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Synthesis of spirocyclic β-methylene-γ-lactone utilizing hydroxymethylation of functionalized allylsilane

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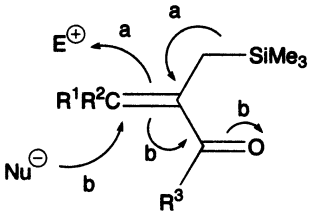
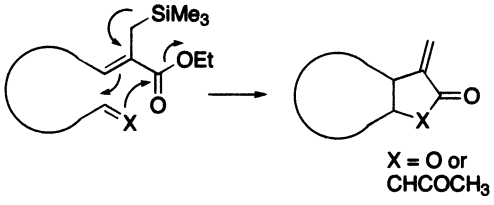
Abstract—A new spiro-β-methylene-γ-lactone annulation reaction is addressed for the synthesis of 4-methylene-2-oxaspiro[4.5]decan-1-one and its derivatives. 2-Cyclohexylidene-3-trimethylsilylprop-1-yl pivalate, obtained from cyclohexanone, was hydroxymethylated followed by desilylation to afford 2-[(1-hydroxymethyl)cyclohexyl]prop-2-en-1-yl pivalate and its -1-en-1-yl isomer. The former was oxidized to carboxylic acid followed by lactonization to the above compound. It was found that the stereochemistry of the hydroxymethylation reaction depends on the substituent on the cyclohexane ring. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

Substituted allylsilanes with carbonyl group at the β-position (β-carbonylallylsilanes) and their reduced form (β-(hydroxymethyl)allylsilanes) are useful precursors for the synthesis of odd-membered rings,[1,2] since these moieties can formally react with both nucleophiles and electrophiles at the same carbon as shown in Scheme 1 (arrow 'a' is for an electrophile and arrow 'b' is for a nucleophile). We[3,4] and Nishitani's group[5,6] independently developed a synthetic strategy towards fused α-methylene-γ-lactones, basic structure of terpenoids, utilizing an intramolecular reaction of β-(ethoxycarbonyl)allylsilane with aldehyde (Scheme 2, X=O). We also reported a synthesis of a five-membered carbocycle by the same strategy (X=$CHCOCH_3$),[7] as well as the synthesis of α-methylene-γ-lactone via a different mode from related functionalized allylsilane.[8,9] While a number of synthesis of five- and seven-membered rings are reported with the use of β-(functionalizedmethyl)-



Scheme 1.



Scheme 2.

allylsilanes, such as β-(dialkoxymethyl)-,[10,11] β-(halomethyl)-,[12–15] and β-(hydroxymethyl)allylsilanes[16,17] including trimethylenemethane developed by Trost's group.[18]

Although α-methylene-γ-lactone is the major unit in natural terpenes, α-methylene-δ-lactone and β-methylene-γ-lactone are also found in nature.[19] Nishitani et al. reported a synthesis of α-methylene-δ-lactone from the related methodoloy,[20] i.e. by replacing the C=X group in Scheme 2 with epoxide. Based on these backgrounds, we currently focus on the synthesis of the third type of methylenelactone, β-methylene-γ-lactone, by the related strategy. α,α′-Spirocyclic β-methylene-γ-lactones are found as a part of bakkenolide A or related sesquiterpenes[19] having some biological activity.[21] These natural sesquiterpenes have a 2-oxaspiro[4.4]nonan-1-one skeleton, however a natural product having a 2-oxaspiro[4.5]decan-1-one skeleton was also found recently.[22] To date, several syntheses have been reported focusing on this interesting structure.[23–27] Our basic strategy is to use exocyclic β-(hydroxymethyl)allylsilane derivative **1**, which can easily be obtained from cycloalkanone and had been used previously as the key intermediate for the synthesis of spiro[4.5]decane **2** or spiro[4.4]nonane **3**.[9b] (Scheme 3). Spirolactones are

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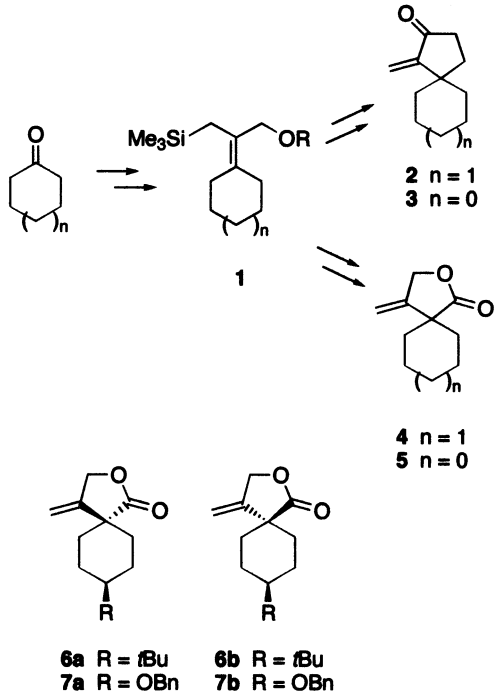
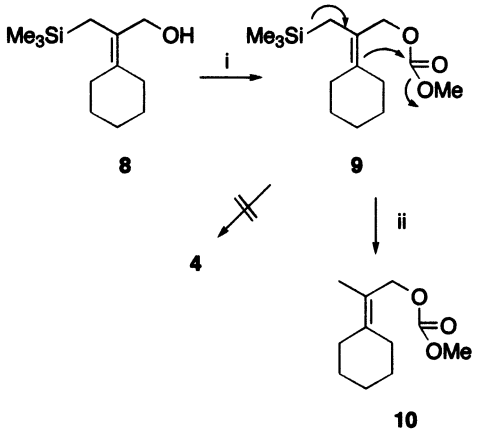
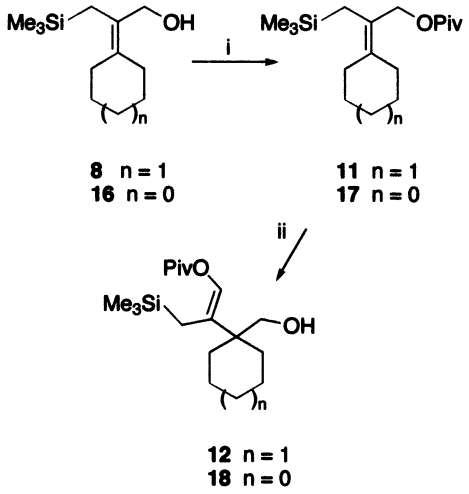


Scheme 3.



Scheme 4. *Reagents and conditions*: (i) ClCOOMe, pyridine, 0°C; (ii) Bu_4NF, THF, rt.

expected to be obtained from **1** via a Hosomi–Sakurai type of one carbon introduction as the key step, and thus the total reaction of the present method forms a spiro-β-methylene-γ-lactone annulation. Here we report the synthesis of spirocyclic β-methylene-γ-lactones **4**, **5**, **6a**, **b**, and **7a**, **b** from the corresponding cycloalkanones by this strategy.



Scheme 5. *Reagents and conditions*: (i) PivCl, pyridine, rt; (ii) $(CH_2O)_n$, Et_2AlCl, CH_2Cl_2, −60°C, see Table 1.

