

# Microwave-assisted regioselective ring opening of non-activated aziridines by lithium aluminium hydride

Sonja Stanković, Matthias D'hooghe and Norbert De Kimpe\*

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A new synthetic protocol for the  $\text{LiAlH}_4$ -promoted reduction of non-activated aziridines under microwave conditions was developed. Thus, ring opening of 2-(acetoxymethyl)aziridines provided the corresponding  $\beta$ -amino alcohols, which were then used as eligible substrates in the synthesis of 5-methylmorpholin-2-ones *via* condensation with glyoxal in THF. The same procedure was applied for the preparation of novel 5(*R*)- and 5(*S*)-methylmorpholin-2-ones starting from the corresponding enantiopure 2-(hydroxymethyl)aziridines. Additionally, 2-(methoxymethyl)- and 2-(phenoxyethyl)aziridines were treated with  $\text{LiAlH}_4$  under microwave irradiation, giving rise to either isopropylamines or 1-methoxypropan-2-amines depending on the reaction conditions.

## Introduction

The aziridine moiety represents a valuable three-membered ring system in organic chemistry due to its versatility as a building block for the preparation of a large variety of ring opened and ring expanded amines.<sup>1,2</sup> Aziridines bearing an electron-withdrawing substituent at the nitrogen (activated aziridines) are known to be reactive towards a large number of nucleophiles with respect to ring opening.<sup>2</sup> On the other hand, electron-donating groups at the nitrogen render the aziridine more stable and activation towards an aziridinium intermediate is, in most cases, required prior to nucleophilic ring opening.<sup>3–7</sup> The resulting electrophilic species is then attacked by a nucleophile at the more or less substituted position of the aziridine ring depending on the substrate, the type of the nucleophile and the solvent, yielding a functionalized amine.<sup>3–11</sup>

In comparison to the huge number of reports on the ring opening of aziridines by other nucleophiles, their ring opening by hydrides has received very limited interest in the literature despite the synthetic potential of this approach. The intermediacy of aziridines in direct, non-regioselective ring opening reactions by  $\text{LiAlH}_4$  has been proposed in an early paper, in which the reduction of *N*-(1,1-dichloro-2-alkylidene)anilines was investigated,<sup>12</sup> and was also deduced indirectly from the experiments of Suzuki.<sup>13</sup> In addition, in one recent report,<sup>14</sup> the reduction of 2-methyl-1-phenylaziridine with  $\text{LiAlH}_4$  in THF yielded a mixture of ring opened amines (derived from hydride attack at both the more and the less hindered aziridine carbon atom in a 1 : 2 ratio, respectively) yet was shown to be slow and not complete after heating under reflux for 20 h. Furthermore, the contribution of the electron-withdrawing effect of the phenyl group at the nitrogen, facilitating ring opening of the aziridine moiety, should not be neglected.

In addition to the above-mentioned reports, the ring opening of reactive 2-chloroaziridine intermediates by  $\text{LiAlH}_4$  has been described.<sup>15</sup> It should be stressed that several syntheses of aziridines have been reported in the literature based on the

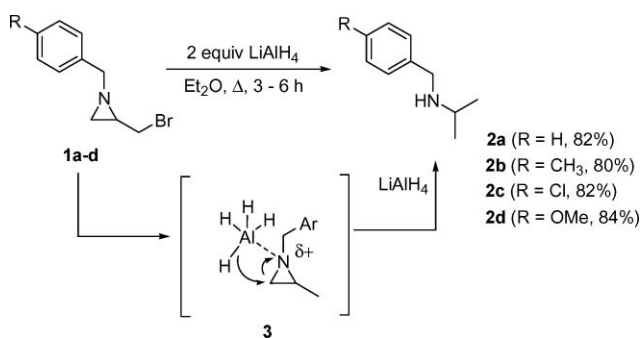
reduction of suitable substrates, such as  $\alpha$ -halo imines,<sup>15a,16</sup> vinyl azides,<sup>17</sup> oximes<sup>18</sup> and azirines,<sup>19</sup> by nucleophilic complex hydrides. Very recently, the reductive ring opening of highly electrophilic aziridinium salts by hydrides has been reported to afford 2-aminopropanes through regiospecific ring opening at the unsubstituted position.<sup>6c,20</sup> However, up to now,  $\text{LiAlH}_4$  has been mainly used to reduce functional groups in compounds incorporating an aziridine unit without affecting the three-membered ring itself,<sup>21–24</sup> and the hydride-promoted ring opening of non-activated aziridines has not been described in the literature so far.

In the present study, special attention was devoted to the  $\text{LiAlH}_4$ -promoted ring opening of non-activated 2-substituted aziridines towards biologically and synthetically relevant species. The lack of studies concerning the reduction of aziridines by  $\text{LiAlH}_4$  is remarkable in view of the large number of papers on the reductive ring opening of their oxygen counterparts, oxiranes. In contrast to previous reports, all of the reactions in the present work proceeded smoothly with high regioselectivity and resulted in full conversion of the substrate, without requiring the presence of Lewis acids. In addition, the regio- and stereoselective reductive ring opening of enantiopure 2-(hydroxymethyl)aziridines by  $\text{LiAlH}_4$  towards chiral  $\beta$ -amino alcohols was performed, and the resulting  $\beta$ -amino alcohols were applied in the synthesis of novel 5-methylmorpholin-2-ones.

## Results and discussion

1-Arylmethyl-2-(bromomethyl)aziridines<sup>25</sup> **1** constitute versatile substrates for further elaboration,<sup>4b,26–28</sup> although their reactivity towards  $\text{LiAlH}_4$  has not been evaluated up until now. The reaction of aziridines **1** with two molar equivalents of  $\text{LiAlH}_4$  in dry  $\text{Et}_2\text{O}$  under reflux for 3–6 h afforded *N*-arylmethyl-*N*-isopropylamines **2** as the sole reaction products quite unexpectedly in high yields (80–84%) (Scheme 1). The suggested mechanistic pathway for this transformation consists of an initial reductive debromination of 2-(bromomethyl)aziridines **1** toward 2-methylaziridines **3** through the action of  $\text{LiAlH}_4$ , either *via* a nucleophilic or a radical reaction.<sup>29</sup> Subsequently, reductive ring opening takes place *via* nucleophilic attack of a hydride ion (from  $\text{LiAlH}_4$ ) at the less substituted carbon atom of the aziridine moiety in intermediates

Department of Sustainable Organic Chemistry and Technology, Faculty of Bioscience Engineering, Ghent University, Coupure Links 653, B-9000 Ghent, Belgium. E-mail: norbert.dekimpe@UGent.be; Fax: +32-92646243; Tel: +32-92645951



Scheme 1

3. Apparently, the reducing agent acts both as the activator of the aziridine ring (through coordination of aluminium with nitrogen<sup>5,14</sup>) and as the provider of the nucleophile (hydride) which opens up the ring at the less hindered position (Scheme 1). However, the alternative mechanistic pathway comprising an initial hydride attack at the less hindered position of the aziridine moiety of 2-(bromomethyl)aziridines **1**, yielding the ring opened intermediates, and their subsequent ring closure towards 2-methylaziridines **3**, should not be neglected. Although attempts to isolate 2-methylaziridines<sup>30</sup> **3** by column chromatography on silica gel failed, their intermediacy was acknowledged upon <sup>1</sup>H NMR and <sup>13</sup>C NMR analysis of some of the crude reaction mixtures. Furthermore, the presence of aziridines **3** was confirmed by MS analysis of these reaction mixtures.

