Synthesis of 6-membered cyclic carbonates from 1,3-diols and low CO\textsubscript{2} pressure: a novel mild strategy to replace phosgene reagents†

Georgina L. Gregory, Marion Ulmann and Antoine Buchard*

Low pressure carbon dioxide is used as the carbonation agent in a simple, safe and efficient procedure for the synthesis of 6-membered cyclic carbonates from 1,3-diols. Using readily available reagents and proceeding at room temperature, this route offers a novel mild alternative to phosgene derivatives.

Unlike aromatic polycarbonates, aliphatic polycarbonates (APCs) have been little explored commercially. However, their low toxicity and biodegradability make them excellent candidates for biomedical applications. Recently, they have also been investigated as thermoplastics, binders for photovoltaics, polymer electrolytes and adhesives.

Part of this renewed attention stems from the possibility to obtain APCs via the copolymerisation of CO\textsubscript{2} and epoxides, an attractive reaction which uses an abundant and virtually free source of carbon, but is limited by the scope of usable epoxides. APCs can also be synthesised by polycondensation of diols with phosgene derivatives or dialkyl carbonates, but the control of the polymer molecular weight is highly sensitive to the reaction conditions. Hence, Ring-Opening Polymerisation (ROP) of cyclic carbonates has become the method of choice for APC synthesis, as the development of ROP catalysts has enabled controlled polymerisation of highly functionalised monomers under mild conditions (usually 6-, 7-, or strained 5-membered rings).

A common preparation of cyclic carbonate monomers involves the transesterification of diols with phosgene, a toxic reagent synthesised from CO and Cl\textsubscript{2} in an energy intensive process. Nevertheless, phosgene is still widely employed due to its efficiency and the lack of a more versatile and sustainable alternative. Safer phosgene derivatives include di-tert-butyldicarbonate, 1,1'-carbonyldiimidazole, and aromatic carbonates, but these reagents all derive from phosgene, and can lead to unwanted side reactions, low reactivity and difficult workups.

Alternative methods, such as the Pd-catalysed oxidative carbonylation of diols using CO pressure, or the catalytic coupling of CO\textsubscript{2} with oxetanes, have also been reported. The latter however, is limited by the availability of oxetanes. Transesterification of diols with urea, industrially produced from CO\textsubscript{2}, is also described but with moderate success.

Using CO\textsubscript{2} as a C1-carbonation agent is an attractive goal for phosgene related emissions mitigation and direct CO\textsubscript{2} utilisation. The direct coupling of CO\textsubscript{2} with diols, where water is the sole by-product, would be an attractive process. However, the reaction is generally not kinetically and thermodynamically favoured. Therefore, a catalyst and an efficient stoichiometric dehydrating strategy (e.g. nitriles, zeolites, orthoesters, or Mitsunobu reagents) are necessary for the reaction to proceed. Despite recent advances, such as the use of CeO\textsubscript{2} catalyst in tandem with a large excess of 2-cyanopyridine as a dehydrating agent, or the in situ introduction of a leaving group based on dibromomethane, high CO\textsubscript{2} pressures (10–50 bar) and high temperatures (70–140 °C) are still required, particularly for the synthesis of 6-membered rings.

Herein, we report a safe and efficient one-pot procedure for the synthesis of 6-membered cyclic carbonates directly from 1,3-diols, which uses CO\textsubscript{2} as the carbonation agent instead of phosgene derivatives. This methodology proceeds at room temperature (usually 6–7 °C) in an energy efficient process. The reaction is catalysed by a mixture of DBU and NE\textsubscript{3}TsCl, which acts as a dehydrating agent.