2. Results and discussion

Our first idea was to cyclize carbonate **9** from which lactone **4** can be obtained directly as described in Scheme 4. The substrate **9** was prepared from **8**[9b] by treatment with methyl chloroformate in pyridine (95%). However, no desired lactone **4** was obtained when **9** was treated with Lewis acids, such as BF_3OEt_2, $SnCl_4$, and $TiCl_4$. While, the desilylated product **10** was afforded in 69% yield from a Bu_4NF treatment. The product of the Lewis acid treatment could not be identified, however, it was shown by TLC monitoring that a non-polar product was produced. This can be understood by the elimination of carbonate under an acidic condition giving a stable allylic carbocation.

Then our strategy was changed to introduce a one carbon unit prior to the lactonization (Scheme 5). The hydroxyl group of **8** was first protected as a pivalate to give **11**. Since the reaction site of **11** (i.e. the γ-position of the allylsilane) is sterically hindered, hydroxymethylation using formaldehyde, the smallest molecule for this purpose, was studied. Reaction of β-(trimethylsilyloxymethyl)allylsilane with formaldehyde in the presence of various Lewis acids as the catalyst was studied by Markó et al.[28] among which the Hosomi–Sakurai type of reaction occurred when $TiCl_4$ was used as the catalyst. Therefore, we first attempted the hydroxymethylation of **11** with paraformaldehyde[29] in the presence of $TiCl_4$, but the result was unsatisfactory. Et_2AlCl was then used as the Lewis acid, expecting that the same product would be obtained after desilylation. The results are summarized in Table 1. When the reaction was carried out at

Table 1. Hydroxymethylation of **11**

Entry	Temperature (°C)	Time	Concentration (mol/l)	Yield of **12**[a] (%)	Recovered **11** (%)
1	rt	30 min	0.01	–	–
2	−20	15 min	0.04	7 (26)	73
3	−60	17 h	0.01	10 (63)	84
4	−60	40 min	0.04	14 (69)	80
5	−60	15 min	0.07	26 (94)	72

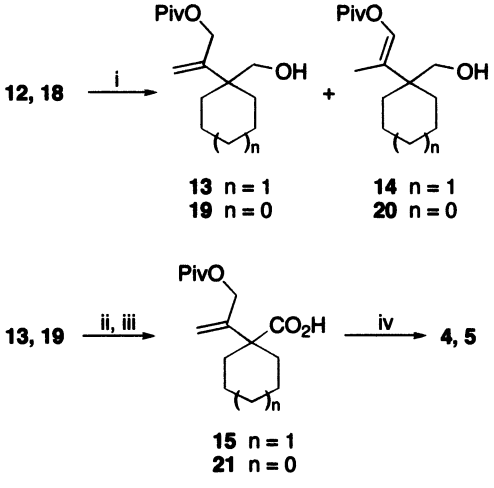
All reactions were carried out with excess amount (ca. 10 equiv.) of paraformaldehyde in the presence of Et_2AlCl (ca. 3 equiv.) in CH_2Cl_2.
[a] Yield based on consumed material is shown in parenthesis.

room temperature, only a complex mixture was afforded, among which **12** was detected by TLC but could not be isolated (entry 1). Then the reaction was carried out at lower temperature. In all cases (entries 2–5), a considerable amount of unreacted substrate **11** was recovered. The yield of **12** was increased when the reaction was carried out in more concentrated solutions, and finally **12** was obtained in 94% yield based on the consumed material (entry 5). Some other Lewis acids, such as $EtAlCl_2$, $SnCl_4$, and BF_3OEt_2 were also tested in the hydroxymethylation reaction but no desired product was obtained. Tetrabutylammonium fluoride promoted anionic reaction conditions also did not afford the alkylated product. Compound **12** was obtained as the single isomer, however, the geometry of the double bond was not determined.[28]

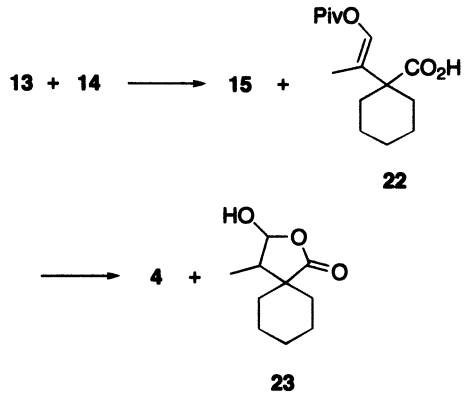
Desilylation of **12** with Bu_4NF was carried out next expecting to produce the *exo*-methylenic product **13**. However, **13** was obtained together with its double-bond isomer **14** (**13**/**14**=ca. 2:1) in a total product yield of 86% (Scheme 6) which could be separated by repeated silica-gel column chromatography. The alcohol **13** was then converted to carboxylic acid **15** by Swern oxidation followed by chlorite oxidation (94% yield in two oxidation steps). Alkali hydrolysis of pivalates **15** did not afford the corresponding hydroxy acid, but the desired lactone **4** was obtained in an 85% yield after the acidic work up.

In the same way, spiro-β-methylene-γ-lactone fused to the cyclopentane ring **5** was synthesized. Thus, hydroxymethylation of compound **17**, prepared from **16**[9b] as above, afforded **18** in an 80% yield based on the consumed material. Desilylation of **18** gave **19** and **20** (totally 90%), the former of which was oxidized to **21** (89%, in two oxidation steps) followed by lactonization to yield **5** in an 88% yield (Schemes 5 and 6).

Since the separation of the double-bond isomers **13** and **14** was not easy, purification of the lactone in the last stage was also examined. Namely, a mixture of **13** and **14** was oxidized as described above giving a mixture of **15** and its



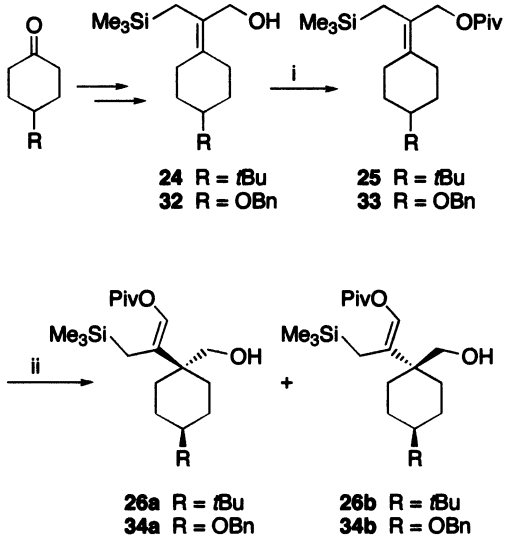
Scheme 6. *Reagents and conditions*: (i) Bu_4NF, THF or DMF, rt; (ii) DMSO, $(COCl)_2$, Et_3N, CH_2Cl_2, rt; (iii) $NaClO_2$, NaH_2PO_4, 2-methyl-2-butene, *t*BuOH, rt; (iv) NaOH aq, THF, rt, then HCl aq, rt.



