A transition-metal-free & diazo-free styrene cyclopropanation†

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An operationally simple and broadly applicable novel cyclopropanation of styrenes using gem-diiodomethyl carbonyl reagents has been developed. Visible-light triggered the photoinduced generation of iodomethyl carbonyl radicals, able to cyclopropanate a wide array of styrenes with excellent chemoselectivity and functional group tolerance. To highlight the utility of our photocyclopropanation, we demonstrated the late-stage functionalization of biomolecule derivatives.

Introduction

Over the last few decades, one of the main challenges in the synthesis of cyclopropane rings – a prevalent structural motif in pharmaceutical agents and natural products – has been to develop robust and general alkene cyclopropanations that avoid the use of explosive, highly toxic, pyrophoric or water-sensitive carbene transfer reagents (diazo reagents and organometallic carbenoids). However, although important advances have been made in this direction, a major limitation remaining is the broad tolerance to functional groups and consequently, the cyclopropanation of complex molecules.

In 1979, Heilbron and co-workers reported a new methodology for the stereocovergent cyclopropanation of E/Z isomeric styrene mixtures and Michael acceptors by means of photoredox catalysis (Scheme 1A). The key to these studies was the use of the well-known [Ru(bpy)_3][PF_6]_2 photocatalyst and photo-reducible diiodomethane as a methylene source that enabled the generation of a carbonoid-like radical (CH_3I) termed radical carbonoid, as a reactive cyclopropanating species. Although the method showed a broad functional group tolerance and excellent chemoselectivity, severe limitations in the styrene scope were found and an excess of diiodomethane (5 equivalents) had to be used. After this, firstly the group of Molander and secondly the group of Li reported two complementary redox-neutral cyclopropanations using photo-oxidizable bis(catecholato)iodomethylsilicate reagents and 4CzIPN or Ir[dF(CF_3)ppy]_2(dtbbpy)PF_6 as photocatalysts. The Molander reaction was demonstrated in a wide variety of activated alkenes and showed an excellent functional group tolerance and chemoselectivity, however, the process was exclusively evaluated for methylene transfer via (CH_3I). Moreover, Charette and co-workers developed a radical borylcyclopropanation enabled by flow techniques, UVA light and xanthone as photocatalyst. This reaction involved the generation of [(CH(Bpin)) and provided valuable cyclopropylboronates as mixtures of diastereoisomers.

The novel photoredox-catalyzed radical cyclopropanations represent a clear advance in the synthesis of cyclopropane rings and a more practical approach to strategies based on diazo reagents and metal-carbenoids. However, it is clearly an underdeveloped methodology and challenges associated with alkene scope, reagent diversity or efficiency of the process (reagent equivalents) should be solved. In addition, the

Scheme 1 New radical cyclopropanations enabled by visible-light: a valuable alternative to methods employing diazo reagents or metal-carbenoids (A and B).
development of novel methodologies that avoid the use of precious Ru/Ir photocatalysts and permit late-stage functionalization of complex molecules would be highly appreciated. Here, we report the first general photocatalyst-free cyclopropanation of styrenes that use underexploited gem-diodomethyl carbonyl compounds as cyclopropanating reagents and a simple compact fluorescence lamp (CFL) as a visible-light source (Scheme 1B). The process generates valuable cyclopropyl carboxylates that could be diversified by well-documented decarboxylative strategies. Its excellent functional group tolerance and chemoselectivity have enabled access to cyclopropyl carboxylates that are not possible to obtain by current catalytic strategies relying on metal-carbenoid species to react with more nucleophilic functionalities than a styrene double bond).

