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Tandem electrocatalytic aziridination – ring expansion of simple aromatic olefins using ammonia and carbon dioxide†

Jef R. Vanhoof, Robin Dirix and Dirk E. De Vos *

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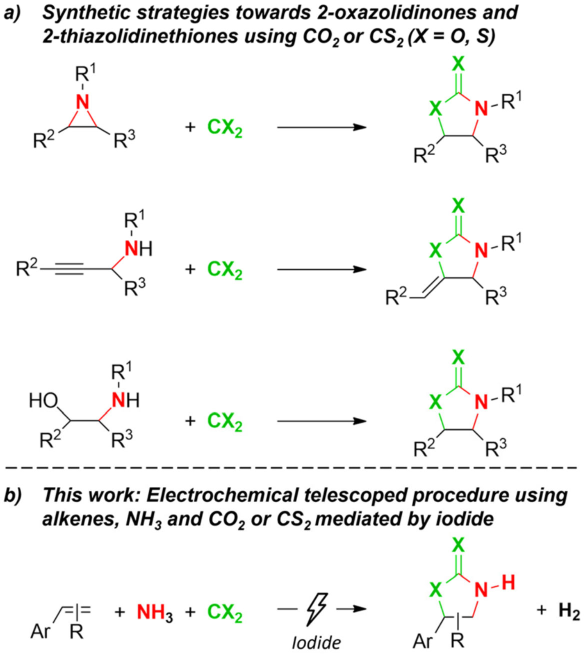
N-heterocycles are prominent structural motifs frequently occurring in organic synthesis and applications. Therefore, straightforward and green synthesis methods using common starting materials like alkenes are highly desired. Here, the metal-free electrochemical coupling of aromatic olefins with NH_3 and CO_2 or CS_2 in a telescoped sequence is reported, forming 2-oxazolidinones or 2-thiazolidinethiones. The reaction proceeds *via* a N–H aziridine, which subsequently undergoes ring expansion with CO_2 or CS_2. Both steps are mediated by the same simple iodide catalyst and total yields of up to 91% referring to the alkene are achieved with excellent regioselectivities. This sustainable reaction using readily available materials possesses an excellent atom efficiency with only H_2 as a potentially useful by-product.

Introduction

2-Oxazolidinones are attractive heterocyclic compounds that are increasingly investigated for their pharmacological activities. For example, linezolid (Zyvox®) and tedizolid (Sivextro®) among others are marketed worldwide for their unique antibacterial activity, even towards multidrug-resistant bacteria.[1–5] Additionally, 2-oxazolidinones are used as intermediates in organic synthesis,[6–8] as chiral auxiliaries[9–15] and in polymers.[16–18] Depending on the starting substrate, intermolecular synthetic routes for these cyclic urethanes may lead through aziridines,[19–25] propargylamines[26–31] or aminoalcohols[32–37] (Scheme 1a). In all three methods, formation of the oxazolidinone scaffold is achieved by using CO_2 as the second reactant, thereby contributing to the global demand for sustainable uses of CO_2.[38–40] However, drawbacks are the need for specialized starting substrates that need to be synthesized beforehand, creating extra waste, and the use of complex metal catalysts.[26,41,42] In addition, only a limited number of reports are successful in directly synthesizing *N*-unsubstituted 2-oxazolidinones.[35,43] Having N–H 2-oxazolidinones is desired for their use as a chiral auxiliary[9–15] and additionally offers the possibility to functionalize the nitrogen atom as required in downstream syntheses, for instance by performing the well-known Buchwald–Hartwig amination,[44,45] even immediately towards active pharmaceutical ingredients.[46,47] By replacing CO_2 with its sulfur analogue CS_2, it is possible to synthesize 2-thiazolidinethiones[19,41,48–53] (Scheme 1a) which possess analogous properties and applications as 2-oxazolidinones regarding both biological



Scheme 1 Synthetic strategies towards 2-oxazolidinones and 2-thioazolidinethiones using CX_2 (X = O, S) reported in literature (a) and this work (b).