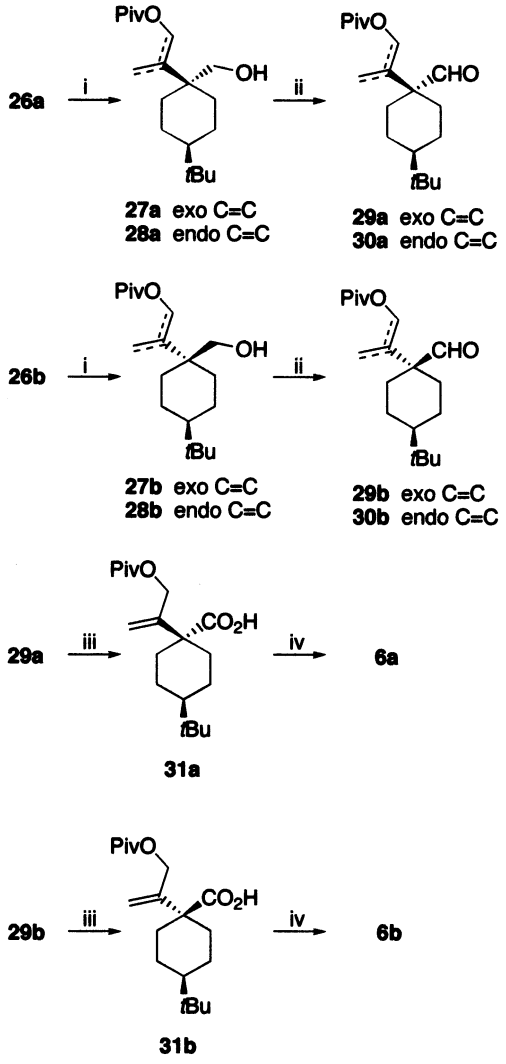
Scheme 7. See Scheme 6 for the reagents and conditions.

double-bond isomer **22** (totally 96%), which was then hydrolyzed to afford lactone **4** and hemiacetal **23**, derived from **22** (Scheme 7). This mixture could easily be separated, and **4** and **23** were obtained in 58 and 27% yields, respectively. It was found that hemiacetal **23** consisted of ca. a 3:1 mixture of diastereomeres, however, the stereochemistry of the isomers was not determined.

To study the substituent effect on the cyclohexane ring, spirolactones **6a**, **b** were synthesized from 4-*t*butylcyclohexanone. Compound **25**, obtained by pivaloylation of **24**,[9b] was subjected to the hydroxymethylation, in which medium stereoselectivity was observed giving a mixture of two diastereomers, **26a** and **26b**, in a 2:5 ratio (97% yield based on the consumed material) (Scheme 8). These isomers could be separated by silica-gel column chromatography, however, the stereochemistry of the products was determined at the latest stage. When Me_2AlCl[29] was used for the hydroxymethylation, instead of Et_2AlCl, the substrate **25** was consumed within 1 h, and the products **26a**, **b** were obtained in a 66% yield with the same ratio (**26a**/**26b**=2:5). Desilylation of **26a** afforded an inseparable mixture of double-bond isomers **27a** and **28a** in a 93% yield



Scheme 8. *Reagents and conditions*: (i) PivCl, pyridine, rt; (ii) $(CH_2O)_n$, Et_2AlCl, CH_2Cl_2, −60°C.



Scheme 9. *Reagents and conditions*: (i) Bu_4NF, THF, rt; (ii) DMSO, $(COCl)_2$, Et_3N, CH_2Cl_2, rt; (iii) $NaClO_2$, NaH_2PO_4, 2-methyl-2-butene, *t*BuOH, rt; (iv) NaOH aq, THF, rt, then HCl aq, rt.

(**27a/28a**=ca. 3:2) (Scheme 9). Similarly, **26b** afforded a mixture of **27b** and **28b** in a 99% yield. Two-step oxidation of these mixtures of alcohols afforded corresponding carboxylic acids as above, however, the separation of the double-bond isomers was successfully made at the intermediate aldehydes. Namely, Swern oxidation of the mixture of **27a** and **28a** gave corresponding aldehydes, which were separated by silica-gel column chromatography to yield **29a** and **30a** in 56 and 35% yields, respectively. Similarly, **29b** and **30b** were obtained in 47 and 37% yields, respectively, after separation. The aldehydes **29a** and **29b** were then converted to lactones **6a** and **6b**, respectively, by chlorite oxidation (**31a**: 93%, **31b**: 80%) followed by hydrolysis (**6a**: 96%, **6b**: 93%).

The stereochemistry of **6a** and **6b** were determined from ^1H NMR spectra including an NOE experiment. Thus, the NOE signal was observed between one of methylenic proton and 6(axial)-H for **6b**, and 7(axial)-H for **6a** (Fig. 1). From this, the stereochemistry of **26a**, **b**, **27a**, **b**, **29a**, **b**, and **31a**, **b** was also established.

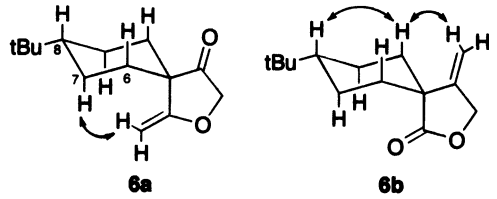
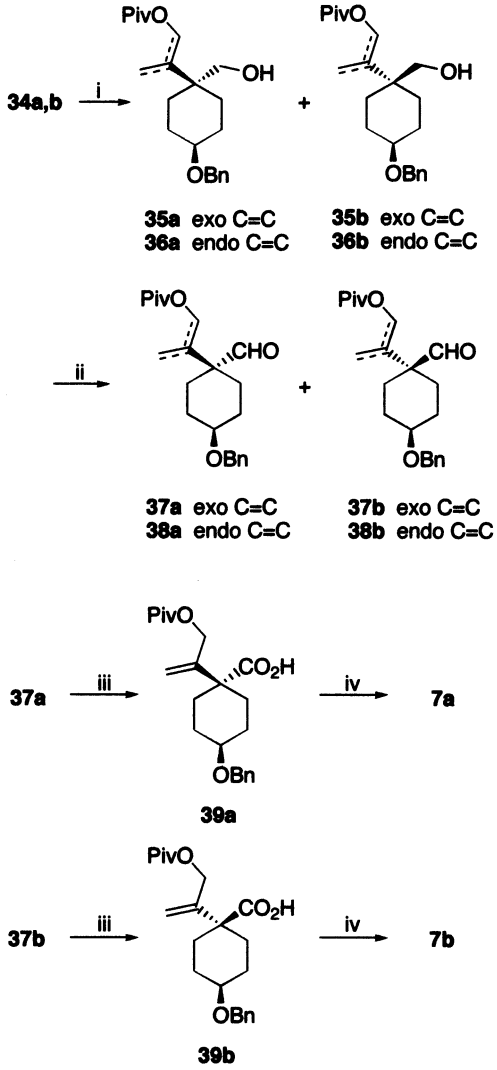


Figure 1.

Spirolactones having an oxygen-functionality, **7a** and **7b**, were also synthesized from 4-benzyloxycyclohexanone. Compound **32** was prepared by the Horner–Emmons reaction followed by $LiAlH_4$ reduction, as reported previously (see Section 3). Although the stereoselectivity of the hydroxymethylation of **33** was lower, it is interesting that the selectivity was opposite to the case of **25**, giving **34a** and **34b** in ca. 3:2 ratio (91% yield based on the consumed material) (Scheme 8). This inseparable mixture of stereoisomers, **34a** and **34b**, was desilylated to afford a mixture of four isomers **35a**, **b**/**36a**, **b** (totally 92%) (Scheme 10).