Results and discussion

During the development of our photoredox-catalyzed cyclopropanation, control experiments revealed that excluding the [Ru(bpy)3][PF6]2 photocatalyst in the reaction resulted in a poor yield of the corresponding cyclopropanes (15–18% yield, 18 hours). These interesting results encouraged us to question whether gem-diodomethyl carbonyl reagents – activated alkyl iodides with more absorbance in the visible region – could provide an efficient photocatalyst-free cyclopropanation and deliver valuable carbonyl-substituted cyclopropane rings. Our investigations started by synthesizing 1-adamantanyl 2,2-diiodomethyl carboxylate (2a) as a potential new cyclopropanating reagent (Scheme 2A). 2a is a white solid that can be prepared on a 12 gram scale from 3-(adamantan-1-yl)-3-oxopropanoic acid and N-iodosuccinimide (NIS). Importantly, 2a features great stability in comparison with the analogue ethyl 2,2-diiodoacetate (2b), which has to be stored in a freezer (<−20 °C) and in solution (0.5 M CH3CN). Differential scanning calorimetry (DSC) studies were performed with reagent 2a and did not show relevant exothermic decompositions, which are commonly found for diazo compounds (see ESI). After this, we evaluated reagent 2a (1 equiv.) for the cyclopropanation of (E)-anethole (1a) with and without the [Ru(bpy)3][PF6]2 photocatalyst. We were delighted to find that both reactions led to the expected tri-substituted cyclopropane 3a in moderate yields (63–60% yield, Scheme 2B) as an equimolar isomeric mixture of diastereoisomers. To explain the formation of 3a we propose the initial generation of iodomethyl radical int-I as a cyclopropanating species. After this, an unbiased attack of the pyramidal sp3-hybridized radical int-I on 1a would generate benzylic radicals int-II and int-III, which would evolve to the corresponding cyclopropane 3a by a radical homolytic substitution (S0,2) 3-exo-tet cyclization. Radical homolytic substitutions are common elementary steps in radical chemistry and in terms of frontier molecular orbitals, this cyclization involves the interaction between the high-energy singly occupied molecular orbital (SOMO) of the benzylic radical, and the lowest unoccupied molecular orbital (LUMO) of the C–I bond. A similar cyclization has been observed previously by Curran and Togo in cyclopropane synthesis using 1,3-dihaloalkanes and radical initiators/reductants.

After these preliminary investigations, we evaluated other solvents, amines and visible-light sources and found that the best reaction conditions involve only 2 equiv. of reagent 2a, i-Pr2EtN (4 equiv.), CH3CN (1 mL), an aqueous solution of NaCl (1.25 M, 0.5 mL) and degassing of the reaction mixture prior to degassing prior to irradiation.

Table 1 Optimization studies

| Entry | Deviation of the reaction conditions | Yield% 3a, % |
|-------|--------------------------------------|-------------|
| 1     | None                                 | 91(75)†    |
| 2     | Without NaCl (H2O)                   | 17         |
| 3     | Without NaCl                         | 48         |
| 4     | Under air                            | 10         |
| 5     | Without i-Pr2EtN                     | 0          |
| 6     | In the dark                          | 0          |

* Reaction conditions: 1a (0.10 mmol), 2a (0.10 mmol), i-Pr2EtN (0.20 mmol), CH3CN (1 mL), NaCl (1.25 M in H2O, 0.5 mL). Reactions were degassed prior to irradiation. † 1H-NMR yields calculated using 1,2-dimethoxymethane as the internal standard. ‡ Yield of the isolated product adding additional 2a (0.10 mmol, 1 equiv.) and i-Pr2EtN (0.20 mmol, 2 equiv.) after 4 hours. § Yield of the isolated product using 1 gram of (E)-1a and 1 equiv. of 2a. See the ESI for the evaluation of other solvents, amines, or visible-light sources.

Scheme 2 Synthesis of gem-diodomethyl carbonylate reagents 2a,b (A) and discovery of a photocatalyst-free cyclopropanation. Ad = 1-adamantyl (B).
to irradiation (91% yield, Table 1, entry 1). We were glad to find that these reaction conditions were also suitable for a 1 gram scale reaction using only 1 equiv. of 2a (75% yield). However, poorer efficiency was observed when reactions were carried out without NaCl (H2O) or H2O (17–48% yield, entries 2 and 3) or under air (10% yield, entry 4). No conversion to 3a was observed without i-Pr2EtN or the CFL (entries 5 and 6).

With the optimized reaction conditions in hand, we evaluated the scope of the new photocyclopropanation using 46 styrene derivatives and reagents 2a, b. As shown in Table 2, our protocol was effective for a variety of diversely substituted styrenes (3b–r).

