# A Cross Metathesis Based Protocol for the Effective Synthesis of Functionalised Allyl Bromides and Chlorides

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Abstract: Functionalised allyl halides, useful starting materials for the preparation of substituted organometallic reagents can be simply obtained by a straightforward approach. Hoveyda's ruthenium carbene catalyst 3, used in catalytic amount (2 mol%), is able to promote the cross metathesis of allyl bromide and chloride with a variety of different substituted olefins giving the corresponding functionalised allyl halides in satisfactory yields. trans-Olefins are obtained as major diastereoisomers reaching 90:10 (trans:cis) ratio when allyl chloride is used as the metathesis partner. This reaction represents a simple and accessible way for the preparation of valuable precursors for functionalised organometallic reagents. In particular, the use of functionalised allyl bromides (10b and 13) in the enantioselective Nozaki–Hiyama reaction promoted bv [Cr(Salen)Cl] is presented.

**Key words:** allyl halides, cross metathesis, ruthenium catalyst, functionalised olefins

In recent years olefin metathesis has become a valuable synthetic tool in the field of organic chemistry. The introduction of definite transition metal catalysts such as the ruthenium benzylidene  $1^1$  and the highly oxophilic Mo catalysts  $5^2$  (Figure 1) has considerably expanded the scope of reaction.



**Figure 1** Organometallic complexes as catalysts for cross metathesis (CM).

Of particular relevance is the olefin cross metathesis (CM) that has emerged as a powerful synthetic shortcut for the synthesis of functionalised acyclic structures. Later, by introducing the 1,3-dimesityl-4,5-dihydroimidazol-2-ylidene ligand into the ruthenium complexes, Grubbs and

SYNTHESIS 2004, No. 3, pp 0409–0414 Advanced online publication: 26.01.2004 DOI: 10.1055/s-2004-815936; Art ID: Z17003SS.pdf © Georg Thieme Verlag Stuttgart · New York Hoveyda developed highly active and stable CM catalysts  $\mathbf{2}^3$  and  $\mathbf{3}^4$ 

Catalysts 2 and 3 can be employed in the presence of a variety of functional groups as they have showed a functional group tolerance characteristic of the catalyst 1. For instance, tri-substituted alkenes, common structural subunits in natural products, can be successfully prepared with the catalyst 3.<sup>4</sup> Moreover highly active organometallic cross metathesis catalysts have been used in the synthesis of small molecules containing a wide range of functional groups including styrenes,<sup>5</sup> sulfones,<sup>6</sup> alkenyl oxiranes,<sup>7</sup> allyl silanes,<sup>8</sup> fluorinated olefins<sup>9</sup> and  $\alpha,\beta$ -unsaturated nitriles.<sup>10</sup> Again, catalyst 3 has been used in key step for total synthesis of natural products.<sup>11</sup>

Moreover, the unprecedented catalytic activity of complexes 2 and 3 was employed in the presence of conjugated electron deficient olefins because the dimerisation rate of  $\alpha$ , $\beta$ -unsaturated carbonyl compounds is negligible.<sup>12</sup>

During our studies focused on catalytic redox allylation reactions of aldehydes mediated by [Cr(Salen)] complexes,<sup>13</sup> we decided to explore the reactivity of functionalised allyl halides in our protocol. To this purpose, we took into account the cross metathesis as a suitable and direct methodology for the preparation of functionalised allyl halides.

To our surprise we found out that olefin cross metathesis of allyl halides was scarcely studied and only few examples were reported.<sup>14</sup> In particular, Castedo and Blanco found that allyl benzene could react with allyl bromides in the presence of 1,<sup>15</sup> while Roy and co-workers have described the coupling of allyl halides with the Grubbs's catalysts 1 and 2 in a general approach to glycosides.<sup>16</sup> However a systematic and comprehensive study involving different olefins has never been reported to date. Herein we describe the application of the CM strategy to the one-pot preparation of functionalised allyl halides employing Hoveyda's catalyst 3 as the promoting agent.