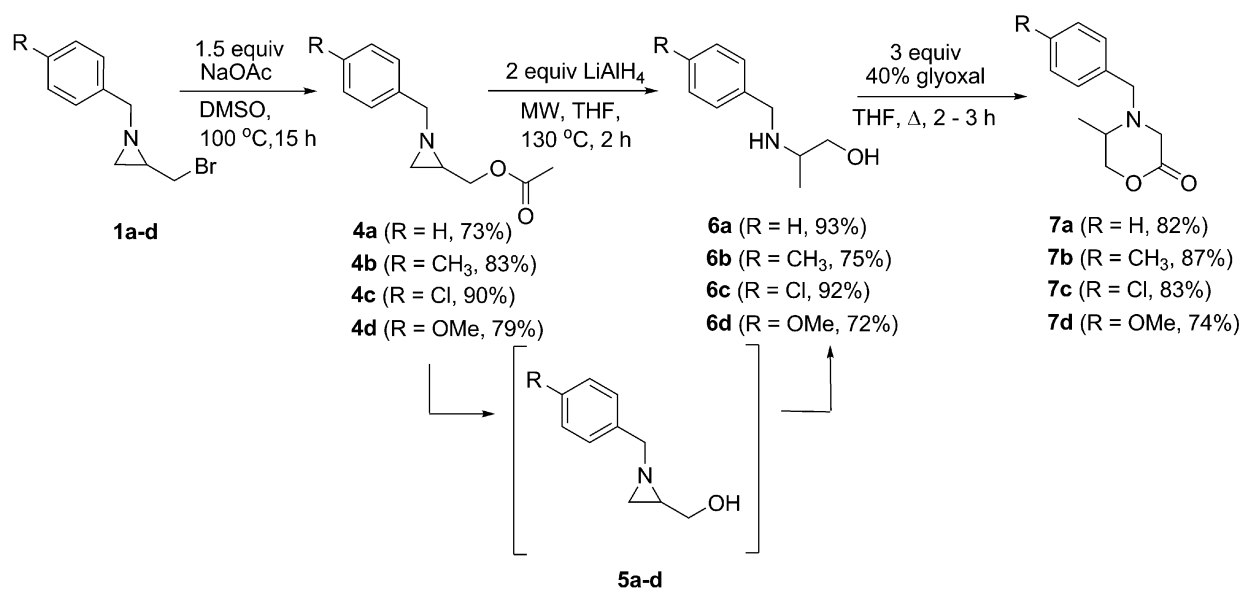
Additionally, in order to confirm the structure of *N*-arylmethyl-*N*-isopropylamines **2**, an independent synthesis of *N*-(4-methoxybenzyl)-*N*-isopropylamine **2d** was performed. Condensation of 4-methoxybenzaldehyde with 1.05 equiv of *i*PrNH<sub>2</sub> in CH<sub>2</sub>Cl<sub>2</sub> in the presence of MgSO<sub>4</sub> afforded the corresponding imine in 75% yield after six hours under reflux, which was then reduced using two molar equiv of NaBH<sub>4</sub> in MeOH for two hours under reflux, furnishing *N*-(4-methoxybenzyl)-*N*-isopropylamine

**2d** in 96% yield. The spectral data of amine **2d** obtained *via* both routes were judged to be identical.

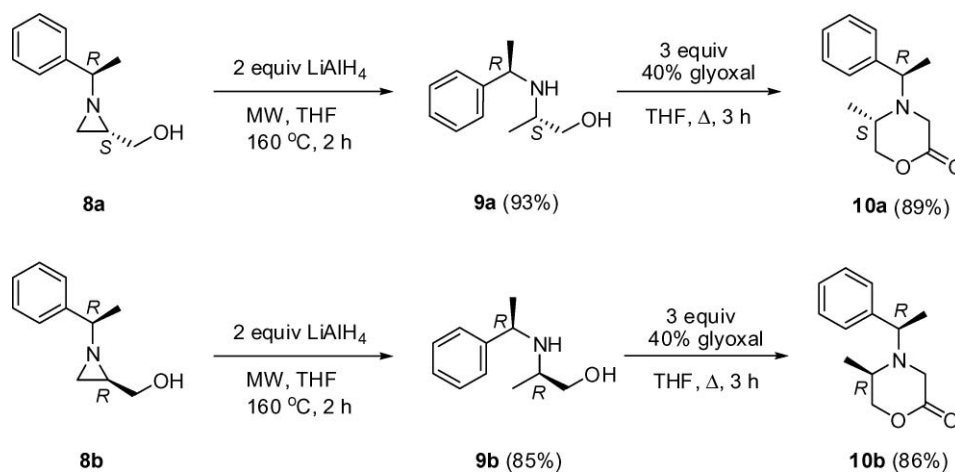
Apart from its use in the preparation of amines **2**, which can of course easily be prepared *via* other routes, this methodology holds significant synthetic potential for the preparation of a large variety of amines in a convenient way through reductive ring opening of the appropriate aziridine derivatives.

The utility of this LiAlH<sub>4</sub>-promoted ring opening of non-activated aziridines was demonstrated by the synthesis of versatile β-amino alcohols starting from 2-(acetoxymethyl)aziridines. 1-Arylmethyl-2-(acetoxymethyl)aziridines **4** were smoothly prepared upon treatment of 2-(bromomethyl)aziridines **1** with an excess (1.5 equiv) of sodium acetate in DMSO at 100 °C for 15 h (Scheme 2). The reaction provided almost pure acetates **4a-d** suitable for further elaboration without prior purification. However, for full characterization, aziridines **4** were purified by column chromatography on silica gel column, affording analytically pure samples.

Further treatment of 2-(acetoxymethyl)aziridines **4** with two molar equiv of LiAlH<sub>4</sub> in Et<sub>2</sub>O and heating for six hours under reflux provided crude mixtures containing mainly alcohols **5**, and no traces of ring opened β-amino alcohols **6** were detected. Increasing the reaction time to 24–62 h led to partial formation of β-amino alcohols **6** (~50%). It was shown that, in order to obtain β-amino alcohols **6** in reasonable yields, a reflux time of several days (4–5) was required. In order to overcome this major drawback, the reaction mixture was subjected to microwave irradiation. Gratifyingly, after heating aziridines **4** in THF at 130 °C for two hours (220 W<sub>max</sub>) in the presence of two molar equiv of LiAlH<sub>4</sub>, only the corresponding β-amino alcohols **6** were formed in high purity without traces of 2-(hydroxymethyl)aziridines **5** (Scheme 2). Thus, the nucleophilic attack of hydride at the less substituted carbon atom of aziridines **5** was confirmed and, as a result, β-amino alcohols **6** were obtained in high yields after purification by column chromatography on silica gel. In this way, 2-aminopropan-1-ols **6** were formed selectively through complete



Scheme 2



Scheme 3

regioselective conversion of 2-(hydroxymethyl)aziridines **5**. Although several useful routes for the synthesis of  $\beta$ -amino alcohols are available in the literature,<sup>31–33</sup> some of these approaches suffer from (minor) drawbacks such as low regioselectivity, cumbersome substrate synthesis or low substrate stability. The synthesis of  $\beta$ -amino alcohols **6** through microwave-assisted ring opening of aziridines **4** utilizing  $\text{LiAlH}_4$  satisfies the requirements for a generally applicable route, *i.e.* the use of commercially available starting compounds, complete regio- and stereoselectivity and high energy efficiency. Thus, the presented methodology can be regarded as a complementary approach or a worthy alternative for other known routes.  $\beta$ -Amino alcohols are applied extensively in organic chemistry as building blocks in designing natural and biologically active substances,<sup>33a,34–44</sup> and their chiral versions are also used in catalytic asymmetric synthesis.<sup>31,45</sup>

In the next part, 2-aminopropan-1-ols **6** were shown to be good substrates for the construction of 5-methylmorpholin-2-ones,<sup>46</sup> which are known as useful substrates for the synthesis of biologically relevant compounds.<sup>47,48</sup> Thus, 2-(arylmethylamino)propan-1-ols **6** were dissolved in THF and treated with three equiv of glyoxal. After heating these mixtures for 2–3 h, 5-methylmorpholin-2-ones **7a–d** were obtained in good yields (Scheme 2) and column chromatography on silica gel provided analytically pure compounds suitable for full characterization.