Table 2  Scope of the styrene photocyclopropanation

| Reaction conditions: 1 (0.20 mmol), 2 (0.40 mmol), i-PrEt2N (0.80 mmol), CH3CN (2 mL), NaCl (1.25 M in H2O, 1 mL); yields of the isolated product. Diastereomeric ratios were between 1 : 1 and 1.5 : 1 and determined by 1H NMR analysis. |  |
|---|---|
| substituted styrenes |  |
| 3b 88% from 1c [2:3] |  |
| 3c 48% from 1d [3:2] |  |
| 3d 64% from 1e [4:1] |  |
| 3e 61% from 1f [4:1] |  |
| 2a,b |  |
|  |
| 3h 73% from 1h [4:1] |  |
| 3i 55% from 1i [3:1] |  |
| 3j 56% |  |
| 3k 46% |  |
| 3l 48% |  |
| 3m 90% |  |
| 3n 91% |  |
| 3o 75% (1:25) |  |
| 3p 39% |  |
| 3q 60% |  |
| 3r 94% |  |
| 3a R = H 0% |  |
| 3b R = Me 0% |  |
|  |
| styrenes |  |
| 3u 88% |  |
| 3v 91% |  |
| 3w 72% |  |
| 3x 67% |  |
| 3y 41% |  |
| 3z 73% |  |
| 3aa 61% |  |
| 3ab 40% |  |
| 3ac 36% |  |
| 3ad 0% |  |
| 3ae 71% |  |
| 3af 75% |  |
| 3ag 40% |  |
| 3ah 69% |  |
| 3ai 62% |  |
| 3aj 56% |  |
| 3ak 38% |  |
| 3al 35% |  |
| 3am 67% |  |
| 3an 57% (3:1) |  |
|  |
| heterostyrenes |  |
| 3ao 73% (1:2) |  |
| 3ap 90% |  |
| 3aq 56% |  |
| 3ar 35% (1:3) |  |
| 3as 38% |  |
| 3at 71% |  |
| 3au 0% |  |

a Reaction conditions: 1 (0.20 mmol), 2 (0.40 mmol), i-PrEt2N (0.80 mmol), CH3CN (2 mL), NaCl (1.25 M in H2O, 1 mL); yields of the isolated product. Diastereomeric ratios were between 1 : 1 and 1.5 : 1 and determined by 1H NMR analysis. E/Z-alkene mixtures 1 are shown in brackets. Reaction conditions 1 (0.40 mmol), 2 (0.20 mmol), i-PrEt2N (0.40 mmol), CH3CN (2 mL), NaCl (1.25 M in H2O, 1 mL).
substituted at the β position with methyl (3b, c) or alkyl groups functionalized with an olefin (3d), phthalimide (3e), alcohol (3f–g) and phenyl (3h) or cyclobutyl rings (3i). We were glad to find that our photocyclopropanation worked well for stilbenes (3j, k), cyclic (3l, q) and α-substituted styrenes (3m–q), which failed in our previous photoredox cyclopropanation.6e In addition, whereas the more substituted acyclic and cyclic trisubstituted styrenes were well tolerated (3q, r), our process did not work for styrenes with a sterically demanding β carbon center (3s, t). It is worth highlighting that although the reaction generates mixtures of diastereoisomers at the α-carbonyl center, which are easily separable by column chromatography, the reaction proceeded with absolute stereoconvergence for E/Z isomeric mixtures of di and tri-substituted styrenes (1c, d, h, i, r).

We then decided to investigate the scope of terminal (hetero) styrenes (3u–as). These substrates provided poor conversion to the cyclopropane in our methylation reaction,6e and instead open-chain dimeric products were found from the homocoupling of benzylic radical intermediates. We were delighted to find that the new photocatalyst-free cyclopropanation was able to cyclopropane a broad variety of functionalized with amine (3u), alkoxide (3v–x), sulfide (3z), halogen (3aa–3ac, 3ae), alkyl (3af, ag), phenyl (3ah), allyl (3ai), aldehyde (3aj), carboxylic acid (3ak), pinacol boronic ester (3al), unsubstituted (3am) or naphthalene (3an) groups. Unfortunately, styrenes substituted with strong electron-withdrawing groups such as CF3 did not yield the desired cyclopropane 3ad. Furthermore, we observed that while our protocol was able to functionalize heteroarylenes containing imidazole (3ao), benzo[b]furan (3ap), benzofuran (3aq), indole (3ar), benzo[b]thiophene (3as) and thiophene (3at), no cyclopropanation reaction was found for pyridine derivatives (3au).