Centre For Membrane Separations, Adsorption, Catalysis and Spectroscopy for Sustainable Solutions (cMACS), KU Leuven, Celestijnenlaan 200F p.o. box 2454, 3001 Leuven, Belgium. E-mail: dirk.devos@kuleuven.be

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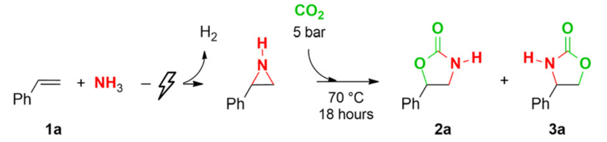
activity[9,54–56] and organic synthetic use.[57–60] Moreover, they are used as a less toxic accelerator in polychloroprene production, an essential class of commercial rubber.[61]

Synthesizing these important heterocycles directly from abundant commodity chemicals like olefins can provide a highly efficient and sustainable approach. However, recent reports using alkenes require the use of a very specific hydroxylamine reagent like 2,2,2-trichloroethyl (2,4-dichlorobenzoyl)oxycarbamate with a homogeneous Fe(II) catalyst[62] or a double protected carbamate (*N*-(fluorosulfonyl)-benzyl carbamate) together with a hypervalent iodine oxidant,[63] both methods resulting in suboptimal atom efficiency. In our previous research, we synthesized unprotected N–H aziridines electrochemically from simple aromatic alkenes using NH_3 as the atom efficient nitrogen source and LiI as the mediator.[64] On the grounds that iodide is frequently used in organic transformations[65–70] and more specifically that iodide-catalyzed ring expansions of *N*-substituted aziridines with CO_2 or CS_2 are known,[71,72] we envisioned that it should be possible to obtain 2-oxazolidinones or 2-thiazolidinethiones from the N–H aziridines by simply adding CO_2 or CS_2 in our system, thereby using iodide twice as the mediator. We here report a telescoped electrochemical synthesis procedure towards *N*-unprotected 2-oxazolidinones and 2-thiazolidinethiones by using NH_3 and CO_2 or CS_2 (Scheme 1b). This sustainable, metal-free method shows excellent atom efficiency and is able to synthesize these unprotected heterocycles directly from simple aromatic olefins using renewable energy and readily available and abundant materials. Additionally, waste formation and energy loss are prevented due to the telescoped sequence while also using the greenhouse gas CO_2 as a sustainable building block.

Results and discussion

To evaluate the telescoped synthesis procedure using CO_2, we performed an electrocatalytic N–H aziridination of styrene with NH_3 according to our previous procedure (94% yield, see ESI†).[64] After completion of the electrolysis, the reaction mixture was transferred into a stainless steel pressure reactor after which the conditions for the CO_2 ring expansion were optimized (Table 1). With a CO_2 pressure of 5 bar at a temperature of 70 °C for 18 h, an overall yield based on styrene of 5-phenyl-2-oxazolidinone **2a** of 86% was achieved (entry 1). The overall yield was diminished to 42% and 73% when operating at room temperature or at 90 °C, respectively (entries 2 and 3). A shorter reaction time of 4 h provided a total yield of 71% (entry 4). Increasing the CO_2 pressure to 15 bar afforded an excellent total yield of 87% (92% CO_2 insertion yield in step 2, entry 5). The 4-phenyl-2-oxazolidinone **3a** was found in a yield of only 4%, showing a remarkable 96% regioselectivity for **2a**. In addition, working with 15 bar CO_2 ensured better reproducibility compared to 5 bar CO_2. Working at room temperature with 15 bar CO_2 provided a lower overall yield of 72% (entry 6). It is known that 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) can facilitate the uptake of CO_2 into solution and catalyze CO_2 insertion reactions.[73–76] In our system, however, it did not improve the yield any further (entries 7 and 8) nor did it provide any catalytic effect with shorter reaction times (entry 9). Also, omitting DBU is beneficial for the environmental factor of the telescoped reaction sequence.