Given the intermediacy of 2-(hydroxymethyl)aziridines **5** in the conversion of acetates **4** into alcohols **6**, efforts were devoted to the evaluation of chiral 2-(hydroxymethyl)aziridines as substrates for a  $\text{LiAlH}_4$ -promoted reductive ring opening. In the literature, only a few studies have been made on ring opening reactions of non-activated enantiomerically pure 2-(hydroxymethyl)aziridines.<sup>32,49–52</sup> For example, the catalytic hydrogenation of aziridine methanols **8a** and **8b** in EtOH using  $\text{Pd}(\text{OH})_2$  has provided  $\beta$ -amino alcohols **9a** and **9b** in good yields.<sup>49</sup> Recently, the preparation of chiral  $\beta$ -amino alcohols *via* regio- and stereocontrolled ring opening reactions of chiral aziridines was examined.<sup>53</sup> This approach comprised the reaction of 2-alkyl-substituted aziridines with acetic acid to yield the ring opened products with excellent regioselectivity, which were then treated with  $\text{LiAlH}_4$  or  $\text{Pd}(\text{OH})_2$  to provide the corresponding  $\beta$ -amino alcohols. On the other hand, the reaction of the same chiral

aziridines with acetyl chloride followed by treatment with water gave isomeric  $\beta$ -amino alcohols through oxazoline intermediates.<sup>53</sup> In addition, the reaction of the latter chiral aziridines with benzyl bromide followed by treatment with sulfuric acid gave secondary  $\beta$ -amino alcohols *via* ring opening at the substituted aziridine carbon atom.

In the present work, the synthesis of enantiopure 2-aminopropan-1-ols by means of  $\text{LiAlH}_4$ -promoted reduction of chiral 2-(hydroxymethyl)aziridines **8a** and **8b** was successfully examined. After failing to prepare amines **9a** and **9b** upon treatment with two molar equiv of  $\text{LiAlH}_4$  under reflux for several days in THF and toluene, the mixture of aziridine **8** and two molar equiv of  $\text{LiAlH}_4$  in THF was subjected to microwave conditions (160 °C, 220  $\text{W}_{\text{max}}$ , two hours). Fortunately, full and selective conversion of aziridines **8a** and **8b** into enantiopure 2-aminopropan-1-ols **9a** and **9b** as single stereoisomers was obtained (Scheme 3).

Again, the mechanism comprises coordination of aluminium with the aziridine nitrogen atom, enabling C(3)–N cleavage induced by nucleophilic attack of a hydride ion to furnish the corresponding ring opened product. The bond cleavage was shown to be highly regioselective, since hydride attack only occurred at the less hindered position. Furthermore, the ring opening reaction of chiral aziridines **8** proceeded not only with high regio- but also high stereoselectivity, furnishing the corresponding enantiopure amino alcohols **9a** and **9b** with full retention of configuration.

The preparation of enantiopure six-membered oxazaheterocycles has received significant attention, due for example to their high potential as chiral substrates. In particular, chiral morpholin-2-ones have been used in the asymmetric synthesis of  $\alpha$ -amino acids<sup>47</sup> and other natural products.<sup>48</sup> In the present study, enantiopure 5-methylmorpholin-2-ones were prepared by condensation of the corresponding chiral amino alcohols with glyoxal. Thus, chiral  $\beta$ -amino alcohols **9a** and **9b** were treated with three equiv of glyoxal (40%), furnishing enantiopure morpholin-2-ones **10a** and **10b** upon reflux for three hours in THF (Scheme 3). The reaction showed high stereoselectivity since no diastereomers were detected in the crude  $^1\text{H}$  NMR spectra, which is in accordance with previously reported analogous condensation reactions.<sup>46</sup>



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*Org. Biomol. Chem.*, 2010, **8**, 4266–4273 | 4269



LiAlH<sub>4</sub> under microwave irradiation, depending on the temperature applied. Thus, LiAlH<sub>4</sub> can be regarded as a useful reagent for a new type of reductive aziridine ring opening in a selective way under microwave conditions, paving the way for a variety of novel applications in organic chemistry.

## Experimental section

### General

<sup>1</sup>H NMR spectra were recorded at 300 MHz (JEOL ECLIPSE+) with CDCl<sub>3</sub> as solvent and tetramethylsilane as internal standard. <sup>13</sup>C NMR spectra were recorded at 75 MHz (JEOL ECLIPSE+) with CDCl<sub>3</sub> as solvent. Mass spectra were recorded on an Agilent 1100 series mass spectrometer using either a direct inlet system (electron spray, 4000 V) or LC-MS coupling (UV detector). IR spectra were recorded on a Perkin-Elmer Spectrum BX FT-IR spectrometer. All compounds were analysed in neat form with an ATR (Attenuated Total Reflectance) accessory. Melting points were measured using a Büchi B-540 apparatus and are uncorrected. Dichloromethane was distilled over calcium hydride, while diethyl ether and THF were distilled from sodium and sodium benzophenone ketyl before use. Microwave reactions were performed in a CEM Discover Microwave Reactor in a 80 ml sealed vessel using a fiber-optic temperature sensor.

### Synthesis of 1-arylmethyl-2-(acetoxymethyl)aziridines 4

As a representative example, the synthesis of 1-(4-chlorophenyl)methyl-2-(acetoxymethyl)aziridine **4c** is described here.

1-(4-Chlorophenyl)methyl-2-(bromomethyl)aziridine (2.60 g, 10 mmol)<sup>25</sup> **1c** was added to a stirred solution of NaOAc (1.23 g, 1.5 equiv) in DMSO (20 ml) at room temperature, and the mixture was heated at 100 °C for 15 h. The reaction mixture was poured into water (20 ml) and extracted with Et<sub>2</sub>O (3 × 20 ml). The combined organic extracts were washed with H<sub>2</sub>O (2 × 15 ml) and brine (20 ml). Drying (MgSO<sub>4</sub>), filtration of the drying agent and evaporation of the solvent afforded 1-(4-chlorophenyl)methyl-2-(acetoxymethyl)aziridine **4c** (2.16 g, 90%), which was purified by filtration through silica gel (hexane–ethyl acetate 2 : 1) in order to obtain an analytically pure sample.

**1-(4-Methylphenyl)methyl-2-(acetoxymethyl)aziridine 4b.** Yield 83%, light-yellow oil, *R*<sub>f</sub> 0.15 (hexane–ethyl acetate 2 : 1). <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>): δ 1.51 (1H, d, *J* = 6.0 Hz); 1.77 (1H, d, *J* = 3.3 Hz); 1.81–1.89 (1H, m); 1.97 (3H, s); 2.34 (3H, s); 3.30 and 3.54 (2H, 2 × d, *J* = 13.2 Hz); 3.82 and 4.17 (2H, 2 × d, *J* = 11.5, 7.2, 4.4 Hz); 7.13–7.25 (4H, m). <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>): δ 20.7, 21.1, 31.8, 36.9, 64.0, 66.6, 128.0, 129.0, 135.7, 136.6, 170.9. IR (neat, cm<sup>-1</sup>): ν<sub>CO</sub> = 1737; ν<sub>max</sub> = 2924; 1370; 1230; 1032; 802. MS (70 eV): *m/z* (%): 220 (M<sup>+</sup> + 1, 100). Anal. Calcd for C<sub>13</sub>H<sub>17</sub>NO<sub>2</sub>: C 71.21, H 7.81, N 6.39. Found: C 71.35, H 8.03, N 6.44.