Scheme 10. *Reagents and conditions*: (i) Bu_4NF, THF, rt; (ii) DMSO, $(COCl)_2$, Et_3N, CH_2Cl_2, rt; (iii) $NaClO_2$, NaH_2PO_4, 2-methyl-2-butene, *t*BuOH, rt; (iv) NaOH aq, THF, rt, then HCl aq, rt.

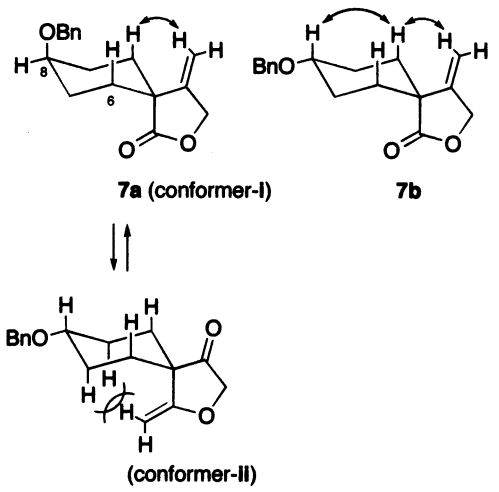
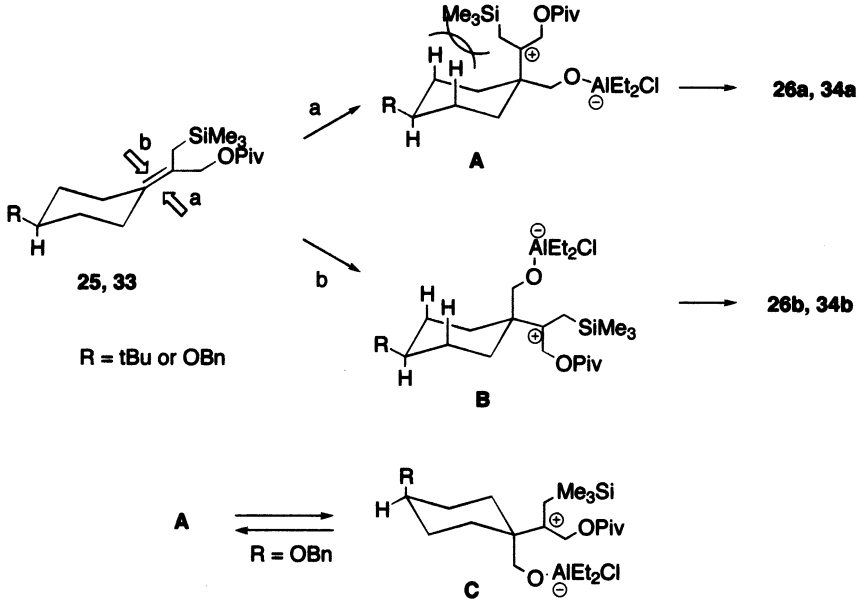


Figure 2.

Without purification, these were subjected to the Swern oxidation to yield a mixture of aldehydes **37a**, **b**/**38a**, **b** in a 75% yield from **34a**, **b**. As in the case of **29**/**30**, regio- and stereoisomers could be separated from each other at this stage to obtain **37a** and **37b**, which were then oxidized to the carboxylic acids, **39a** (96%) and **39b** (82%), followed by lactonization to afford **7a** (94%) and **7b** (94%), respectively. The structure of **7a** and **7b** was determined from the *J*-value of 8-H, the benzyloxy-bearing position, together with the NOE measurements (Fig. 2). Namely, the *J*-value of 8-H indicates that the benzyloxy group is axial for **7a** (tt, J=3.1, 6.0 Hz; conformer **i**) and equatorial for **7b** (tt-like, J=3.9, 9.3 Hz). The NOE was observed between 6-H and 8-H for **7b** but not for **7a**, while the NOE between 6-H and one of the *exo*-methylene was observed for both **7a** and **7b**. From these data, it was established that 8-H and *exo*-methylene are located on the same side of the cyclohexane ring for **7b** and opposite side for **7a**. It is interesting that the spectral data of **7a** are explained by conformer **i**, a 'flipped' conformation from the related compound **6a** (see Fig. 1). This indicates that *exo*-methylene group in conformer **ii** comes over the cyclohexane ring, which makes **ii** less stable than **i**.

The preferential formation of **26b** over **26a** in the hydroxymethylation reaction of **25** can be rationalized by steric effects based on the assumption that the *t*Bu substituent takes an equatorial orientation (Scheme 11). It is known that the equatorial attack on the *exo*-cyclic double-bond (direction 'a', the less-hindered side attack) is normally more favored over the axial attack (direction 'b', the more hindered side attack).[30] However, in this case, attacking from the 'b' side is more favorable than from the 'a' side, since the exocyclic double-bond have bigger substituents than the attacking reagent. Thus, attacking the activated formaldehyde to **25** from direction 'a' gives the sterically congested intermediate **A** in which the bigger substituent is located in the axial orientation. This makes intermediate **B**, generated from the 'b' side attack, more favored. The related stereoselectivity was also observed in the synthesis of **2** via the Nazarov cyclization.[9b] The reversed stereoselectivity for **33** can be justified by the flip of the cyclohexane ring from **A** to **C**, in which the biggest substituent takes the equatorial conformation. Thus, in contrast to **26a**, the product of the less-hindered side attack (direction 'a') **34a** is not sterically congested. The related flipping of cyclohexane ring is also observed for the conformation of the four lactones **6a**, **b** and **7a**, **b** (see Figs. 1 and 2). The formation of the sterically hindered transition state also explains the low reactivity of **11**, **17**, **25**, and **33**.

In conclusion, a new spiroannulation strategy for the synthesis of α,α-spirocyclic β-methylene-γ-lactone from cycloalkanone was established via a hydroxymethylation of β-(acyloxymethyl)allylsilane derivative. It was shown that β-(functionalizedmethyl)allylsilane is a useful organic bifunctional unit by which three types of methylenelactones, α-methylene-γ-lactones, β-methylene-γ-lactones, and α-methylene-δ-lactones could be synthesized based on the



Scheme 11.

same concept. In addition, the β-(acyloxymethyl)allylsilane derivative **1** was shown to be a good intermediate for the synthesis of two types of spirocyclic compounds, carbocycles (**2**, **3**) and lactones (**4**, **5**), from cycloalkanone. Moreover, it was found that the stereochemistry of the hydroxymethylation of the cyclohexylidene system depends on the substitution pattern, as well as, the possibility to adopt the flipped conformation.