In our initial approach, the functionalised allyl bromides were synthesised in three steps, as indicated in Scheme 1. Reaction of aldehydes **6a–c** with ylide **7**<sup>17</sup>afforded the esters **8a–c** as the *E* diastereoisomers in good yields (87– 91%). A straightforward reduction with DIBALH in toluene gave the allylic alcohols **9a–c**, which were transformed into the desired allyl bromides **10a–c** by treatment with PBr<sub>3</sub> in moderate to good yields. The overall procedure was simple to perform although three steps and fol-



Scheme 1 Synthesis of functionalised allyl bromides in three steps reactions.

lowing purifications were necessary in order to obtain the desired allyl bromides in good chemical purity.

So we decided to explore the alternative strategy taking into consideration the metathesis reaction. According to this aim, Grubbs catalysts 1 and 2, Hoveyda's catalyst 3 and the Ciba catalyst  $4^{18}$  were tested in the CM reaction between allyl bromide (12a) and olefin 11a as the model reaction (Scheme 2). After a brief survey of experimental conditions (solvent temperature, loading of catalyst) complex 3 proved to be highly active in catalysing this reaction. On the other hand, no activity was observed for catalyst 1 while 4 was able to perform the metathesis to some extents but rapidly decomposed under the reaction conditions employed.



Scheme 2 CM of allyl bromides with functionalised alkenes.

By choosing  $CH_2Cl_2$  as the solvent, complex 3 (2 mol%) allowed functionalised allyl bromides to be effectively prepared starting from a 1:2 olefin-allyl bromide ratio (Table 1). A large excess of olefin as well as the use of 4– 5 equivalents of **12a** did not improve the yields; the homocoupling of allyl bromide becoming the main product. This is a consequence of the fact that CM of olefins is essentially a competition between three different reaction pathways: the selective cross metathesis and the dimerisations of each starting materials.<sup>12,19</sup> Functionalised allyl bromides were isolated as inseparable mixture of E:Z diastereoisomers (75:25-86:14) and a variety of functional groups (CN, COOR, OSiR<sub>3</sub>, OBn, COR, OH) were well tolerated. The yields were satisfactory and the functionalised allyl bromides were purified by chromatography (Table 1, entries 1-8).

**Table 1**CM Reaction Between Functionalised Olefins and Allyl<br/>Halides Catalysed by  $\mathbf{3}^{a}$ 

Entry	Allyl halide	Olefin	Product	Yield (%) <sup>b</sup>	$E:Z^{c}$
1	12a	11a	13a	35	76:24
2	12a	11b	10b	58	86:14
3	12a	11c	13c	49	78:22
4	12a	11d	13d	46	80:20
5	12a	11e	13e	30	83:17
6	12a	11f	13f	37	83:17
7	12a	11g	13g	51	85:15
8	12a	11h	13h	39	75:25
9	12b	11a	14a	39	95:5
10	12b	11b	14b	65	89:11
11	12b	11d	14d	49	93:7

 $^{\rm a}$  All the reactions were carried out in anhyd  $\rm CH_2Cl_2$  by using 2 mol% of catalyst.

<sup>b</sup> Isolated yield after chromatographic purification.

The reaction appeared more stereoselective when allyl chloride (**12b**) was employed. In fact, by reacting allyl chloride and substituted alkenes in the presence of catalyst **3**, the corresponding functionalised allyl chloride was isolated as a mixture of diasteroisomers (89:11–95:5) in yields ranging between 39–65% (Table 1, entries 9–12).

The isolated allyl bromides and chlorides could be exploited in the preparation of highly functionalised organometallic reagents.<sup>20</sup> In this context, Grubbs<sup>14b</sup> and Miyaura<sup>21</sup> recently reported on the use of CM to obtain functionalised allylating boron reagents. Miyaura also reported that the protocol could be used with chiral allylboranes achieving the desired homoallylic alcohols in good enantiomeric excesses (up to 82% ee).

A major problem in the synthesis of organometallic reagent precursors via CM reaction is the poor diastereoselection frequently encountered in the preparation of the stereogenic allyl halide precursors. However, chromium organometallic reagents are peculiar in this aspect; in fact, the high *anti* diastereoselection obtained in the chromiummediated allylation of aldehydes is generally independent of the Z/E ratio of the stereogenic allyl halide.<sup>22</sup>

We recently reported the first catalytic enantioselective Nozaki–Hiyama (NH) addition of crotyl bromide<sup>23</sup> and 1,3-dichloropropene<sup>24</sup> to aromatic aldehydes in the presence of [Cr(Salen)] complexes in which the simple diaste-reoselection can be easily modulated through the amount of chiral ligand employed. In particular, the use of a 1:2 ratio of chromium–Salen and Mn as the stoichiometric reductant allows the homoallylic alcohols to be isolated with good *syn* diastereoselection and high enantioselectivity. A few representative functionalised allyl bromides,