Table 1 Optimization of the telescoped CO_2 ring expansion of electrocatalytically synthesized 2-phenylaziridine



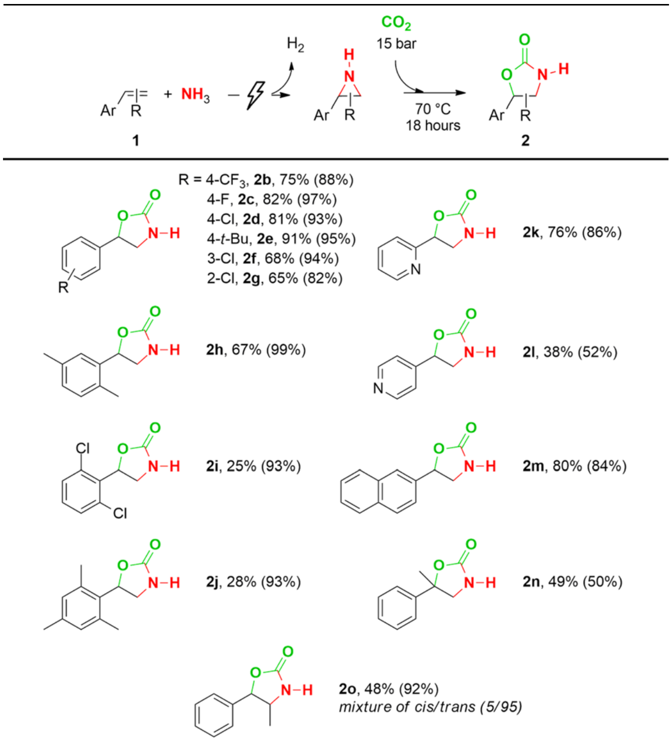
Entry	Deviation from optimization conditions[a]	Yield **2a** (%)	Yield **3a** (%)
1	—	86	5
2	Room temperature	42	4
3	90 °C	73	5
4	4 hours	71	9
5	**15 bar CO_2**	**87 (81)**	**4**
6	15 bar CO_2, room temperature	72	3
7	+DBU (0.2 equiv.)	84	9
8	+DBU (1.4 equiv.)	77	5
9	+DBU (0.2 equiv.), 4 hours	67	5

Conditions for the electrocatalytic N–H aziridination with LiI: see ESI.† Reaction mixture is transferred to a stainless steel pressure reactor. [a] Optimization conditions: 5 bar CO_2 pressure, 70 °C, 18 h. Yields are based on ^{1}H-NMR spectra of crude mixtures, referring to the starting alkene. Number in parentheses indicates the isolated yield. DBU = 1,8-diazabicyclo[5.4.0]undec-7-ene.

With the optimized conditions in hand (Table 1, entry 5), we applied this procedure to different aromatic olefins (Table 2). Generally, the yield of the CO_2 insertion step varies between 82% and 99%, which results in good to excellent total yields up to 91% with respect to the starting olefin (**2b–h**). Only when both *ortho*-positions are occupied, lower total yields are achieved due to a poor aziridination step (**2i–j**). Whereas 2-vinylpyridine still shows a good overall yield of 76% (**2k**), 4-vinylpyridine showed a moderate yield in the CO_2 insertion step, therefore leading to a lower total yield of 38% (**2l**). Moreover, a CO_2 insertion yield of 84% and a total yield of 80% are obtained with 2-vinylnaphthalene (**2m**). When α-methylstyrene (**2n**) is used, steric hindrance impedes the CO_2 insertion and a total yield of 49% is achieved, despite the 98% aziridination yield. In the N–H aziridination of *trans*-β-methyl styrene, a mixture of *cis*- and *trans*-2-methyl-3-phenylaziridine in a combined yield of 52% was obtained with the *trans* isomer as the major product (83/17 ratio).[64] Ring expansion with CO_2 resulted in an almost exclusive formation of *trans*-4-methyl-5-phenyl-2-oxazolidinone (**2o**) in a 95/5 ratio over the *cis* isomer in a combined overall yield of 48%. Finally, a gram-scale synthesis of compound **2a** resulted in an overall yield of 80% (see ESI†).