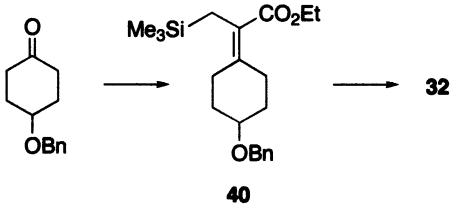
3. Experimental

3.1. General procedure

Melting points were collected on a Laboratory Devices Mel-Temp apparatus. IR spectra were taken on a Jasco FT/IR-230 spectrometer. Both ^{1}H and ^{13}C NMR spectra were measured on a Jeol GSX-400 (400 MHz for ^{1}H; 100 MHz for ^{13}C) spectrometer. Chemical shifts were reported on the δ scale (ppm) with solvent ($CHCl_3$=7.26) as an internal standard, unless otherwise noted. The signal of the solvent ($CDCl_3$=77.00) was used as a standard for all ^{13}C NMR spectra. Both low-resolution mass spectra (MS) and high-resolution mass spectra (HRMS) were obtained on a Jeol SX-102A, JMS-700, JMS-HX100, or Shimadzu GCMS-QP5050 mass spectrometer with the EI method unless otherwise noted. Analytical TLC was done on precoated TLC plates (Kieselgel 60 F254, layer thickness 0.2 mm). Wakogel C-200 or C-300 were used for column chromatography. Anhydrous Na_2SO_4 or $MgSO_4$ was used for drying the extracted organic layers.

3.2. Horner–Emmons reaction and reduction

See Ref. 9b for the preparation and spectral data of **8**, **16**, and **24**. Compound **32** was prepared from 4-benzyloxycyclohexanone by the same way (Scheme 12).



Scheme 12.

3.2.1. Ethyl 2-(4-benzyloxy)cyclohexylidene-3-trimethylsilylpropanoate (40). An oil; IR (neat) 1711 (C=O), 1453, 1248, 1102, and 852 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.00 (9H, s, $SiMe_3$), 1.30 (3H, t, J=7.1 Hz, OCH_2CH_3), 1.58–1.68 (2H, m), 1.81 (2H, br s, CH_2SiMe_3), 1.87–2.04 (3H, m), 2.20 (1H, ddd, J=3.9, 5.7, 14.0 Hz), 2.41–2.50 (1H, m), 2.75 (1H, ddd, J=3.6, 6.6, 13.3 Hz), 3.59 (1H, tt, J=3.6, 7.9 Hz, C*H*OBn), 4.17 (2H, q, J=7.1 Hz, OCH_2CH_3), 4.55 (1H, d, J=12.0 Hz, OC*H*HPh), 4.58 (1H, d, J=12.0 Hz, OCH*H*Ph), and 7.24–7.38 (5H, m, Ph); ^{13}C NMR ($CDCl_3$) δ=−1.23 (3C), 14.20, 20.03, 27.55, 28.31, 32.06, 32.40, 60.14, 69.89, 75.32, 123.52, 127.36, 127.43 (2C), 128.31 (2C), 139.01, 140.98, and 170.69; MS m/z 360 (M^+, 85%), 315 (43), 205 (84), 145 (100), and 65 (79); HRMS [Found: m/z 360.2094 (M^+). Calcd for $C_{21}H_{32}O_3Si$: M, 360.2122].

3.2.2. 2-(4-Benzyloxy)cyclohexylidene-3-trimethylsilylpropanol (32). An oil; IR (neat) 3390 (OH), 1453, 1246, 1094, 847, and 696 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.02 (9H, s, $SiMe_3$), 1.27 (1H, br, OH), 1.47–1.59 (2H, m), 1.70 (2H, br s, CH_2SiMe_3), 1.87–2.06 (4H, m), 2.40–2.48 (1H, m), 2.60–2.68 (1H, m), 3.56 (1H, tt, J=3.4, 8.5 Hz, C*H*OBn), 4.04 (1H, d, J=11.4 Hz, C*H*HOH), 4.07 (1H, d, J=11.4 Hz, CH*H*OH), 4.58 (2H, s, OCH_2Ph), and 7.25–7.39 (5H, m, Ph); ^{13}C NMR ($CDCl_3$) δ=−0.85 (3C), 21.45, 26.33, 27.46, 32.31, 32.98, 63.32, 69.81, 75.95, 127.32, 127.42 (2C), 127.93, 128.27 (2C), 133.09, and 139.03; MS m/z 318 (M^+, 90%), 298 (100), 242 (12), 229 (12), 160 (15), and 63 (15); HRMS [Found: m/z 318.2032 (M^+). Calcd for $C_{19}H_{30}O_2Si$: M, 318.2016].

3.3. Pivaloylation

In a 100 cm^3 round bottomed flask attached to a $CaCl_2$ drying tube was placed a solution of **8** (991.3 mg, 4.67 mmol) in dry pyridine (50 cm^3; distilled from CaH_2). After being cooled to 0°C, pivaloyl chloride (0.69 cm^3) was added, and the mixture was stirred at room temperature overnight. Subsequently, water was added, and the mixture was extracted with ether and dried. Evaporation of the solvent followed by silica gel (20 g) column chromatography using hexane–AcOEt (99:1) as eluent afforded **11** (1247.1 mg, 90%).

Compounds **17**, **25**, and **33** were obtained by the same procedure in 92, 94, and 94% yields, respectively.

3.3.1. 2-Cyclohexylidene-3-trimethylsilylprop-1-yl pivalate (11). An oil; IR (neat) 1727 (C=O), 1479, 1247, 1153, and 849 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.00 (9H, s, $SiMe_3$), 1.19 (9H, s, *t*Bu), 1.45–1.58 (6H, m), 1.62 (2H, s, CH_2SiMe_3), 2.07–2.18 (4H, m), and 4.48 (2H, s, CH_2OPiv); ^{13}C NMR ($CDCl_3$) δ=−0.93 (3C), 21.88, 26.75, 27.24 (3C), 27.80, 28.45, 30.64, 31.16, 38.79, 65.46, 121.79, 137.39, and 178.69; MS m/z 296 (M^+, 14%), 176 (9), 144 (14), 113 (96), and 65 (100); HRMS [Found: m/z 296.2141 (M^+). Calcd for $C_{17}H_{32}O_2Si$: M, 296.2173]; Analysis [Found: C, 68.81; H, 10.76%. Calcd for $C_{17}H_{32}O_2Si$: C, 68.86; H, 10.88%].

3.3.2. 2-Cyclopentylidene-3-trimethylsilylprop-1-yl pivalate (17). An oil; IR (neat) 1731 (C=O), 1480, 1283, 1156, and 840 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.01 (9H, s, $SiMe_3$), 1.20 (9H, s, *t*Bu), 1.55 (2H, br s, CH_2SiMe_3), 1.60–1.67 (4H, m), 2.12–2.18 (2H, m), 2.24–2.30 (2H, m), and 4.49 (2H, s, CH_2OPiv); ^{13}C NMR ($CDCl_3$) δ=−0.67 (3C), 22.05, 26.40, 26.91, 27.30 (3C), 30.14, 31.52, 38.92, 66.44, 122.41, 140.16, and 178.65; MS m/z 180 (M^+−PivOH, 5%), 165 (6), 159 (9), 93 (23), and 73 (100); HRMS [Found: m/z 180.1291 (M^+−PivOH). Calcd for $C_{11}H_{20}Si$: M, 180.1335].