Scheme 3 Stereoselective Nozaki–Hiyama reaction catalysed by [Cr(Salen)] with functionalised allyl bromides.

obtained via the present metathesis strategy (10b, 13a), were reacted with benzaldeyde in the presence of [Cr(Salen)Cl] (10 mol%) and 10 mol% of the free Salen ligand (Scheme 3).<sup>25</sup>

The corresponding homoallylic alcohols (**15a,b**) were isolated after de-silylation and flash chromatographic purification in moderate yields and good diastereoselectivity (up to 83:17 *syn*) and enantioselectivity (ee up to 81%). The absolute configuration of the isolated products were assigned by analogy considering the general trend obtained in the reaction of aldehydes promoted by [Cr(Salen)Cl] with crotyl bromides.<sup>23–25</sup>

Although not optimised, these preliminary results clearly showed the functional group tolerance of our catalytic protocol in the enantioselective addition of functionalised allyl bromides to aldehydes.

In conclusion, we have presented a new valuable methodology for the preparation of functionalised allyl bromides and chlorides through CM. The desired functionalised allyl halides were obtained one-pot in satisfactory yields by using the catalyst **3** (2 mol%) and various functionalised olefins. Although the yield of the cross metathesis of allyl halides are only moderate and more active and selective catalysts still need to be found,<sup>26</sup> these results are of general interest for the preparation of useful starting materials for highly functionalised organometallic reagents.

Anhydrous Et<sub>2</sub>O, THF and CH<sub>2</sub>Cl<sub>2</sub> were supplied by Fluka in Sureseal® bottles and were used without any further purification. <sup>1</sup>H NMR spectra were recorded on Varian 200 (200 MHz) or Varian 300 (300 MHz) spectrometers. Chemical shifts are reported in ppm from TMS with the solvent resonance as the internal standard (CDCl<sub>3</sub>:  $\delta$  = 7.27 ppm). Data are reported as follows: chemical shift, multiplicity (s = singlet, d = duplet, t = triplet, q = quartet, br = broad, m = multiplet), coupling constants (Hz). <sup>13</sup>C NMR spectra were recorded on a Varian 200 (50 MHz) or Varian 300 (75 MHz) spectrometers with complete proton decoupling. Chemical shifts are reported in ppm from TMS with the solvent as the internal standard (CDCl<sub>3</sub>:  $\delta = 77.0$  ppm). Mass spectra were recorded at an ionising voltage of 70 eV. Chromatographic purification was done with 240-400 mesh silica gel. Analytical GC was performed on a Hewlett-Packard HP 6890 gas chromatograph with a flame ionisation detector and split mode capillary injection system, using a Crosslinked 5% PH ME Siloxane (30 m) column or a Megadex-5 chiral (25 m) column (flow rate 15 mL/min, method: 50 °C for 2 min, ramp @ 10 °C/min to 250 °C for 15 min). Analytical HPLC was performed on a HP 1090 liquid chromatograph equipped with a variable wavelength UV detector (deuterium lamp 190-600 nm) and using a Daicel Chiralcel<sup>TM</sup> OD column (0.46 cm I.D. × 25 cm) (Daicel Inc.). HPLC grade *i*-PrOH and *n*-hexane were used as the eluting solvents. Elemental analyses were carried out by using a EACE 1110 CHNOS analyzer. All the reactions were carried out under a  $N_2$  atmosphere in flame-dried glassware using standard inert techniques for introducing reagents and solvents. All the commercially available reagents were used without further purification (CrCl<sub>3</sub>: sublimed 99%, Aldrich; Mn powder: 99.9%, -50 mesh, Aldrich).

Cross Metathesis Reactions Catalysed by 3; General Procedure In a two-necked flask, catalyst 3 (0.02 mmol) was dissolved in  $CH_2Cl_2$  (2 mL) and the resulting solution was stirred under N<sub>2</sub> at r.t. for 10 min. A separately prepared mixture of olefin (1 mmol) and the allyl halide (2 mmol) were added to the solution of the catalyst. The reaction mixture was stirred for 3–8 h at r.t. and the consumption of the olefin was checked by TLC or GC–MS. The solvent was evaporated under reduced pressure and the resulting black oil was purified by flash chromatography.