Next, we also investigated if this telescoped procedure could be extrapolated to CS_2, thereby synthesizing 2-thiazolidinethiones. We started with modified conditions compared to

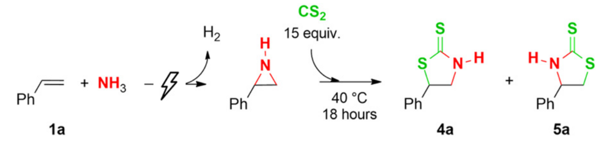
Table 2 Telescoped CO_2 ring expansion of N–H aziridines synthesized electrocataytically from simple aromatic olefins[a]



[a] Reaction conditions: see Table 1, entry 5. Yields are based on ^{1}H-NMR spectra of crude mixtures, referring to the starting alkene. Yields in parentheses refer to the CO_2 insertion of the N–H aziridine.

the CO_2 ring expansion, exchanging the 15 bar CO_2 for 15 equivalents of CS_2 at a temperature of 40 °C for 18 h (Table 3). A total yield of 51% of 5-phenyl-2-thiazolidinethione **4a** was achieved (entry 1). No improvement of the yield was observed at a higher temperature of 70 °C (49%, entry 2), while room temperature lowered the total yield to 34% (entry 3). Interestingly, a higher overall yield of 64% was obtained with a shorter reaction time of 4 h (entry 4). Moreover, the same yield

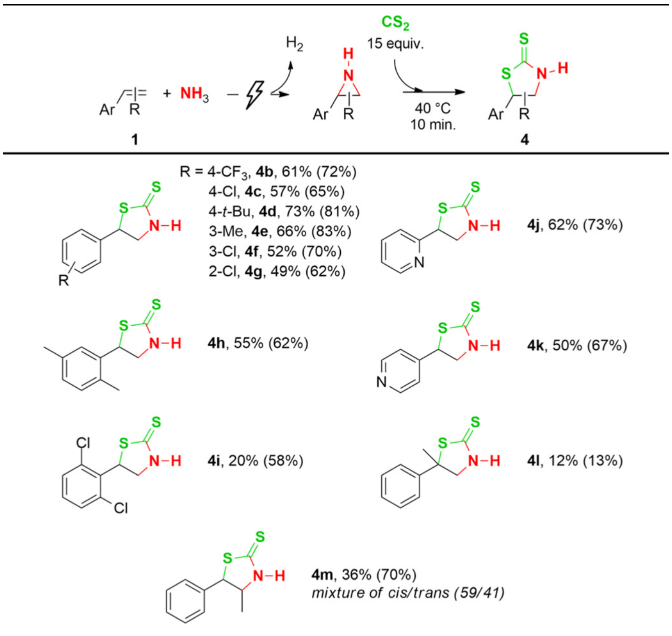
Table 3 Optimization of the telescoped CS_2 ring expansion of electrocatalytically synthesized 2-phenylaziridine



Entry	Deviation from optimization conditions[a]	Yield 4a (%)	Yield 5a (%)
1	—	51	3
2	70 °C	49	1
3	Room temperature	34	2
4	4 hours	64	3
5	**10 minutes**	**66 (58)**	**2**
6	10 minutes, 5 equiv. CS_2	61	2

Conditions for the electrocatalytic N–H aziridination with LiI: see ESI.† Reaction mixture is transferred to a glass reaction vial. [a] Optimization conditions: 15 equiv. CS_2, 40 °C, 18 h. Yields are based on ^{1}H-NMR spectra of crude mixtures, referring to the starting alkene. Number in parentheses indicates the isolated yield.

Table 4 Telescoped CS_2 ring expansion of N–H aziridines electrocatalytically synthesized from simple aromatic olefins[a]



[a] Reaction conditions: see Table 3, entry 5. Yields are based on ^{1}H-NMR spectra of crude mixtures, referring to the starting alkene. Yields in parentheses refer to the CS_2 insertion of the N–H aziridine.