3.3.3. 2-4-*t*Butylcyclohexylidene-3-trimethylsilylprop-1-yl pivalate (25). An oil; IR (neat) 1727 (C=O), 1479, 1365, 1282, 1247, 1151, and 849 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.01 (9H, s, $SiMe_3$), 0.84 (9H, s, *t*Bu), 0.91–1.19 (3H, m), 1.20 (9H, s, *t*Bu), 1.63 (1H, d, J=14.3 Hz, C*H*HSiMe$_3$),

1.65 (1H, d, J=14.3 Hz, CH*H*SiMe$_3$), 1.66–1.87 (4H, m), 2.57 (1H, dq, J=13.5, 2.7 Hz), 2.66 (1H, dq, J=13.5, 2.7 Hz), 4.48 (1H, d, J=11.8 Hz, C*H*HOPiv), and 4.51 (1H, d, J=11.8 Hz, CH*H*OPiv); ^{13}C NMR ($CDCl_3$) δ=−0.90 (3C), 21.85, 27.26 (3C), 27.54 (3C), 28.35, 28.99, 30.39, 30.99, 32.39, 38.82, 48.16, 65.51, 121.54, 137.22, and 178.75; MS m/z 250 (M^+−PivOH, 4%), 235 (2), 193 (5), 159 (11), 73 (85), and 57 (100); HRMS [Found: m/z 250.2081 (M^+−PivOH). Calcd for $C_{16}H_{30}Si$: M, 250.2118].

3.3.4. 2-(4-Benzyloxy)cyclohexylidene-3-trimethylsilylprop-1-yl pivalate (33). An oil; IR (neat) 1725 (C=O), 1479, 1282, 1247, 1152, 849, and 696 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.02 (9H, s, SiMe$_3$), 1.20 (9H, s, *t*Bu), 1.47–1.59 (2H, m), 1.64 (1H, d, J=14.3 Hz, C*H*HSiMe$_3$), 1.66 (1H, d, J=14.3 Hz, CH*H*SiMe$_3$), 1.87–2.01 (4H, m), 2.41–2.57 (2H, m), 3.55 (1H, tt, J=3.4, 8.5 Hz, C*H*OBn), 4.48 (1H, d, J=11.9 Hz, OC*H*HPh), 4.51 (1H, d, J=11.9 Hz, OCH*H*Ph), 4.57 (2H, s, CH_2OPiv), and 7.25–7.38 (5H, m, Ph); ^{13}C NMR ($CDCl_3$) δ=−0.94 (3C), 22.19, 26.82, 27.24 (3C), 27.48, 32.35, 32.85, 38.82, 65.43, 69.91, 75.96, 123.02, 127.37, 127.48 (2C), 128.32 (2C), 135.39, 139.07, and 178.67; MS m/z 402 (M^+, 7%), 345 (7), 302 (92), 283 (94), 239 (100), 191 (95), and 102 (98); HRMS [Found: m/z 402.2599 (M^+). Calcd for $C_{24}H_{38}O_3Si$: M, 402.2591].

3.4. Hydroxymethylation

To a stirred solution of paraformaldehyde (502.3 mg, 16.73 mmol) in dry CH_2Cl_2 (15 cm^3; distilled from CaH_2) was added a solution of Et_2AlCl (5.8 cm^3, 5.4 mmol; 0.93 mol/l solution in hexane) at −60°C under Ar. After 30 min stirring, a solution of **11** (557.3 mg, 1.879 mmol) in CH_2Cl_2 (5 cm^3) was added, and the mixture was stirred at the same temperature. A dilute HCl aq (2 mol/l) was added and the mixture was warmed to room temperature, and then extracted with CH_2Cl_2. Drying the organic layer followed by evaporation of the solvent gave an oily residue, which was chromatographed on silica gel (13 g) using hexane–AcOEt (97:3, 95:5, and 90:10) as eluent to yield recovered **11** (400.7 mg, 72%) and **12** (162.1 mg, 26%; 94% based on the consumed material) (entry 5 of Table 1).

Similarly, compounds **18**, **26a**, **b**, and **34a**, **b** were obtained in 80, 97, and 91% yields based on the consumed materials, respectively. The isomers **26a** and **26b** were separated by repeated column chromatography. The isomers **34a** and **34b** could not be separated.

3.4.1. 2-[(1-Hydroxymethyl)cyclohexyl]-3-trimethylsilylprop-1-en-1-yl pivalate (12). Mp 44–46°C; IR (neat) 3460 (OH), 1738 (C=O), 1654 (C=C), 1479, 1280, 1249, 1142, and 853 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.08 (9H, s, SiMe$_3$), 1.27 (9H, s, *t*Bu), 1.39–1.50 (7H, m), 1.56 (2H, br s, CH_2SiMe$_3$), 1.54–1.66 (4H, m), 3.38 (2H, s, CH_2OH), and 6.92 (1H, s, C=CH); ^{13}C NMR ($CDCl_3$) δ=0.00 (3C), 14.95, 22.14 (2C), 26.32, 27.23 (3C), 31.60 (2C), 38.79, 43.04, 66.6 (br), 126.80, 132.24, and 175.67; MS m/z 326 (M^+, 2%), 295 (M^+−CH$_2$OH, 10), 223 (9), 195 (13), 139 (24), 73 (53), and 57 (100); HRMS [Found: m/z 295.2106 (M^+−CH$_2$OH). Calcd for $C_{17}H_{31}O_2Si$: M, 295.2094].

3.4.2. 2-[(1-Hydroxymethyl)cyclopentyl]-3-trimethylsilylprop-1-en-1-yl pivalate (18). Mp 61–62°C; IR (neat) 3450 (OH), 1730 (C=O), 1655 (C=C), 1266, 1144, and 741 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.08 (9H, s, SiMe$_3$), 1.26 (9H, s, *t*Bu), 1.52–1.69 (8H, m), 1.56 (2H, br s, CH_2SiMe$_3$), 1.76 (1H, br OH), 3.30 (2H, s, CH_2OH), and 6.85 (1H, s, C=CH); ^{13}C NMR ($CDCl_3$) δ=0.02 (3C), 16.72, 23.43 (2C), 27.22 (3C), 32.89 (2C), 38.78, 52.53, 65.24, 128.44, 130.58, and 175.87; MS m/z 209 (M^+−PivOH–H, 2%), 195 (2), 180 (5), 159 (9), 125 (10), 73 (68), and 57 (100); HRMS [Found: m/z 209.1346 (M^+−PivOH–H). Calcd for $C_{12}H_{21}OSi$: M, 209.1362].

3.4.3. 2-[(*trans*-4-*t*Butyl-1-hydroxymethyl)cyclohexyl]-3-trimethylsilylprop-1-en-1-yl pivalate (26a). An oil; IR (neat) 3450 (OH), 1739 (C=O), 1654 (C=C), 1141, and 852 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.09 (9H, s, SiMe$_3$), 0.82 (9H, s, *t*Bu), 0.95–1.61 (8H, m), 1.28 (9H, s, *t*Bu), 1.55 (2H, br s, CH_2SiMe$_3$), 1.98–2.05 (2H, m), 3.23 (2H, br d, J=4 Hz, CH_2OH), and 6.92 (1H, s, C=CH); ^{13}C NMR ($CDCl_3$) δ=0.00 (3C), 15.16, 23.46 (2C), 27.26 (3C), 27.55 (3C), 31.97 (2C), 32.43, 38.82, 43.90, 48.82, 70.56, 124.29, 133.22, and 175.66; MS m/z 280 (M^+−PivOH, 0.1%), 279 (0.2), 251 (0.5), 195 (3), 159 (2), 85 (13), 73 (21), and 57 (100); HRMS [Found: m/z 280.2286 (M^+−PivOH). Calcd for $C_{17}H_{32}OSi$: M, 280.2224].