### 13a

Yield: 35% (*E*/*Z*, 76:24); pale yellow oil.

IR (neat): 3026 (w), 2959 (s), 2881 (m), 2860 (s), 1641 (s), 1472 (m), 1363 (w), 1160 (s), 960 (s), 730 (s), 691 (s)  $cm^{-1}$ .

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>): δ (*E*-diastereoisomer) = 0.08 (s, 6 H), 0.92 (s, 9 H), 3.98 (dd,  $J_1$  = 1.0 Hz,  $J_2$  = 6.6 Hz, 2 H), 4.19–4.22 (m, 2 H), 5.85–5.93 (m, 2 H), <sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>): δ (*E*-diastereoisomer) = -2.9, 25.8, 26.8, 44.5, 62.8, 127.2, 134.1.

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>):  $\delta$  (Z-diastereoisomer) = 27.0.

MS: m/z (%) = 266 (1), 264 (1), 251 (1), 209 (70), 207 (90), 165 (19), 139 (100), 137 (100), 127 (78) 113 (15), 89 (28), 73 (51), 57 (48).

Anal. Calcd for  $C_{10}H_{21}BrOSi$ : C, 45.28; H, 7.98. Found: C, 45.22; H, 7.91.

#### 10b

Yield: 58% (E/Z, 86:14); pale yellow oil.

IR (neat): 3065 (w), 3038 (m), 2926 (m), 2853 (s), 1660 (w), 1447 (m), 1427 (w), 1361 (m), 1195 (s), 1096 (s), 963 (m), 738 (s), 691 (s) cm<sup>-1</sup>.

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>): δ (*E*-diastereoisomer) = 2.35-2.50 (m, 2 H), 3.95-3.99 (m, 2 H), 4.54 (s, 2 H), 5.77-5.86 (m, 1 H), 5.95-6.04 (m, 1 H), 7.29-7.42 (m, 5 H).

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>):  $\delta$  (Z-diastereoisomer) = 4.02–4.04 (m, 2 H).

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>): δ (*E*-diastereoisomer) = 40.5, 69.2, 72.9, 127.5, 128.0, 128.3, 130.7, 132.6, 138.2.

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>):  $\delta$  (Z-diastereoisomer) = 69.6.

MS: *m/z* (%) = 175 (15), 145 (6), 121 (3), 107 (9), 91 (100), 65 (28), 51 (11).

Anal. Calcd for  $C_{11}H_{13}BrO: C$ , 54.79; H, 5.43. Found: C, 54.71; H, 5.38.

## 13c

Yield: 49% (*E*/*Z*, 78:22); pale yellow oil.

IR (neat): 3065 (w), 2959 (w), 2919 (m), 2853 (w), 1712 (s), 1600 (m), 1454 (s), 1275 (s), 1109 (s), 963 (s), 904 (m), 711 (s) cm<sup>-1</sup>.

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>): δ (*E*-diastereoisomer) = 2.43–2.61 (m, 2 H), 3.90–3.98 (m, 2 H), 4.34–4.41 (m, 2 H), 5.80–5.90 (m, 2 H), 7.38–7.50 (m, 2 H), 7.98–8.10 (m, 2 H), 7.50–7.58 (m, 1 H).

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>):  $\delta$  (Z-diastereoisomer) = 4.01–4.08 (m, 2 H), 4.21–4.30 (m, 2 H).

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>): δ (*E*-diastereoisomer) = 31.6, 32.6, 63.6, 128.3, 129.1, 129.5, 130.1, 131.2, 132.9, 166.4.

MS: *m*/*z* (%) = 189 (19), 148 (3), 146 (3), 123 (4), 105 (88), 77 (59), 67 (100), 51 (30).

Anal. Calcd for  $C_{12}H_{13}BrO_2$ : C, 44.00; H, 5.80. Found: C, 43.95; H, 5.75.

## 13d

Yield: 46% (*E*/*Z*, 80:20); pale yellow oil.

IR (neat): 2999 (w), 2972 (m), 2912 (m), 2846 (w), 1712 (s), 1659 (w), 1427 (m), 1368 (s), 1202 (s), 1162 (s), 970 (s), 725 (w) cm<sup>-1</sup>.