Scheme 1. Strategy for the synthesis of cyclic carbonate from 1,3-diols and CO\textsubscript{2} (R\textsuperscript{1}–R\textsuperscript{3} are the various substituents of 1,3-diols used; see Table 2).
temperature, needs only 1 atm. of CO$_2$ and common lab reagents (Scheme 1), and does not require the preliminary preparation of oxetanes or chloroalcohols.$^{25}$

In 2005, Jessop and coworkers reported the reversible carbonation of alcohols with CO$_2$ promoted by 1,8-diazabicyclo-[5.4.0]-undec-7-ene (DBU).$^{26}$ The conversion was later found to depend on the choice of solvent with almost full conversion of 1-hexanol being achieved in CDCl$_3$.$^{27}$ Inspired by these reports, we investigated the selective mono-insertion of CO$_2$ into one alcohol moiety of 1,3-diols in various solvents. The slow addition of DBU under 1 atm of CO$_2$ to solutions of (+)-1,3-butanediol (1a) was monitored and the conversion to alkyl carbonate species assessed by $^1$H NMR (Table 1). Regardless of the solvent used, the carbonation of 1a by CO$_2$ proceeded quickly at low pressure and room temperature, with good selectivity towards the mono-insertion products (ca. 90% of products). A slight preference for the primary alcohol moiety was also observed, in agreement with DFT calculations (see ESI Fig. S4). In neat diol, the conversion was limited by the increased viscosity upon CO$_2$ insertion (Table 1, Entry 1), but even in solution and with the addition of ionic liquid bmimPF$_6$, as used by Lim et al. (Table 1, Entry 5),$^{24}$ full conversion of 1a was not observed with only one DBU equivalent. Apolar toluene-$d_8$ gave less conversion than more polar solvents, whereas more dicarbonated product was obtained in acetonitrile-$d_3$ (Table 1, Entry 2 and 4). Overall, optimal results were obtained in CDCl$_3$, and despite it not being a desirable solvent which should be replaced in the future, chloroform was used in the rest of our study. Addition of DBU at low temperature resulted in no further improvement in mono-insertion selectivity (Table 1, Entry 7), while increasing the temperature promoted decarboxylation. A lower concentration of diol slightly decreased the amount of disubstituted product (Table 1, Entry 6) but did not affect the global conversion. The use of stronger base 1,5,7-diazabicyclo[4.3.0]-undec-7ene (TBD) in place of DBU resulted in less conversion, which is attributed to an increased sensitivity to moisture (Table 1, Entry 8). The use of triethylamine resulted in no carbonation of 1a.

Further DFT calculations showed that the direct coupling of 1a and CO$_2$ to form cyclic carbonate 2a is slightly thermodynamically disfavoured ($\Delta G = +3.0$ kcal mol$^{-1}$). Following the DBU-aided insertion of CO$_2$, the activation barriers are then too high for the cyclisation of 1$_a^a$ (or 1$_a^u$) to proceed under mild conditions ($61.1$ and $42.2$ kcal mol$^{-1}$ via an S$_2$2 or addition/elimination mechanism, respectively) (see Fig. S4). An in situ leaving group strategy was thus applied experimentally to overcome the kinetic as well as the thermodynamic limitation of the reaction. After the selective mono-insertion of CO$_2$ into 1a in CDCl$_3$ at low concentration, 1 equivalent of tosyl chloride and triethylamine were added to the reaction mixture and stirred at room temperature overnight. Rapidly, the cyclic carbonate 2a was detected by $^1$H NMR (addition of triethylamine alone did not result in any product). The pure product was later isolated by column chromatography in a 44% yield, i.e. 60% conversion based on the mono-CO$_2$ inserted products (Table 2, Entry 1). A higher concentration of diol (1.7 M), despite being slightly detrimental to the first step of the procedure, proved to lead to a higher isolated yield of cyclic carbonate (68%, i.e. 99% conversion based on CO$_2$ mono-insertion, Table 2, Entry 2). This compares well with the traditional phosgene-based method (50%)$^{28}$ as well as oxidative carbonylation methods (45%).$^{18a}$ The procedure was found to be robust: CO$_2$ from sublimed dry ice could be used and yielded cyclic carbonate 2a, albeit in lower yield (48%, Table 2, Entry 3). The reaction also proceeded without solvent (30% yield). Investigation into the scope of the procedure was carried out with various 1,3-diols. The cyclisation step proceeded efficiently from the CO$_2$-mono-insertion products and all cyclic carbonates were isolated in moderate yields (Table 2), comparative with phosgene-based and alternative methods. For example, the isolation of 2d from 2,2-dimethyl-1,3-propanediol (53%, Table 2, Entry 8) was previously reported using phosgene derivatives (60%),$^{29}$ oxidative carbonylation (50%),$^{18b}$ and metal free cyclisation (50%).$^{24}$ O-isopropylidene-xylene was also successfully transformed, though isolation proved challenging (11%, Table 2, Entry 12).