3.4.4. 2-[(*cis*-4-*t*Butyl-1-hydroxymethyl)cyclohexyl]-3-trimethylsilylprop-1-en-1-yl pivalate (26b). Mp 103–104°C; IR (CH_2Cl_2) 3520 (OH), 1733 (C=O), 1654 (C=C), 1479, 1146, and 849 cm^{-1}; ^{1}H NMR ($CDCl_3$) δ=0.07 (9H, s, SiMe$_3$), 0.84 (9H, s, *t*Bu), 0.90–1.37 (5H, m), 1.26 (9H, s, *t*Bu), 1.55–1.68 (3H, m), 1.56 (2H, br s, CH_2SiMe$_3$), 1.87–1.93 (2H, m), 3.52 (2H, br d, J=5 Hz, CH_2OH), and 6.91 (1H, s, C=CH); ^{13}C NMR ($CDCl_3$) δ=0.10 (3C), 14.83, 22.51, 27.21 (3C), 27.45 (3C), 31.68, 32.34, 38.78, 41.55, 47.64, 61.93, 129.73, 130.97, and 175.72; MS m/z 280 (M^+−PivOH, 0.4%), 279 (M^+−PivO, 0.3), 251 (0.5), 195 (3), 159 (2), 85 (11), 73 (23), and 57 (100); Analysis [Found: C, 68.85; H, 10.78%. Calcd for $C_{22}H_{42}O_3Si$: C, 69.05; H, 11.06%].

3.4.5. 2-[(4-Benzyloxy-1-hydroxymethyl)cyclohexyl]-3-trimethylsilylprop-1-en-1-yl pivalate (34a, b). Mp 84–86°C; IR (neat) 3450 (OH), 1737 (C=O), 1654 (C=C), 1479, 1280, 1249, 1144, and 852 cm^{-1}; ^{1}H NMR ($CDCl_3$) assigned for **34a**: δ=0.09 (9H, s, SiMe$_3$), 1.27 (9H, s, *t*Bu), 1.41–1.98 (9H, m), 1.58 (2H, br s, CH_2SiMe$_3$), 3.31 (2H, s, CH_2OH), 3.38–3.50 (1H, m, C*H*OBn), 4.53 (2H, s, OCH_2Ph), 6.98 (1H, s, C=CH), and 7.26–7.35 (5H, m, Ph); assigned for **34b**: δ=0.07 (9H, s, SiMe$_3$), 1.27 (9H, s, *t*Bu), 1.41–1.98 (9H, m), 1.57 (2H, br s, CH_2SiMe$_3$), 3.38–3.50 (1H, m, C*H*OBn), 3.47 (2H, s, CH_2OH), 4.53 (2H, s, OCH_2Ph), 6.93 (1H, s, C=CH), and 7.26–7.35 (5H, m, Ph); ^{13}C NMR ($CDCl_3$; assignment was not made) δ=−0.03 (3C), 0.00 (3C), 15.05,[†] 27.08 (2C), 27.17 (3C),[†] 27.71 (2C), 27.91 (2C), 28.69 (2C), 38.74,[†] 42.31, 42.97, 65.1 (br), 67.9 (br), 69.72, 69.78, 75.35, 76.39, 127.31, 127.34, 127.40 (2C), 127.42 (2C), 128.26 (2C), 128.28 (2C),

[†] The signal for both isomers.

131.80,† 132.65,† 138.93,† 175.47, and 175.65; GC–MS for **34a**: *m/z* 330 (M^+−PivOH, 0.5%), 227 (1), 221 (1), 209 (2), 91 (42), 73 (26), and 57 (100); for **34b**: *m/z* 345 (M^+−CH_2SiMe_3, 0.4%), 222 (1), 209 (1), 91 (45), 73 (19), and 57 (100); HRMS [Found: *m/z* 330.2001 (M^+−PivOH). Calcd for $C_{20}H_{30}O_2Si$: *M*, 330.2016].

3.5. Desilylation

Vacuum dried tetrabutylammonium fluoride (1.565 g) was prepared in a 100 cm^3 two-necked round bottomed flask under an Ar atmosphere. Dry DMF (20 cm^3; distilled from 4A molecular sieve) was then added, and the resulting solution was cooled to 0°C. A solution of **12** (474.9 mg, 1.454 mmol) in DMF (30 cm^3) was added, the mixture was stirred at 0°C for 15 min, and then water was added. Extraction with ether followed by drying and evaporation of the solvent gave an oily residue, which was chromatographed on silica gel (20 g) using hexane–AcOEt (99:5) to afforded a mixture of **13** and **14** (338.9 mg, 86%, ratio 2:1). Further separation of **13** and **14** was carried out by repeated silica gel chromatography.

For the synthesis of related compounds, dry THF (distilled from CaH_2) was used instead of DMF. Compounds **19/20**, **27a/28a**, and **27b/28b** were obtained in 90, 93, and 99% yields, respectively. A mixture of four isomers **35a**, **b/36a**, **b** were inseparable and not purified at this stage.

3.5.1. 2-[(1-Hydroxymethyl)cyclohexyl]prop-2-en-1-yl pivalate (13). An oil; IR (neat) 3450 (OH), 1729 (C=O), 1637 (C=C), 1480, 1283, 1151, and 1042 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.23 (9H, s, *t*Bu), 1.26–1.57 (8H, m), 1.75–1.82 (2H, m), 1.90 (1H, br, OH), 3.44 (2H, s, C*H*$_2$OH), 4.56 (2H, t, *J*=1.1 Hz, C*H*$_2$OPiv), 5.11 (1H, q, *J*=1.0 Hz, C=C*H*H), and 5.34 (1H, q, *J*=1.0 Hz, C=CH*H*); ^{13}C NMR ($CDCl_3$) δ=22.05 (2C), 26.36, 27.17 (3C), 31.67 (2C), 38.81, 44.62, 64.29, 69.5 (br), 114.53, 145.20, and 178.54; MS *m/z* 152 (M^+−PivOH, 4%), 122 (76), 107 (27), 93 (58), 79 (57), and 57 (100); HRMS [Found: *m/z* 152.1220 (M^+−PivOH). Calcd for $C_{10}H_{16}O$: *M*, 152.1202].

3.5.2. 2-[(1-Hydroxymethyl)cyclohexyl]prop-1-en-1-yl pivalate (14). An oil; IR (neat) 3450 (OH), 1740 (C=O), 1669 (C=C), 1480, 1281, 1149, and 1045 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.27 (9H, s, *t*Bu), 1.23–1.56 (9H, m), 1.62 (3H, d, *J*=1.3 Hz, Me), 1.72–1.80 (2H, m), 3.35 (2H, s, C*H*$_2$OH), and 6.92 (1H, q, *J*=1.3 Hz, C=CH); ^{13}C NMR ($CDCl_3$) δ=9.84, 21.88 (2C), 26.39, 27.11 (3C), 31.32 (2C), 38.89, 43.19, 68.0 (br), 123.21, 134.62, and 175.88; MS *m/z* 153 (M^+−PivO, 6%), 139 (26), 122 (8), 85 (11), 71 (11), and 57 (100); HRMS [Found: *m/z* 153.1306 (M^+−PivO). Calcd for $C_{10}H_{17}O$: *M*, 153.1280].