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>):  $\delta$  (*E*-diastereoisomer) = 2.16 (s, 3 H), 2.33–2.39 (m, 2 H), 2.51–2.59 (m, 2 H), 3.93 (d, *J* = 6.6 Hz, 2 H), 5.68–5.81 (m, 2 H).

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>):  $\delta$  (*Z*-diastereoisomer) = 4.02 (d, *J* = 8.2 Hz, 2 H), 2.17 (s, 3 H).

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>): δ (*E*-diastereoisomer) = 25.9, 29.8, 32.9, 42.3, 127.0, 134.2, 207.

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>):  $\delta$  (Z-diastereoisomer) = 26.7, 126.1, 133.5.

MS: *m*/*z* (%) = 135 (3), 133(3), 111 (100), 93 (34), 81 (6), 67 (42), 53 (44).

Anal. Calcd for  $C_7H_{11}BrO$ : C, 56.94; H, 5.18. Found: C, 56.88; H, 5.14.

### 13e

Yield: 30% (*E*/*Z*, 83:17); pale yellow oil.

IR (neat): 3032 (w), 2932 (s), 2859 (m), 2249 (m), 1653 (w), 1460 (m), 1421 (m), 1202 (s), 963 (s), 910 (w), 738 (m) cm<sup>-1</sup>.

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>): δ (*E*-diastereoisomer) = 1.56-1.68 (m, 4 H), 2.12-2.15 (m, 2 H), 2.36 (t, *J* = 7.0 Hz, 2 H), 3.93-3.96 (m, 2 H), 5.71-5.76 (m, 2 H),.

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>):  $\delta$  (Z-diastereoisomer) = 2.33–2.41 (m, 2 H), 3.98–4.03 (m, 2 H).

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>): δ (*E*-diastereoisomer) = 17.1, 24.7, 27.7, 31.1, 33.0, 119.5, 127.3, 134.8.

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>):  $\delta$  (Z-diastereoisomer) = 132.8, 135.2.

MS: *m*/*z* (%) = 203 (1), 201 (1), 175 (1), 135 (3), 122 (73), 105 (10), 94 (16), 81 (100), 67 (31), 53 (62).

Anal. Calcd for  $C_8H_{12}BrN$ : C, 47.55; H, 5.99; N, 6.93. Found: C, 47.50; H, 5.94, N, 6.92.

### 13f

Yield: 37% (E/Z, 83:17); pale yellow oil.

IR (neat): 3314 (br), 3025 (m), 2944 (s), 2878 (s), 1709 (m), 1661 (w), 1434 (m), 1369 (w), 1205 (s), 1044 (s), 967 (s), 750 (w), 725 (w) cm<sup>-1</sup>.

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>):  $\delta$  (*E*-diastereoisomer) = 2.31–2.40 (m, 2 H), 3.70 (t, *J* = 6.2 Hz, 2 H), 3.96 (dd, *J*<sub>1</sub> = 0.8 Hz, *J*<sub>2</sub> = 5.8 Hz, 2 H), 5.78–5.85 (m, 2 H).

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>):  $\delta$  (Z-diastereoisomer) = 3.73 (t, J = 6.2 Hz, 2 H), 4.03 (d, J = 8.0 Hz, 2 H).

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>):  $\delta$  (*E*-diastereoisomer) = 32.8, 35.3, 61.6, 129.0, 132.1.

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>):  $\delta$  (Z-diastereoisomer) = 128.0, 131.3.

MS: *m*/*z* (%) = 166 (2), 164 (2), 146 (10), 133 (6), 119 (5), 107 (5), 95 (5), 85 (43), 67 (48), 54 (100).

Anal. Calcd for  $C_5H_9BrO:$  C, 36.39; H, 5.50. Found: C, 36.35; H, 5.45.

## 13g

Yield: 51% (*E*/*Z*, 85:15); pale yellow oil.

IR (neat): 2952 (w), 2952 (m), 2853 (w), 1732 (s), 1659 (w), 1434 (s), 1367 (m), 1255 (s), 1202 (s), 1162 (s), 963 (m), 857 (w) cm<sup>-1</sup>.

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>): δ (*E*-diastereoisomer) = 1.88-2.03 (m, 2 H), 2.16-2.30 (m, 2 H), 3.38-3.47 (m, 2 H), 3.94-3.96 (m, 2 H), 5.43-5.46 (m, 1 H), 5.73-5.79 (m, 1 H).

