in the formation of **2**, and no **3** was formed. From this result, it is deciphered that non-silyl amide nitrogen sources preferentially gave primary amides **2** whereas silyl amide ones move forward to give **3** by reacting with aryl chloride.

Based on the above studies and literature report, a plausible mechanism for the formation of primary amides and imides is depicted in Scheme 7. Initially, nucleophilic addition of the nitrogen in $\text{LiN}(\text{SiMe}_3)_2$ to the electrophilic carbonyl carbon of **1** forms a tetrahedral intermediate **I**. Then, **I** proceeds to form a key silyl amide intermediate **II**²¹ ($\text{ArC}(=\text{O})\text{N}(\text{SiMe}_3)_2$) *via* LiCl elimination. Intermediate **II** can proceed through two different pathways based on the chosen solvent. In the presence of DCE (polar solvent), the chlorine atom in DCE coordinates with silicon in silyl amide intermediate **II**, which helps to cleave both nitrogen–silicon bonds simultaneously in silyl amide intermediate **II** instead of one more acid chloride to deliver amide **2** during the acidic work up. In the case of dioxane (non-polar solvents), the cleavage of the nitrogen–silicon bond in silyl amide intermediate **II** is difficult due to less solubility.³⁷ Further, one more acid chloride is required to cleave the nitrogen–silicon bond in silyl amide intermediate **II** to form a new intermediate **III**, which leads to symmetric imides **3** during acidic work up.

Conclusions

In summary, we developed a straightforward and efficient synthetic methodology for the synthesis of primary amides, symmetric and unsymmetric imides. Both the amidation (34 examples) and the late-stage functionalization of drugs (7 examples) worked smoothly with the yields ranging from 50 to 70%. The major advantages of the presented methodology over

the existing ones are that (i) there is no need for the external amine source and oxidant, (ii) it does not require any metal catalyst, (iii) it enables the selective synthesis of primary amides and imides in high yields, (iv) it allows the derivatization of drug molecules, (v) it uses safe solvents at room temperature, and (vi) the reaction completes in a very short time, thus avoiding harsh conditions. Therefore, we think that this solvent-controlled amidation and imidation protocol will create a new perspective for the synthesis of primary amides/imides and related drug molecules.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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