The excellent functional group tolerance and chemoselectivity observed towards the styrene double bond are in sharp contrast to current catalytic methods that cyclopropane styrenes involving electrophilic metal-carbenes from diazoacetates. These methods may suffer from chemo- and site-selectivity in challenging substrates bearing additional alkenes (3d, w, ai),21 or functionalities able to interrupt the corresponding metal-carbene intermediate such as alcohol (3f, gi),22 aldehyde (3aj),23 alkyn (3x),24 carboxylic acid (3ak)25 or sulfide (3e, z) groups.26

On the other hand, although our process was successfully extended to other gem-diiodomethyl esters (3au, aw) or ketone reagents (4a–c, Scheme 3A), the corresponding analogues substituted with amides (4d) or other electron-withdrawing groups did not provide the expected cyclopropane ring (5a–c). The synthetic potential of our photocyclopropanation was further illustrated with the late-stage functionalization of biomolecule derivatives (Scheme 3B). Our process was able to functionalize styrenes derived from estrone (6a), L-valine (6b) and B-glucose pentaacetate (6c).27 In addition, we were delighted to find that the process could also work with the unprotected glucose derivative (6d).28 This final example clearly highlights the potential of our methodology to be applicable in alternative complex scenarios.29

Moreover, we wanted to prove the formation of radical int-1.30 Firstly, an experiment carried out without styrene resulted in the isolation of iodoacetate 7 (Scheme 3C). Its formation can be explained involving abstraction of a hydrogen atom with int-1. An additional experiment carried out with the classic cyclopropyl radical probe 8 also supports the formation of int-1 as an intermediate by forming an atom-transfer radical addition (ATRA) product 9.

Scheme 3 Reagent scope (A), late-stage functionalization (B) and radical trapping experiments (C). Diastereomeric ratios of cyclopropanes were between 1 : 1 and 1.5 : 1 and determined by 1H NMR analysis.

Scheme 4 Mechanistic hypotheses for the photogeneration of int-1 (A and B).
Finally, our current hypotheses for the photogeneration of radical carbeneind int-1 are depicted in Scheme 4. Considering that our reagent 2a absorbs in the visible region (tail of absorption: 460 nm at 0.1 M, see ESI†), we believe that one of the possible scenarios could involve the photogeneration of the excited state [2a]* and its evolution to int-1 and I(•) by homolysis (Scheme 4A).† In this particular case, i-Pr₂EtN might be acting as a quencher of the iodine species, I(•) or I₂, formed during the reaction.† Recently, the group of Aggarwal hypothesized a homolytic cleavage of the C-I bond in z-iodo ketones by visible light as a suitable pathway for the generation of electrophilic alkyl radicals, analogous to int-1.†

On the other hand, another possible scenario involves the formation of a short-lived exciplet [i-Pr₂EtN·2a]* that undergoes photoinduced electron transfer and generates int-1.† Exciplet analogues have been proposed recently in the generation of radicals from inactivated alkyl iodides.†

The quantum yield measured for the model photocyclopropanation of (E)-1a with 2a was found to be 1.5 (λ = 410 nm in CH₃CN/H₂O, using potassium ferrioxalate as the actinometer), suggesting that if a radical-chain is operating, it is very inefficient. At this point, this result does not allow us to discriminate between one of the two mechanistic hypotheses depicted in Scheme 4.

Conclusions

In summary, we have developed a robust, scalable, and safe photochemical cyclopropanation reaction with gem-diiodomethyl carbonyl reagents. Our new cyclopropanation features an excellent functional group tolerance that permitted the functionalization of a broad range of functionalized styrenes and biomolecules.

Conflicts of interest

A patent application describing the results presented in this manuscript has been filled.

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