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>):  $\delta$  (*Z*-diastereoisomer) = 4.02 (d, *J* = 8.0 Hz, 2 H).

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>): δ (*E*-diastereoisomer) = 30.4, 31.6, 32.3, 32.5, 127.8, 134.0.

 $^{13}$ C NMR (50 MHz, CDCl<sub>3</sub>):  $\delta$  [Z-diastereoisomer (diagnostic signals)] = 30.8, 33.3, 129.7.

MS: *m*/*z* (%) = 163 (27), 161 (33), 150 (36), 95 (35), 81 (100), 67 (47), 59 (35), 53 (36), 51(36).

Anal. Calcd for  $C_6H_{10}Br_2$ : C, 29.78; H, 4.17. Found: C, 29.71; H, 4.13.

### 13h

Yield: 39% (E:Z, 75:25); pale yellow oil.

IR (neat): 3038 (w), 2939 (w), 2853 (w), 1719 (m), 1660 (m), 1520 (s), 1507 (s), 1301 (m), 1268 (m), 1202 (m), 1116 (s), 996 (s), 957 (s), 725 (w) cm<sup>-1</sup>.

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>): δ (*E*-diastereoisomer) = 3.39–3.48 (m, 2 H), 3.90–3.93 (m, 2 H), 5.76–5.86 (m, 2 H).

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>): δ (Z-diastereoisomer) = 3.39–3.40 (m, 2 H), 3.96–3.98 (m, 2 H), 5.55–5.64 (m, 2 H).

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>):  $\delta$  (*E*-diastereoisomer) = 30.8, 33.2, 112.6 (m), 117.3, 130.8, 135.9 (m), 139.2 (m), 143.1 (m), 146.6 (m).

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>):  $\delta$  (Z-diastereoisomer) = 118.2.

MS: *m*/*z* (%) = 302 (1), 300 (1), 221 (65), 201 (12), 181 (100), 151 (23), 143 (8), 117 (8), 105 (34), 77 (20), 54 (26).

Anal. Calcd for  $C_{10}H_6BrF_5$ : C, 39.90; H, 2.01. Found: C, 39.85; H, 1.99.

### 14a

Yield: 39% (E:Z, 95:5); pale yellow oil.

IR (neat): 3025 (w), 2959 (s), 2926 (s), 2880 (m), 2859 (s), 1665 (w), 1467 (m), 1129 (s), 1049 (m), 957 (m), 837 (s), 771 (s), 678 (m) cm<sup>-1</sup>.

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>):  $\delta$  (*E*-diastereoisomer) = 0.09 (s, 6 H), 0.92 (s, 9 H), 4.06–4.11 (m, 2 H), 4.18–4.22 (m, 2 H), 5.84–5.90 (m, 2 H).

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>)  $\delta$  (Z-diastereoisomer) = 4.28–4.33 (m, 2 H).

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>):  $\delta$  (*E*-diastereoisomer) = -5.2, 25.9, 29.7, 44.7, 62.6, 125.3, 134.1.

MS: *m*/*z* (%) = 220 (1), 205 (1), 185 (3), 163 (45), 149 (2), 127 (54), 113 (5), 93 (100), 73 (20), 57 (7).

Anal. Calcd for  $C_{10}H_{21}$ ClOSi: C, 54.39; H, 9.59. Found: C, 54.31; H, 9.50.

## 14b

Yield: 65% (E:Z, 89:11); pale yellow oil.

IR (neat): 3086 (w), 3058 (w), 3038 (m), 2926 (m), 2853 (s), 1666 (w), 1460 (m), 1354 (m), 1255 (m), 1102 (s), 970 (s), 731 (s), 698 (s) cm<sup>-1</sup>.

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>):  $\delta$  (*E*-diastereoisomer) = 2.35–2.48 (m, 2 H), 4.05 (d, *J* = 6.6 Hz, 2 H), 4.53 (s, 2 H), 5.67–5.87 (m, 2 H), 7.29–7.40 (m, 5 H).

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>): δ (Z-diastereoisomer) = 4.12 (d, J = 6.6 Hz, 2 H) 4.58 (s, 2 H).

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>): δ (*E*-diastereoisomer) = 45.2, 69.2, 72.9, 127.5, 127.6, 128.0, 128.3, 132.2, 138.1.