As cyclisation happens readily, reaction intermediates could not be isolated, but DFT calculations on model compound (R)-1a and additional experiments with optically active diols were carried out to investigate the reaction mechanism. After insertion of CO$_2$, tosylation can occur at the carbonate or at the remaining alcohol group, so that cyclisation proceeds via either an addition/elimination or a S$_2$2 pathway, leading to retention or inversion of stereochemistry (see Scheme 2). However, the exclusive formation and isolation of (R,R)-cyclocarbonate 2b from (R,R)-2,4-pentanediol, as well as the optical activities of the cyclic carbonates obtained from enantiopure (R) and (S)-1,3-butanediol (Table 2, Entries 4–6),$^{28}$ both indicated an addition/
Table 2  Synthesis of various cyclic carbonates from 1,3-diols and CO₂

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>% Yield$^a$ [conv.$^b$-]</th>
<th>Product</th>
</tr>
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<tr>
<td>1$^c$</td>
<td>1a</td>
<td>44 [60]</td>
<td>2a</td>
</tr>
<tr>
<td>2</td>
<td>1a</td>
<td>68 [99]</td>
<td>2a</td>
</tr>
<tr>
<td>3$^d$</td>
<td>1a</td>
<td>48</td>
<td>2a</td>
</tr>
<tr>
<td>4</td>
<td>(R)-1a</td>
<td>68</td>
<td>(R)-2a</td>
</tr>
<tr>
<td>5</td>
<td>(S)-1a</td>
<td>70</td>
<td>(S)-2a</td>
</tr>
<tr>
<td>6</td>
<td>1b</td>
<td>53 [71]</td>
<td>2b</td>
</tr>
<tr>
<td>7</td>
<td>1c</td>
<td>55 [96]</td>
<td>2c</td>
</tr>
<tr>
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<td>53 [82]</td>
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</tr>
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<td>2g</td>
</tr>
<tr>
<td>12</td>
<td>1h</td>
<td>11</td>
<td>2h</td>
</tr>
</tbody>
</table>

$^a$ Isolated yield based on starting diol. $^b$ Spectroscopic conversion of CO₂ mono-insertion products 1 into cyclic carbonate 2. $^c$ [Diol] = 0.1 M. $^d$ CO₂ from the sublimation of dry ice was used.
Communication

On-going work is now aiming at replacing chloroform for a more environmental benign solvent and making the procedure catalytic in order to reduce the amount of salts produced.

Acknowledgements

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Notes and references

† Typical procedure for the synthesis of cyclic carbonate monomers: under a CO₂ atmosphere, DBU (1 equiv.) was added dropwise to a stirring solution/suspension of diol (0.5 g, 1 equiv.) in dry chloroform (1.7 M). After stirring at room temperature for 2 hours, triethylamine (1 equiv.) was added dropwise to the resulting viscous solution. A solution of TsCl in chloroform (1 equiv., 0.5 M) was then added slowly and the mixture stirred overnight. Removal of volatiles in vacuo afforded an oily residue, which was purified by column chromatography.


30 Low volatility and UV sensitivity prevented chiral GC/HPLC study.