**1-(4-Chlorophenyl)methyl-2-(acetoxymethyl)aziridine 4c.** Yield 90%, light-yellow oil, *R*<sub>f</sub> 0.12 (hexane–ethyl acetate 2 : 1). <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>): δ 1.51 (1H, d, *J* = 6.6 Hz); 1.79 (1H, d, *J* = 3.9 Hz); 1.80–1.90 (1H, m); 1.98 (3H, s); 3.26 and 3.56 (2H, 2 × d, *J* = 13.8 Hz); 3.79 and 4.20 (2H, 2 × d, *J* = 11.6, 7.4, 4.4 Hz); 7.24–7.32 (4H, m). <sup>13</sup>C NMR (75 MHz, ref = CDCl<sub>3</sub>): δ 20.9, 32.0, 37.2, 63.5, 66.6, 128.5, 129.5, 132.9, 137.4,

171.0. IR (neat, cm<sup>-1</sup>): ν<sub>CO</sub> = 1737; ν<sub>max</sub> = 2986; 2832; 1491; 1370; 1231; 1087; 1033; 806. MS (70 eV): *m/z* (%): 240/2 (M<sup>+</sup> + 1, 100). Anal. Calcd for C<sub>12</sub>H<sub>14</sub>ClNO<sub>2</sub>: C 60.13, H 5.89, N 5.84. Found: C 60.28, H 6.12, N 5.79.

**1-(4-Methoxyphenyl)methyl-2-(acetoxymethyl)aziridine 4d.** Yield 79%, light-yellow oil, *R*<sub>f</sub> 0.08 (hexane–ethyl acetate 2 : 1). <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>): δ 1.51 (1H, d, *J* = 6.6 Hz); 1.77 (1H, d, *J* = 3.3 Hz); 1.79–1.89 (1H, m); 1.97 (3H, s); 3.26 and 3.52 (2H, 2 × d, *J* = 13.0 Hz); 3.80 (3H, s); 3.86 and 4.17 (2H, 2 × d, *J* = 11.6, 7.7, 4.7 Hz); 6.85–6.88 and 7.25–7.28 (4H, 2 × m). <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>): δ 20.8, 31.8, 36.9, 55.3, 63.6, 66.6, 113.7, 129.3, 131.0, 158.8, 170.9. IR (neat, cm<sup>-1</sup>): ν<sub>CO</sub> = 1736; ν<sub>max</sub> = 2952; 2835; 1511; 1234; 1031; 818. MS (70 eV): *m/z* (%): 236 (M<sup>+</sup> + 1, 100). Anal. Calcd for C<sub>13</sub>H<sub>17</sub>NO<sub>3</sub>: C 66.36, H 7.28, N 5.95. Found: C 66.45, H 7.57, N 5.81.

### Synthesis of 2-(arylmethylamino)propan-1-ols 6 from 1-arylmethyl-2-(acetoxymethyl)aziridines 4

As a representative example, the synthesis of 2-{[(4-chlorophenyl)methyl]amino}propan-1-ol **6c** is described here. 1-(4-Chlorophenyl)methyl-2-(acetoxymethyl)aziridine **4c** (1.20 g, 5 mmol) was dissolved in dry THF (50 ml), after which LiAlH<sub>4</sub> (0.38 g, 2 molar equiv) was added in small portions at 0 °C. The resulting mixture was then placed in an 80 ml sealed glass vessel, provided with appropriate stirrer bar and subjected to microwave conditions (130 °C, 220 W<sub>max</sub>, two hours, CAUTION). Afterwards, the reaction mixture was poured into water (20 ml) and extracted with Et<sub>2</sub>O (3 × 20 ml). Drying (MgSO<sub>4</sub>), filtration of the drying agent and evaporation of the solvent afforded 2-{[(4-chlorophenyl)methyl]amino}propan-1-ol **6c** (0.92 g, 92%), which was purified by filtration through silica gel column (dichloromethane–methanol 9 : 1) in order to obtain an analytically pure sample. CAUTION: strict safety measurements have to be applied for LiAlH<sub>4</sub>-promoted reactions under microwave irradiation in order to cover the risk of explosion.

**2-{[(4-Methylphenyl)methyl]amino}propan-1-ol 6b.** Yield 75%, light-yellow crystals, *R*<sub>f</sub> 0.17 (dichloromethane–methanol 9 : 1), Mp = 71.7–72.2 °C. <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>): δ 1.07 (3H, d, *J* = 6.6 Hz); 2.33 (3H, s); 2.74 (2H, br s); 2.77–2.88 (1H, m); 3.27 and 3.57 (2H, 2 × d, *J* = 11.0, 6.9, 3.9 Hz); 3.68 and 3.83 (2H, 2 × d, *J* = 12.9 Hz); 7.07–7.25 (4H, m). <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>): δ 16.7, 21.2, 50.5, 53.9, 65.2, 128.4, 129.3, 136.0, 137.1. IR (neat, cm<sup>-1</sup>): ν<sub>NH,OH</sub> = 3277; ν<sub>max</sub> = 2846; 1460; 1063; 886; 812. MS (70 eV): *m/z* (%): 180 (M<sup>+</sup> + 1, 100). Anal. Calcd for C<sub>11</sub>H<sub>17</sub>NO: C 73.70, H 9.56, N 7.81. Found: C 73.92, H 9.48, N 9.47.

**2-{[(4-Chlorophenyl)methyl]amino}propan-1-ol 6c.** Yield 92%, light-yellow crystals, *R*<sub>f</sub> 0.19 (dichloromethane–methanol 9 : 1), Mp = 64.6–65.6 °C. <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>): δ 1.06 (3H, d, *J* = 6.6 Hz); 2.31 (2H, br s); 2.75–2.85 (1H, m); 3.27 and 3.56 (2H, 2 × d, *J* = 10.8, 7.2, 3.8 Hz); 3.68 and 3.83 (2H, 2 × d, *J* = 13.2 Hz); 7.23–7.33 (4H, m). <sup>13</sup>C NMR (75 MHz, ref = CDCl<sub>3</sub>): δ 17.2, 50.4, 53.9, 65.6, 128.7, 129.5, 132.9, 138.8. IR (neat, cm<sup>-1</sup>): ν<sub>NH,OH</sub> = 3312; ν<sub>max</sub> = 2927; 1491; 1256; 1043; 730. MS (70 eV): *m/z* (%): 200/2 (M<sup>+</sup> + 1, 100). Anal. Calcd for C<sub>10</sub>H<sub>14</sub>ClNO: C 60.15, H 7.07, N 7.01. Found: C 60.05, H 7.18, N 7.10.

**2-[(4-Methoxyphenyl)methyl]amino]propan-1-ol 6d.** Yield 72%, light-yellow crystals,  $R_f$  0.08 (dichloromethane–methanol 9 : 1),  $M_p$  = 59.4–60.4 °C.  $^1\text{H}$  NMR (300 MHz,  $\text{CDCl}_3$ ):  $\delta$  1.02 (3H, d,  $J$  = 7.2 Hz); 1.95 (2H, br s); 2.72–2.81 (1H, m); 3.20 and 3.52 (2H, 2 x d x d,  $J$  = 10.5, 6.6, 3.9 Hz); 3.61 and 3.74 (2H, 2 x d,  $J$  = 12.9 Hz); 3.72 (3H, s); 6.78–6.81 and 7.15–7.19 (4H, 2 x m).  $^{13}\text{C}$  NMR (75 MHz,  $\text{ref} = \text{CDCl}_3$ ):  $\delta$  17.1, 50.6, 53.7, 55.4, 65.6, 113.9, 129.4, 132.4, 158.8. IR (neat,  $\text{cm}^{-1}$ ):  $\nu_{\text{NH,OH}}$  = 3294;  $\nu_{\text{max}}$  = 2834; 1511; 1245; 1034; 819. MS (70 eV):  $m/z$  (%): 196 ( $M^+$  + 1, 100). Anal. Calcd for  $\text{C}_{11}\text{H}_{17}\text{NO}_2$ : C 67.66, H 8.78, N 7.17. Found: C 67.76, H 8.91, N 7.14.