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>):  $\delta$  (Z-diastereoisomer) = 72.0, 127.0, 131.2.

MS: *m*/*z* (%) = 210 (1), 175 (17), 126 (3), 107 (3), 91 (100), 77 (3), 65 (7).

Anal. Calcd for C<sub>11</sub>H<sub>13</sub>ClO: C, 67.18; H, 6.66. Found: C, 67.05; H, 6.60.

## 14d

Yield: 49% (*E*:*Z*, 93:7); pale yellow oil.

IR (neat): 3000 (w), 2952 (m), 2919 (m), 2860 (w), 1712 (s), 1659 (w), 1427 (m), 1361 (m), 1255 (m), 1162 (m), 963 (m), 930 (w), 740 (w), 671 (m) cm<sup>-1</sup>.

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>):  $\delta$  (*E*-diastereoisomer) = 2.16 (s, 3 H), 2.27–2.42 (m, 2 H), 2.51–2.58 (m, 2 H), 4.01 (d, *J* = 6.6 Hz, 2 H), 5.70–5.86 (m, 2 H).

<sup>1</sup>H NMR (200 MHz, CDCl<sub>3</sub>):  $\delta$  (Z-diastereoisomer) = 2.17 (s, 3 H), 4.12 (d, J = 7.2 Hz, 2 H).

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>): δ (*E*-diastereoisomer) = 26.0, 30.0, 42.5, 45.1, 126.8, 133.9, 207.5.

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>):  $\delta$  (Z-diastereoisomer) = 126.2, 133.2.

MS: *m*/*z* (%) = 146 (1), 129 (1), 111 (100), 97 (6), 93 (21), 88 (4), 75 (8), 67 (48), 53 (31).

Anal. Calcd for  $C_7H_{11}$ ClO: C, 57.34; H, 7.56. Found: C, 57.28; H, 7.50.

## Addition of Functionalised Allyl Bromides to Benzaldehyde Mediated by [Cr(Salen)] Complex; General Procedure

CrCl<sub>3</sub> (0.016 g, 0.1 mmol) was suspended in anhyd CH<sub>3</sub>CN to which Mn powder (0.16 g, 3 mmol) was added. The mixture was kept at r.t. without stirring for 5–8 min. After that, the mixture was vigorously stirred until a green-white precipitate was formed (10–15 min.). Then Salen (0.11 g, 0.2 mmol) and anhyd Et<sub>3</sub>N (0.028 mL, 0.2 mmol) were added. The resulting heterogeneous mixture was stirred at r.t. for 1 h, then the functionalised allyl bromide (**13a** or **10b**, 1.5 mmol) was added. The colour of the mixture turned maroon-red and the resulting suspension was stirred for 1 h at r.t. After that time benzaldehyde (1 mmol) and Me<sub>3</sub>SiCl (1.5 mmol) were added to the reaction mixture. The mixture was stirred until complete consumption of the aldehyde (checked by GC, 48 h). The reaction mixture was quenched with a sat. solution of NaHCO<sub>3</sub> (5 mL) and filtered over celite<sup>®</sup>. The organic phase was separated and the aq phase was extracted with Et<sub>2</sub>O (2×4 mL). The combined organ-

ic phases were combined and evaporated under reduced pressure. The resulting brown oil was dissolved in THF (2 mL) and 2 N HCl (2 mL) was added. The reaction mixture was stirred at r.t. until complete desilylation (checked by TLC, 2–4 h). THF was evaporated under reduced pressure and the aq phase was extracted with Et<sub>2</sub>O (2 × 4 mL). The organic layers were dried over Na<sub>2</sub>SO<sub>4</sub> and evaporated under reduced pressure to give an oil which was further purified by chromatography.

## 15a

Yield: 28% (*syn:anti* 76.24, dr was evaluated by GC analysis on the crude silylated product); pale yellow oil;  $R_f$  0.3 (cyclohexane–EtOAc, 7:3).

<sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>):  $\delta$  (*syn* diastereoisomer) = 2.57–2.77 (m, 1 H), 3.77–3.92 (m, 2 H), 4.72 (d, *J* = 7.6 Hz, 1 H), 4.95 (dd, *J*<sub>1</sub> = 2.2 Hz, *J*<sub>2</sub> = 10.8 Hz, 1 H), 5.02 (dd, *J*<sub>1</sub> = 0.8 Hz, *J*<sub>2</sub> = 2.6 Hz, 1 H), 5.56 (ddd, *J*<sub>1</sub> = 8.2 Hz, *J*<sub>2</sub> = 10.8 Hz, *J*<sub>3</sub> = 17.0 Hz, 1 H), 7.13–7.30 (m, 5 H).

<sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>): δ (*anti* diastereoisomer) = 2.31-2.69 (m, 1 H), 3.56-3.62 (m, 2 H), 4.79-4.89 (m, 1 H), 5.07-5.24 (m, 2 H), 5.82 (ddd,  $J_1 = 8.8$  Hz,  $J_2 = 10.6$  Hz,  $J_3 = 17.0$  Hz, 1 H).

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>): δ (*syn* diastereoisomer) = 29.7, 52.2, 64.9, 118.2, 126.6, 127.8, 128.3, 135.3, 142.5.

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>): δ (*anti* diastereoisomer) = 53.5, 62.8, 119.6, 126.3, 128.1, 133.2.

MS (silylated alcohol): *m*/*z* (%) = 259 (10), 219(10), 189 (25), 163 (15), 147 (100), 115 (8), 107 (15), 75 (37).

The enantiomeric excess was determined by HPLC analysis (Chiralcel OF, isocratic, *n*-hexane–IPA, 75:25, flow 0.35 mL/min); *anti*: [(1*R*,2*S*) 15.8 min.; (1*S*,2*R*) 16.7 min.]; *syn*: [(1*S*,2*S*) 17.1 min, (1*R*,2*R*) 20.6 min]; ee<sub>anti</sub> = 16%, ee<sub>syn</sub> = 81%.

## 15b

Yield = 40% (*syn:anti* 83:17, dr was evaluated by GC analysis on the silylated crude product); pale yellow oil;  $R_f 0.3$  (cyclohexane–Et<sub>2</sub>O, 8:2).

<sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>): δ (*syn* diastereoisomer) = 2.63–2.80 (m, 1 H), 3.49–3.60 (m, 2 H), 3.75 (d, J = 4.5 Hz, 1 H), 4.56 (s, 2 H), 4.83 (dd,  $J_1 = 3.6$  Hz,  $J_2 = 6.6$  Hz, 1 H), 5.02 (d, J = 10.2 Hz, 1 H), 5.06 (d, J = 1.5 Hz, 1 H); 5.68 (ddd,  $J_1 = 8.1$  Hz,  $J_2 = 10.2$  Hz,  $J_3 = 17.3$  Hz, 1 H), 7.20–7.43 (m, 10 H).

<sup>1</sup>H NMR (300 MHz, CDCl<sub>3</sub>):  $\delta$  (*anti* diastereoisomer) = 2.94 (br s, 1 H), 3.43–3.90 (m, 1 H), 4.51 (s, 2 H), 4.88–4.94 (m, 1 H), 5.14–5.22 (m, 1 H), 5.19 (dd,  $J_1 = 1.8$  Hz,  $J_2 = 10.5$  Hz, 1 H); 5.87 (ddd,  $J_1 = 1.6$  Hz,  $J_2 = 8.7$  Hz,  $J_3 = 10.5$  Hz, 1 H).

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>): δ (*syn* diastereoisomer) = 50.4, 72.3, 73.6, 76.4, 117.5, 126.6, 127.1, 127.6, 127.8, 128.4, 128.9, 135.6, 137.5, 142.5.

<sup>13</sup>C NMR (50 MHz, CDCl<sub>3</sub>): δ (*anti* diastereoisomer) = 51.4, 71.6, 73.4, 74.7, 118.5, 126.4, 127.7, 128.0, 128.4, 135.2, 137.9, 142.1.

MS (silylated alcohol): *m*/*z* (%) = 325 (1), 195 (1), 179 (100), 163 (2), 149 (2), 129 (3), 91 (22), 73 (28).

The enantiomeric excess was determined by <sup>1</sup>H NMR analysis with Eu(Hfc)<sub>3</sub>. (1*R*,2*R*)  $\delta$ : 8.17 (d, *J* = 7.8 Hz, 1 H); (1*S*,2*S*)  $\delta$ : 8.13 (d, *J* = 7.8 Hz, 1 H): ee<sub>syn</sub> = 81%.

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