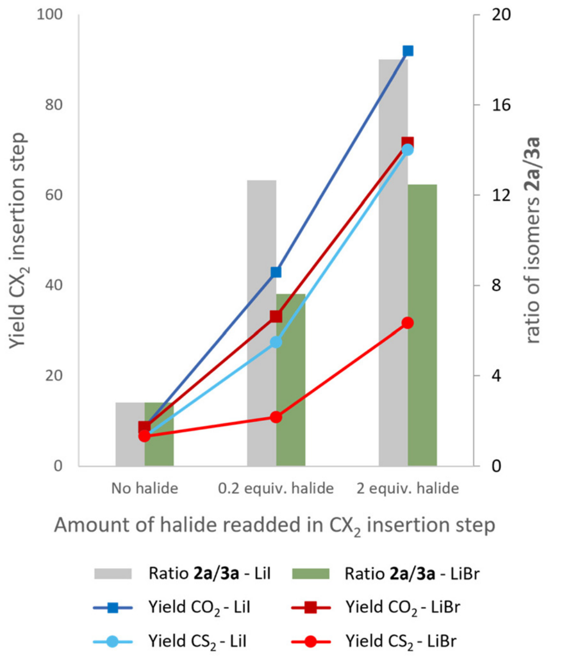
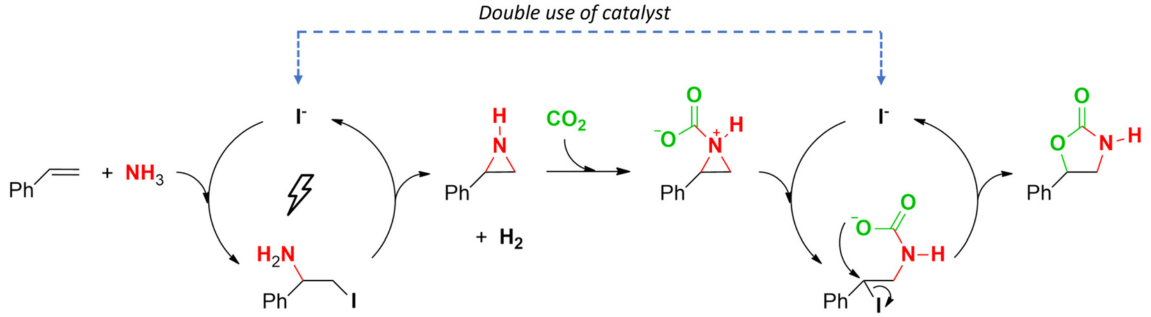


Fig. 1 Control experiments where the influence of the halide is studied regarding the yield of the CX_2 insertion step towards products **2a** or **4a** (curves, left y-axis) and the distribution of isomers **2a** and **3a** (bars, right y-axis) using ^{1}H-NMR. See ESI for more experimental details.†



Scheme 2 Proposed reaction mechanism for the telescoped electrocatalytic coupling of simple aromatic alkenes with NH_3 and CO_2. A similar mechanism for CS_2 can be imagined.

is already observed after just 10 minutes of reaction time (66%, entry 5). Similar as for CO_2, the CS_2 ring expansion shows an excellent regioselectivity for the 5-phenyl isomer **4a** of 97%. Additionally, with a lower CS_2 amount of 5 equivalents, a slightly decreased yield of 61% is obtained (entry 6).

Different aromatic olefins were subjected to the optimized conditions (Table 3, entry 5) to synthesize 2-thiazolidinethiones (Table 4). Generally, the yield of the CS_2 insertion step is around 15% lower than for CO_2, with values ranging from 62% to 83%, resulting in total yields of up to 73% (**4b–h**). Additionally, the substituent type on the aromatic ring, *i.e.* electron-withdrawing *versus* electron-donating, did not influence the CO_2 insertion yield (Table 2, **2b–h**), whereas a noticeable difference in the CS_2 insertion reaction is found between them of around 10–15%. For 2,6-dichlorostyrene, together with a poor aziridination yield, this results in a low total yield of 20% (**4i**). Good yields for both steps are achieved with 2- and 4-vinylpyridine, resulting in total yields of 62% and 50% respectively (**4j–k**). A low overall yield of 12% is achieved with α-methylstyrene (**4l**), despite the 98% aziridination yield, most likely due to the increased steric hindrance of the larger S-atoms compared to CO_2 (Table 2, **n**). Using *trans*-β-methyl styrene, a *cis*/*trans* product mixture in an overall yield of 36% is obtained (**4m**), but interestingly this time with the *cis* isomer as the major product (59/41 ratio *cis*/*trans*). Finally, a gram-scale synthesis of compound **4a** resulted in an overall yield of 59% (see ESI†).