#### Synthesis of optically active 2-aminopropan-1-ols 9 from chiral aziridine alcohols 8

As a representative example, the synthesis of (S)-[1(R)-phenylethylamino]propan-1-ol **9a** is described here. Aziridine alcohol **8a** (0.88 g, 5 mmol) was diluted in dry THF (50 ml), and  $\text{LiAlH}_4$  (0.38 g, 2 molar equiv) was added in small portions at 0 °C. The resulting mixture was then placed in an 80 ml sealed vessel, provided with appropriate stirrer bar and subjected to microwave conditions (160 °C, 220  $W_{\text{max}}$ , two hours, CAUTION). The resulting reaction mixture was subsequently poured into water (15 ml) and extracted with  $\text{Et}_2\text{O}$  (3 x 20 ml). Drying ( $\text{MgSO}_4$ ), filtration of the drying agent and evaporation of the solvent afforded 2(S)-[1(R)-phenylethylamino]propan-1-ol **9a** (0.83 g, 93%), which was purified by filtration through silica gel (dichloromethane–methanol 9 : 1) in order to obtain an analytically pure sample.

**2(S)-[1(R)-Phenylethylamino]propan-1-ol 9a.** Yield 93%, colorless liquid,  $R_f$  0.18 (dichloromethane–methanol 9 : 1),  $[\alpha]_{\text{D}}^{28}$  = +115.6 ( $c$  = 0.41,  $\text{CDCl}_3$ ).  $^1\text{H}$  NMR (300 MHz,  $\text{CDCl}_3$ ):  $\delta$  0.98 (d x d,  $J$  = 6.9, 1.4 Hz); 1.36 (3H, d,  $J$  = 6.6 Hz); 2.51–2.61 (1H, m); 2.55 (2H, br s); 3.16–3.23 (1H, m); 3.40 (1H, d x d,  $J$  = 10.8, 4.2 Hz); 3.93 (1H, q,  $J$  = 6.6 Hz); 7.19–7.34 (5H, m).  $^{13}\text{C}$  NMR (75 MHz,  $\text{CDCl}_3$ ):  $\delta$  16.6, 25.2, 51.4, 54.9, 66.5, 126.6, 127.1, 128.6, 145.1. IR (neat,  $\text{cm}^{-1}$ ):  $\nu_{\text{NH,OH}}$  = 3292;  $\nu_{\text{max}}$  = 2965; 1452; 1044; 762; 731; 699. MS (70 eV):  $m/z$  (%): 180 ( $M^+$  + 1, 100). Anal. Calcd for  $\text{C}_{11}\text{H}_{17}\text{NO}$ : C 73.70, H 9.56, N 7.81. Found: C 73.94, H 9.84, N 7.69.

**2(R)-[1(R)-Phenylethylethylamino]propan-1-ol 9b.** Yield 85%, white crystals,  $R_f$  0.08 (dichloromethane–methanol 9 : 1),  $M_p$  = 49.5–51.1 °C,  $[\alpha]_{\text{D}}^{28}$  = –2.3 ( $c$  = 0.36,  $\text{CDCl}_3$ ).  $^1\text{H}$  NMR (300 MHz,  $\text{CDCl}_3$ ):  $\delta$  0.98 (3H, d,  $J$  = 6.6 Hz); 1.35 (3H, d,  $J$  = 6.4 Hz); 2.30 (2H, br s); 2.68–2.80 (1H, m); 3.20 and 3.59 (2H, 2 x d x d,  $J$  = 10.5, 6.1, 3.8 Hz); 3.87 (1H, q,  $J$  = 6.4 Hz); 7.22–7.36 (5H, m).  $^{13}\text{C}$  NMR (75 MHz,  $\text{CDCl}_3$ ):  $\delta$  18.2, 24.1, 51.6, 55.4, 64.9, 126.4, 127.1, 128.6, 145.9. IR (neat,  $\text{cm}^{-1}$ ):  $\nu_{\text{NH,OH}}$  = 3292;  $\nu_{\text{max}}$  = 2965; 1452; 1045; 761; 700. MS (70 eV):  $m/z$  (%): 180 ( $M^+$  + 1, 100). Anal. Calcd for  $\text{C}_{11}\text{H}_{17}\text{NO}$ : C 73.70, H 9.56, N 7.81. Found: C 73.78, H 9.72, N 7.82.

#### Synthesis of 5-methylmorpholin-2-ones 7 from 2-(arylmethylamino)propan-1-ols 6

As a representative example, the synthesis of 4-(4-methylphenyl)methyl-5-methylmorpholin-2-one **7b** is described here. To a solution of 2-[(4-methylphenyl)methyl]amino]propan-1-ol **6b** (0.72 g, 4 mmol) in THF (30 ml) an aqueous solution of glyoxal (40%, 1.74 g, 3 equiv) was added, and the resulting

mixture was heated for 2.5 h under reflux. The reaction mixture was then poured into water (20 ml) and extracted with  $\text{CH}_2\text{Cl}_2$  (3 x 10 ml). The combined organic layers were dried with anhydrous  $\text{Na}_2\text{SO}_4$ , filtered and evaporated. The crude product was purified by column chromatography on silica gel (petroleum ether–ethyl acetate 7 : 1) in order to obtain an analytically pure sample (0.76 g, 87%).

**4-(4-Methylphenyl)methyl-5-methylmorpholin-2-one 7b.** Yield 87%, yellow liquid,  $R_f$  0.07 (petroleum ether–ethyl acetate 7 : 1).  $^1\text{H}$  NMR (300 MHz,  $\text{CDCl}_3$ ):  $\delta$  1.17 (3H, d,  $J$  = 6.1 Hz); 2.34 (3H, s); 2.82–2.92 (1H, m); 3.11 and 3.43 (2H, 2 x d,  $J$  = 18.2 Hz); 3.27 and 3.88 (2H, 2 x d, 12.9 Hz); 4.09 and 4.34 (2H, 2 x d x d,  $J$  = 11.0, 7.7, 3.6 Hz); 7.09–7.19 (4H, m).  $^{13}\text{C}$  NMR (75 MHz,  $\text{CDCl}_3$ ):  $\delta$  12.4, 21.1, 51.1, 52.5, 57.3, 73.7, 128.8, 129.3, 133.6, 137.3, 168.2. IR (neat,  $\text{cm}^{-1}$ ):  $\nu_{\text{CO}}$  = 1742;  $\nu_{\text{max}}$  = 2923; 1227; 1055; 807. MS (70 eV):  $m/z$  (%): 220 ( $M^+$  + 1, 100). Anal. Calcd for  $\text{C}_{13}\text{H}_{17}\text{NO}_2$ : C 71.21, H 7.81, N 6.39. Found: C 71.47, H 8.06, N 6.27.

**4-(4-Chlorophenyl)methyl-5-methylmorpholin-2-one 7c.** Yield 83%, yellow solid,  $R_f$  0.05 (petroleum ether–ethyl acetate 7 : 1),  $M_p$  = 55.5–58.5 °C.  $^1\text{H}$  NMR (300 MHz,  $\text{CDCl}_3$ ):  $\delta$  1.16 (3H, d,  $J$  = 6.0 Hz); 2.84–2.93 (1H, m); 3.11 and 3.41 (2H, 2 x d,  $J$  = 17.6 Hz); 3.29 and 3.88 (2H, 2 x d, 13.2 Hz); 4.09 and 4.35 (2H, 2 x d x d,  $J$  = 11.0, 7.7, 3.6 Hz); 7.23–7.35 (4H, m).  $^{13}\text{C}$  NMR (75 MHz,  $\text{ref} = \text{CDCl}_3$ ):  $\delta$  12.5, 51.4, 52.6, 57.1, 73.7, 128.8, 130.2, 133.4, 135.6, 168.0. IR (neat,  $\text{cm}^{-1}$ ):  $\nu_{\text{CO}}$  = 1741;  $\nu_{\text{max}}$  = 2969; 1490; 1227; 1056; 810. MS (70 eV):  $m/z$  (%): 240/2 ( $M^+$  + 1, 100). Anal. Calcd for  $\text{C}_{12}\text{H}_{14}\text{ClNO}_2$ : C 60.13, H 5.89, N 5.84. Found: C 60.27, H 6.11, N 5.98.

**4-(4-Methoxyphenyl)methyl-5-methylmorpholin-2-one 7d.** Yield 74%, yellow solid,  $R_f$  0.05 (petroleum ether–ethyl acetate 7 : 1),  $M_p$  = 48.3–51.3 °C.  $^1\text{H}$  NMR (300 MHz,  $\text{CDCl}_3$ ):  $\delta$  1.17 (3H, d,  $J$  = 6.6 Hz); 2.82–2.92 (1H, m); 3.11 and 3.43 (2H, 2 x d,  $J$  = 17.6 Hz); 3.26 and 3.86 (2H, 2 x d,  $J$  = 12.6 Hz); 3.81 (3H, s); 4.09 and 4.34 (2H, 2 x d x d,  $J$  = 11.0, 7.7, 3.3 Hz); 6.84–6.89 and 7.18–7.25 (4H, 2 x m).  $^{13}\text{C}$  NMR (75 MHz,  $\text{CDCl}_3$ ):  $\delta$  12.4, 51.1, 52.4, 55.3, 57.0, 73.7, 114.0, 130.1, 128.6, 161.3, 167.9. IR (neat,  $\text{cm}^{-1}$ ):  $\nu_{\text{CO}}$  = 1739;  $\nu_{\text{max}}$  = 2965; 1511; 1243; 1031; 822. MS (70 eV):  $m/z$  (%): 236 ( $M^+$  + 1, 100). Anal. Calcd for  $\text{C}_{13}\text{H}_{17}\text{NO}_3$ : C 66.36, H 7.28, N 5.95. Found: C 66.31, H 7.24, N 5.88.

#### Synthesis of chiral 5-methylmorpholin-2-ones 10 from chiral 2-aminopropan-1-ols 9

As a representative example, the synthesis of 5(S)-methyl-4-[1(R)-phenylethyl]morpholin-2-one **10a** is described here. To a solution of 2(S)-[1(R)-phenylethylamino]propan-1-ol **9a** (0.72 g, 4 mmol) in THF (30 ml) an aqueous solution of glyoxal (40%, 1.74 g, 3 equiv) was added, and the resulting mixture was heated for 3 h under reflux. The reaction mixture was then poured into water (20 ml) and extracted with  $\text{CH}_2\text{Cl}_2$  (3 x 10 ml). The combined organic layers were dried with anhydrous  $\text{Na}_2\text{SO}_4$ , filtered and evaporated. The crude product was purified by column chromatography on silica gel (hexane–ethyl acetate 3 : 1) in order to obtain an analytically pure sample (0.78 g, 89%).

**5(S)-Methyl-4-[1(R)-phenylethyl]morpholin-2-one 10a.** Yield 89%, light yellow solid,  $R_f$  0.25 (hexane–ethyl acetate 3 : 1),  $M_p$  = 37.1–40.2 °C,  $[\alpha]_{\text{D}}^{28}$  = +25.0 ( $c$  = 0.44,  $\text{CDCl}_3$ ).  $^1\text{H}$  NMR (300 MHz,

CDCl<sub>3</sub>):  $\delta$  1.04 (3H, d,  $J$  = 6.6 Hz); 1.35 (3H, d,  $J$  = 6.8 Hz); 2.82–2.91 (1H, m); 3.38 and 3.74 (2H, 2 x d,  $J$  = 17.9 Hz); 3.66 (1H, q,  $J$  = 6.8 Hz); 4.00 and 4.37 (2H, 2 x d x d,  $J$  = 11.0, 3.3, 3.3 Hz); 7.24–7.34 (5H, m). <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>):  $\delta$  9.0, 21.0, 47.2, 48.3, 60.2, 74.1, 127.3, 127.6, 128.7, 142.7, 168.6. IR (neat, cm<sup>-1</sup>):  $\nu_{\text{CO}}$  = 1737;  $\nu_{\text{max}}$  = 2973; 1224; 1004; 701. MS (70 eV):  $m/z$  (%): 220 ( $M^+$  + 1, 100). Anal. Calcd for C<sub>13</sub>H<sub>17</sub>NO<sub>2</sub>: C 71.21, H 7.81, N 6.39. Found: C 71.27, H 7.93, N 6.33.

**5(R)-Methyl-4-[1(R)-phenylethyl]morpholin-2-one 10b.** Yield 86%, light yellow liquid,  $R_f$  0.18 (hexane–ethyl acetate 3:1), [ $\alpha_D^{28}$  = + 9.6 ( $c$  = 0.37, CDCl<sub>3</sub>). <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>):  $\delta$  1.16 (3H, d,  $J$  = 6.6 Hz); 1.34 (3H, d,  $J$  = 6.6 Hz); 3.11 and 3.28 (2H, 2 x d,  $J$  = 18.2 Hz); 3.26–3.36 (1H, m); 3.74 (1H, q,  $J$  = 6.6 Hz); 4.14 and 4.47 (2H, 2 x d x d,  $J$  = 10.8, 5.2, 3.6 Hz); 7.22–7.39 (5H, m). <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>):  $\delta$  10.6, 16.6, 47.6, 48.3, 59.1, 73.9, 127.38, 127.44, 128.6, 142.8, 168.8. IR (neat, cm<sup>-1</sup>):  $\nu_{\text{CO}}$  = 1740;  $\nu_{\text{max}}$  = 2972; 1206; 1050; 700. MS (70 eV):  $m/z$  (%): 220 ( $M^+$  + 1, 100). Anal. Calcd for C<sub>13</sub>H<sub>17</sub>NO<sub>2</sub>: C 71.21, H 7.81, N 6.39. Found: C 71.01, H 8.00, N 6.52.

#### Synthesis of 1-methoxypropan-2-amines 12 from 1-arylmethyl-2-(methoxymethyl)aziridines 11a and 11b

As a representative example, the synthesis of *N*-(4-methylphenyl)methyl-*N*-(2-methoxy-1-methylethyl)amine **12a** is described here. 1-(4-Methylphenyl)methyl-2-(methoxymethyl)-aziridine **11a** (0.96 g, 5 mmol) was dissolved in dry THF (25 ml), after which LiAlH<sub>4</sub> (0.38 g, 2 molar equiv) was added in small portions at 0 °C. The resulting mixture was then placed in an 80 ml sealed vessel, provided with appropriate stirrer bar and subjected to microwave conditions (130 °C, 250 W<sub>max</sub>, 12 h). Afterwards, the reaction mixture was poured into water (20 ml) and extracted with Et<sub>2</sub>O (3 x 20 ml). Drying (MgSO<sub>4</sub>), filtration of the drying agent and evaporation of the solvent afforded *N*-(4-methylphenyl)methyl-*N*-(2-methoxy-1-methylethyl)amine **12a** (0.27 g, 80%), which was purified by filtration through a silica gel column (dichloromethane–methanol 9:1) in order to obtain an analytically pure sample.