Next, control experiments were performed to obtain mechanistic insights (Fig. 1). To see if iodide, which is already needed for the electrocatalytic N–H aziridination, also catalyzes the ring expansion of the aziridine,[65,66] we removed the salts after the aziridination step according to our work-up procedure (see ESI†). Afterwards, the solvent was added again and the homogeneous mixture was equally divided over three pressure reactors. LiI was added in three different amounts of 0, 0.2 and 2 equivalents and standard reaction conditions for the CO_2 insertion were applied (dark blue curve). As mentioned before, a CO_2 insertion yield of 92% is observed with our telescoped condition of 2 equivalents of LiI. Reducing the amount of LiI greatly decreases the yield, even down to only 9% when the halide is completely absent, despite a full conversion of the aziridine. Most likely formation of oligomers and homo- or copolymerization with CO_2 occur as reported before in similar conditions with elevated temperatures.[19,22,71,76,77] These results strongly suggest that an increasing amount of LiI suppresses these parasitic side reactions and favors the selective CO_2 fixation. When standard conditions for the CS_2 insertion are applied, a similar trend is observed (light blue curve). Analogous experiments where LiBr was added resulted in similar trends compared to the iodide counterparts, albeit to a lesser extent, especially for CS_2 (red curves). The ratio of the 2-oxazolidinone isomers **2a** and **3a** for all three halide contents was also determined and is depicted on the right *y*-axis of Fig. 1. With LiI (grey bars) a strong increase is observed up to a ratio of 18 which reflects the yields observed for both products (Table 1, entry 5). Again, a similar trend is found with LiBr but less pronounced (green bars). In summary, not only does iodide mediates both ring expansion reactions; it also strongly improves the regioselectivity and it is the better halide to perform these reactions.

Based on the results described above, a reaction mechanism is proposed in Scheme 2. The iodide-mediated N–H aziridination proceeds *via* a reaction of an electrochemically generated NH_2I with styrene towards a vicinal iodoamine. Base-assisted cyclization provides the N–H aziridine.[64] Next, the lone pair of the aziridine nitrogen can bond with a molecule of CO_2 to create a charged adduct.[21–23,71,72] Due to electronic effects of the aryl substituent, nucleophilic substitution with iodide occurs on the benzylic carbon, even though it is sterically less accessible.[21,24,78] This also explains the excellent regioselectivity of the resulting products, as was also found in the control experiments (Fig. 1). Finally, ring closing with expulsion of the iodide mediator yields the 2-oxazolidinone product. An analogous mechanism with CS_2 can be envisioned.

Conclusion

In summary, we demonstrate for the first time the coupling of simple aromatic olefins with NH_3 and CO_2 or CS_2 in an electrochemical telescoped procedure to synthesize 2-oxazolidinones or 2-thiazolidinethiones. Overall yields referring to the alkene of up to 91% are obtained with remarkable regioselectivities for the 5-aryl-2-oxazolidinone and 5-aryl-2-thiazolidinethione of 96% and 97% respectively. Additionally, gram-scale experiments resulted in an overall yield of 80% and 59% of compound **2a** and **4a**, respectively. Valuable assets in this sustainable metal-free procedure towards these important heterocycles include starting from commodity chemicals, waste prevention due to a telescoped reaction sequence, CO_2 utilization, excellent atom efficiency and an efficient twofold use of a simple iodide catalyst.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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