***N*-(4-Methylphenyl)methyl-*N*-(2-methoxy-1-methylethyl)amine 12a.** Yield 80%, light-yellow oil,  $R_f$  0.23 (dichloromethane–methanol 9:1). <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>):  $\delta$  1.06 (3H, d,  $J$  = 6.1 Hz); 2.33 (3H, s); 2.08 (1H, br s); 2.89–2.99 (1H, m); 3.27 and 3.34 (2H, 2 x d x d,  $J$  = 9.4, 7.7, 4.4 Hz); 3.32 (3H, s); 3.69 and 3.86 (2H, 2 x d,  $J$  = 12.9 Hz); 7.12–7.26 (4H, m). <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>):  $\delta$  16.9, 21.1, 50.9, 51.8, 58.9, 77.1, 128.2, 129.1, 136.5, 137.2. IR (neat, cm<sup>-1</sup>):  $\nu_{\text{NH}}$  = 3325;  $\nu_{\text{max}}$  = 2923; 2875; 2826; 1514; 1450; 1373; 1197; 1162; 1106; 805. MS (70 eV):  $m/z$  (%): 194 ( $M^+$  + 1, 100). Anal. Calcd for C<sub>12</sub>H<sub>19</sub>NO: C 74.57, H 9.91, N 7.25. Found: C 74.68, H 9.48, N 7.47.

***N*-(4-Methoxyphenyl)methyl-*N*-(2-methoxy-1-methylethyl)amine 12b.** Yield 60%, dark-yellow oil,  $R_f$  0.21 (dichloromethane–methanol 9:1). <sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>):  $\delta$  1.07 (3H, d,  $J$  = 6.1 Hz); 2.24 (1H, br s); 2.89–2.99 (1H, m); 3.25–3.36 (2H, m); 3.67 and 3.83 (2H, 2 x d,  $J$  = 12.7 Hz); 3.80 (3H, s); 6.85–6.88 (4H, m). <sup>13</sup>C NMR (75 MHz, CDCl<sub>3</sub>):  $\delta$  16.8, 50.7, 51.8, 55.3, 58.8, 77.0, 113.8, 129.4, 132.4, 158.6. IR (neat, cm<sup>-1</sup>):  $\nu_{\text{NH}}$  = 3324;  $\nu_{\text{max}}$  = 2928; 2877; 2832; 1612; 1511; 1462; 1244; 1105; 1035; 822. MS (70 eV):  $m/z$  (%): 210 ( $M^+$  + 1, 100). Anal. Calcd for

C<sub>12</sub>H<sub>19</sub>NO<sub>2</sub>: C 68.87, H 9.15, N 6.69. Found: C 68.61, H 9.48, N 6.47.

#### References

- (a) D. Tanner, *Angew. Chem., Int. Ed. Engl.*, 1994, **33**, 599–619; (b) W. H. Pearson, B. W. Lian and S. C. Bergmeier, in *Comprehensive Heterocyclic chemistry II*, ed. A. Padwa, Pergamon press, New York, 1980, vol. 1A, pp. 1–60; (c) H. M. I. Osborn and J. B. Sweeney, *Tetrahedron: Asymmetry*, 1997, **8**, 1693–1715; (d) W. McCoull and F. A. Davis, *Synthesis*, 2000, 1347–1365; (e) B. Zwanenburg and I. ten Holte, in *Stereoselective Heterocyclic chemistry III*, ed. P. Metz, Springer, Berlin, 2001, pp. 93–124; (f) J. B. Sweeney, *Chem. Soc. Rev.*, 2002, **31**, 247–258; (g) G. S. Singh, M. D'hooghe and N. De Kimpe, *Chem. Rev.*, 2007, **107**, 2080–2135.
- (a) X. E. Hu, *Tetrahedron*, 2004, **60**, 2701–2743; (b) P. Lu, *Tetrahedron*, 2010, **66**, 2549–2560.
- W. K. Lee and H.-J. Ha, *Aldrichimica Acta*, 2003, **36**, 57–63 and references cited therein.
- (a) M. D'hooghe, K. Vervisch, A. Van Nieuwenhove and N. De Kimpe, *Tetrahedron Lett.*, 2007, **48**, 1771–1774; (b) M. D'hooghe, A. Waterinckx, T. Vanlangendonck and N. De Kimpe, *Tetrahedron*, 2006, **62**, 2295–2303.
- T. Katagiri, M. Takahashi, Y. Fujiwara, H. Ihara and K. Uneyama, *J. Org. Chem.*, 1999, **64**, 7323–7329.
- (a) M. D'hooghe, V. Van Speybroeck, M. Waroquier and N. De Kimpe, *Chem. Commun.*, 2006, 1554–1556; (b) M. D'hooghe, V. Van Speybroeck, A. Van Nieuwenhove, M. Waroquier and N. De Kimpe, *J. Org. Chem.*, 2007, **72**, 4733–4740; (c) S. Catak, M. D'hooghe, N. De Kimpe, M. Waroquier and V. Van Speybroeck, *J. Org. Chem.*, 2010, **75**, 885–896.
- Y. Kim, H.-J. Ha, H. Yun, B. K. Lee and W. K. Lee, *Tetrahedron*, 2006, **62**, 8844–8849.
- (a) P. O'Brien and T. D. Towers, *J. Org. Chem.*, 2002, **67**, 304–307; (b) K. Weber, S. Kuklinski and P. Gmeiner, *Org. Lett.*, 2000, **2**, 647–649; (c) A. S. Nagle, R. N. Salvatore, B.-D. Chong and K. W. Jung, *Tetrahedron Lett.*, 2000, **41**, 3011–3014.
- B. A. B. Prasad, G. Sekar and V. K. Singh, *Tetrahedron Lett.*, 2000, **41**, 4677–4679.
- J. M. Concellon and E. Riego, *J. Org. Chem.*, 2003, **68**, 6407–6410.
- I. D. G. Watson and A. K. Yudin, *J. Org. Chem.*, 2003, **68**, 5160–5167.
- N. De Kimpe, R. Verhé, L. De Buyck and N. Schamp, *Bull. Soc. Chim. Belg.*, 1975, **84**, 701–707.
- K. Suzuki, K. Okano, K. Nakai, Y. Terao and M. Sekiya, *Synthesis*, 1983, 723–725.
- M. H. Vilhelmsen, L. F. Ostergaard, M. B. Nielsen and S. Hammerum, *Org. Biomol. Chem.*, 2008, **6**, 1773–1778.
- (a) N. De Kimpe, R. Verhé, L. De Buyck and N. Schamp, *J. Org. Chem.*, 1981, **46**, 2079–2081; (b) N. De Kimpe, R. Verhé, L. De Buyck and N. Schamp, *Bull. Soc. Chim. Belg.*, 1983, **92**, 233–239.
- (a) N. De Kimpe, R. Verhé, L. De Buyck and N. Schamp, *J. Org. Chem.*, 1980, **45**, 5319–5325; (b) N. De Kimpe, R. Verhé, L. De Buyck and N. Schamp, *Recl. Trav. Chim. Pays-Bas*, 1977, **96**, 242–246; (c) N. De Kimpe, N. Schamp and R. Verhé, *Synth. Commun.*, 1975, **5**, 403–408; (d) N. De Kimpe, R. Verhé, L. De Buyck and N. Schamp, *Synth. Commun.*, 1975, **5**, 269–274; (e) N. De Kimpe and D. De Smaele, *Tetrahedron Lett.*, 1994, **35**, 8023–8026; (f) T. Nguyen Van and N. De Kimpe, *Tetrahedron*, 2000, **56**, 7299–7304.
- A. Hassner, Jr. B. A. Belinka, M. Haber and P. Hunger, *Tetrahedron Lett.*, 1981, **22**, 1863–1866.
- (a) K. Kotera, Y. Matsukawa, H. Takahashi, T. Okada and K. Kitahonoki, *Tetrahedron*, 1968, **24**, 6177–6184; (b) K. Kotera, T. Okada and S. Miyazaki, *Tetrahedron*, 1968, **24**, 5677–5690; (c) K. Kitahonoki, Y. Takano and H. Takahashi, *Tetrahedron*, 1968, **24**, 4605–4623; (d) K. Kotera, S. Miyazaki, H. Miyazaki, T. Okada and K. Kitahonoki, *Tetrahedron*, 1968, **24**, 3681–3696; (e) K. Kotera, M. Motomura, S. Miyazaki, T. Okada and Y. Matsukawa, *Tetrahedron*, 1968, **24**, 1727–1735.
- (a) F. Palacios, A. M. O. De Retana and J. I. Gil, *Tetrahedron Lett.*, 2000, **41**, 5363–5366; (b) F. Palacios, A. M. O. De Retana, J. I. Gil and J. M. Ezpeleta, *J. Org. Chem.*, 2000, **65**, 3213–3217.
- S. Y. Yun, S. Catak, W. K. Lee, M. D'hooghe, N. De Kimpe, V. Van Speybroeck, M. Waroquier, Y. Kim and H.-J. Ha, *Chem. Commun.*, 2009, 2508–2510.



- 21 J. L. Pierre, H. Handel and P. Baret, *Tetrahedron*, 1974, **30**, 3213–3223.
- 22 P. Baret, P. M. Bourgeois, C. Gey and J. L. Pierre, *Tetrahedron*, 1979, **35**, 189–196.
- 23 J. M. Concellón, J. R. Suárez, S. García-Granda and M. R. Díaz, *Angew. Chem., Int. Ed.*, 2004, **43**, 4333–4336.
- 24 L. Yu, A. Kokai and A. K. Yudin, *J. Org. Chem.*, 2007, **72**, 1737–1741.
- 25 (a) N. De Kimpe, R. Jolie and D. De Smaele, *J. Chem. Soc., Chem. Commun.*, 1994, 1221–1222; (b) N. De Kimpe, D. De Smaele and Z. Szakonyi, *J. Org. Chem.*, 1997, **62**, 2448–2452; (c) M. D'hooghe, A. Waterinckx and N. De Kimpe, *J. Org. Chem.*, 2005, **70**, 227–232; (d) M. D'hooghe, M. Rottiers, R. Jolie and N. De Kimpe, *Synlett*, 2005, 931–934.
- 26 M. D'hooghe and N. De Kimpe, *Chem. Commun.*, 2007, 1275–1277.
- 27 M. D'hooghe, W. Van Brabant and N. De Kimpe, *J. Org. Chem.*, 2004, **69**, 2703–2710.
- 28 M. D'hooghe, W. Van Brabant and N. De Kimpe, *Tetrahedron*, 2003, **59**, 5383–5386.
- 29 (a) C. O. Welder and E. C. Ashby, *J. Org. Chem.*, 1997, **62**, 4829–4833; (b) M. D'hooghe, S. Dekeukeleire and N. De Kimpe, *Org. Biomol. Chem.*, 2008, **6**, 1190–1196.
- 30 (a) J. R. Pfister, *Synthesis*, 1984, 969–970; (b) S. Boivin, F. Outurquin and C. Paulmier, *Tetrahedron Lett.*, 2000, **41**, 663–666; (c) C. Miniejew, F. Outurquin and X. Pannecoucke, *Org. Biomol. Chem.*, 2004, **2**, 1575–1576; (d) J. L. Vicario, D. Badia and L. Carillo, *Arkivoc*, 2007, **4**, 304–311.
- 31 Y.-C. Jeong, Y. D. Huang, S. Choi and K.-H. Ahn, *Tetrahedron: Asymmetry*, 2005, **16**, 3497–3501.
- 32 G.-I. Hwang, J. H. Chung and W. K. Lee, *J. Org. Chem.*, 1996, **61**, 6183–6188.
- 33 (a) E. G. Mesropyan, A. A. Avetisyan and A. S. Galstyan, *Russ. J. Org. Chem.*, 2007, **43**, 1176–1179; (b) B. Olofsson and P. Somfai, *J. Org. Chem.*, 2002, **67**, 8574–8583.
- 34 S. C. Bergmeier, *Tetrahedron*, 2000, **56**, 2561–2576.
- 35 M. Karpf and R. J. Trussardi, *J. Org. Chem.*, 2001, **66**, 2044–2051.
- 36 T. Inaba, Y. Yamada, H. Abe, S. Sagawa and H. Cho, *J. Org. Chem.*, 2000, **65**, 1623–1628.
- 37 H.-J. Cristau, J.-L. Pirat, M. Drag and P. Kafarski, *Tetrahedron Lett.*, 2000, **41**, 9781–9785.
- 38 F. Bennet, N. M. Patel, V. M. Girijavallabhan and A. K. Ganguly, *Synlett*, 1993, 703–704.
- 39 T. J. Tucker, W. C. Lumma, L. S. Payne, J. M. Wai, S. J. De Solms, F. A. Giuliani, P. L. Darke, J. C. Heimbach, J. A. Zugay, W. A. Schleif and J. C. Quinero, *J. Med. Chem.*, 1992, **35**, 2525–2533.
- 40 D. Bell, M. R. Davies, F. J. L. Finney, G. R. Geen, P. M. Kinsey and I. S. Mann, *Tetrahedron Lett.*, 1996, **37**, 3895–3898.
- 41 (a) C. T. Gnewuch and G. Sosnovsky, *Chem. Rev.*, 1997, **97**, 829–1014; (b) T.-X. Métro, B. Duthion, D. G. Pardo and J. Cossy, *Chem. Soc. Rev.*, 2010, **39**, 89–102.
- 42 T. Hudlicky, K. F. Abbod, D. A. Entwistle, R. Fan, R. Maurya, A. J. Thorpe, J. Bolonick and B. Myers, *Synthesis*, 1996, 897–911.
- 43 G. Sabitha, R. S. Babu, M. Rajkumar and J. S. Yadav, *Org. Lett.*, 2002, **4**, 343–345.
- 44 M. E. Maier, F. Bobe and A. J. Niestroj, *Eur. J. Org. Chem.*, 1999, 1–13.
- 45 A. V. Malkov, M. A. Kabeshov, M. Bella, O. Kysilka, D. Malyshev, K. Pluhackova and P. Kocovski, *Org. Lett.*, 2007, **9**, 5473–5476.
- 46 M. Sosa-Rivadeneira, L. Quintero, C. A. De Parrodi, S. Bernès, E. Castellanos and E. Juaristi, *Arkivoc*, 2003, **11**, 61–71.
- 47 (a) R. Chinchilla, L. R. Falvello, N. Galindo and C. Nájera, *J. Org. Chem.*, 2000, **65**, 3034–3041; (b) C. Agami, F. Couty and C. Puchot-Kaudori, *Synlett*, 1998, 449–456.
- 48 (a) P. R. Jain and R. M. Williams, *J. Org. Chem.*, 2002, **67**, 6361; (b) P. R. Jain, B. K. Albrecht, D. E. De Mong and R. M. Williams, *Org. Lett.*, 2001, **3**, 4287–4289; (c) C. Agami, S. Comesse and C. Kadouri-Puchot, *J. Org. Chem.*, 2000, **65**, 4435–4439.
- 49 Y. Lim and W. K. Lee, *Tetrahedron Lett.*, 1995, **36**, 8431–8434.
- 50 S.-K. Choi, J.-S. Lee and W. K. Lee, *J. Org. Chem.*, 1997, **62**, 743–745.
- 51 J. M. Yun, T. B. Sim, H. S. Hahm and W. K. Lee, *J. Org. Chem.*, 2003, **68**, 7675–7680.
- 52 H. G. Park, H. G. Choi, H. Lee, W. K. Lee and H.-J. Ha, *Tetrahedron: Asymmetry*, 2000, **11**, 3283–3292.
- 53 K. Higashiyama, M. Matsumura, H. Kojima and T. Yamauchi, *Heterocycles*, 2009, **78**, 471–485.
- 54 (a) M. D'hooghe and N. De Kimpe, *Synlett*, 2004, 271–274; (b) M. D'hooghe and N. De Kimpe, *Arkivoc*, 2008, **9**, 6–19.