3.5.3. 2-[(1-Hydroxymethyl)cyclopentyl]prop-2-en-1-yl pivalate (19). An oil; IR (neat) 3470 (OH), 1724 (C=O), 1639 (C=C), 1480, 1284, 1156, and 739 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.23 (9H, s, *t*Bu), 1.62–1.67 (8H, m), 1.94 (1H, br, OH), 3.44 (2H, s, C*H*$_2$OH), 4.57 (2H, dd, *J*=0.7, 1.3 Hz, C*H*$_2$OPiv), 5.07 (1H, dt, *J*=1.0, 0.7 Hz, C=C*H*H), and 5.19 (1H, dt, *J*=1.0, 1.3 Hz, C=CH*H*); ^{13}C NMR ($CDCl_3$) δ=23.47 (2C), 27.17 (3C), 32.77 (2C), 38.79, 53.50, 64.80, 67.13, 112.91, 147.77, and 178.49; MS *m/z* 125 (M^+−CH_2OPiv, 5%), 108 (52), 93 (40), 79 (50), and 57 (100); HRMS [Found: *m/z* 125.0956 (M^+−CH_2OPiv). Calcd for $C_8H_{13}O$: *M*, 125.0967].

3.5.4. 2-[(1-Hydroxymethyl)cyclopentyl]prop-1-en-1-yl pivalate (20). An oil; IR (neat) 3450 (0H), 1737 (C=O), 1671 (C=C), 1480, 1281, 1150, and 739 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.26 (9H, s, *t*Bu), 1.60–1.68 (9H, m), 1.68 (3H, d, *J*=1.3 Hz, Me), 3.38 (2H, s, C*H*$_2$OH), and 6.93 (1H, q, *J*=1.3 Hz, C=CH); ^{13}C NMR ($CDCl_3$) δ=11.4, 23.5 (2C), 27.1 (3C), 32.5 (2C), 38.9, 52.3, 65.5, 125.2, 132.4, and 175.8; MS *m/z* 209 (M^+−CH_2OH, 1%), 138 (3), 125 (39), 108 (9), 85 (10), and 57 (100); HRMS [Found: *m/z* 209.1555 (M^+−CH_2OH). Calcd for $C_{13}H_{21}O_2$: *M*, 209.1542].

3.5.5. 2-[(*trans*-4-*t*Butyl-1-hydroxymethyl)cyclohexyl]-prop-2-en-1-yl pivalate and 2-[(*trans*-4-*t*butyl-1-hydroxymethyl)cyclohexyl]prop-1-en-1-yl pivalate (27a, 28a). Mp 59–61°C; IR (CH_2Cl_2) 3480 (OH), 1729 (C=O), 1637 (C=C), 1479, 1365, 1282, and 1155 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.81 (9H, s, *t*Bu of **27a**), 0.81 (9H, s, *t*Bu of **28a**), 0.96–1.26 (5H×2, m), 1.23 (9H, s, *t*Bu of **27a**), 1.27 (9H, s, *t*Bu of **28a**), 1.56–1.66 (2H×2 plus 1H, m), 1.60 (3H, d, *J*=1.1 Hz, Me of **28a**), 1.98–2.08 (2H×2 plus 1H, m), 3.23 (2H, s, C*H*$_2$OH of **28a**), 3.34 (2H, s, C*H*$_2$OH of **27a**), 4.54 (2H, s, CH$_2$OPiv of **27a**), 5.12 (1H, br s, C=C*H*H of **27a**), 5.38 (1H, br s, C=CH*H* of **27a**), and 6.87 (1H, q, *J*=1.1 Hz, C=CH of **28a**); ^{13}C NMR ($CDCl_3$) assigned for **27a**: δ=23.02 (2C), 27.16 (3C), 27.49 (3C), 32.13 (2C), 32.38, 38.79, 44.94, 48.49, 64.42, 71.82, 115.33, 143.51, and 178.56; assigned for **28a**: δ=9.95, 22.83 (2C), 27.09 (3C), 27.49 (3C), 31.75 (2C), 32.38, 38.88, 43.45, 48.62, 70.34, 121.73, 135.19, and 175.93; GC-MS for **27a**: *m/z* 178 (M^+−PivOH–CH_2OH, 12%), 135 (5), 121 (11), 107 (14), and 57 (100); for **28a**: *m/z* 279 (M^+−CH_2OH, 1%), 208 (M^+−PivOH, 2), 195 (7), 178 (4), 85 (11), and 57 (100). Analysis [Found: C, 73.45; H, 10.98%. Calcd for $C_{19}H_{34}O_3$: C, 73.50; H, 11.04%].

3.5.6. 2-[(*cis*-4-*t*Butyl-1-hydroxymethyl)cyclohexyl]prop-2-en-1-yl pivalate and 2-[(*cis*-4-*t*butyl-1-hydroxymethyl)-cyclohexyl]prop-1-en-1-yl pivalate (27b, 28b). Mp 78–81°C; IR (CH_2Cl_2) 3450 (OH), 1728 (C=O), 1637 (C=C), 1480, 1154, and 1039 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.84 (9H×2, s, *t*Bu), 0.90–1.36 (5H×2, m), 1.22 (9H, s, *t*Bu of **27b**), 1.26 (9H, s, *t*Bu of **28b**), 1.59–1.66 (2H×2 plus 1H, m), 1.66 (3H, d, *J*=1.2 Hz, Me of **28b**), 1.90–2.02 (2H×2 plus 1H, m), 3.58 (2H, br s, C*H*$_2$OH of **28b**), 3.66 (2H, d, *J*=5.5 Hz, C*H*$_2$OH of **27b**), 4.59 (2H, s, CH$_2$OPiv of **27b**), 5.07 (1H, s, C=C*H*H of **27b**), 5.19 (1H, s, C=CH*H* of **27b**), and 6.93 (1H, q, *J*=1.2 Hz, C=CH of **28b**); ^{13}C NMR ($CDCl_3$) assigned for **27b**: δ=22.50 (2C), 27.16 (3C), 27.46 (3C), 31.49 (2C), 32.36, 38.79, 42.68, 47.70, 63.16, 64.05, 112.66, 149.40, and 178.56; assigned for **28b**: δ=9.67, 22.50 (2C), 27.10 (3C), 27.46 (3C), 31.29 (2C), 32.36, 38.90, 41.41, 47.81, 61.90, 127.08, 132.86, and 175.77; GC-MS for **27b**: *m/z* 208 (M^+−PivOH, 1%), 178 (11), 135 (6), 121 (11), 107 (13), and 57 (100); for **28b**: *m/z* 279 (M^+−CH_2OH, 0.5%), 208 (3), 195 (5), 109 (6), 96 (7), 85 (9), and 57 (100). Analysis [Found: C, 73.40; H, 10.99%. Calcd for $C_{19}H_{34}O_3$: C, 73.50; H, 11.04%].

3.6. Oxidation

To a stirred solution of $(COCl)_2$ (0.21 cm^3) in dry CH_2Cl_2 (15 cm^3) was added DMSO (0.34 cm^3) at −60°C under Ar. After this had been stirred for 30 min, a solution of **13** (151.1 mg, 0.594 mmol) in CH_2Cl_2 (10 cm^3) was added, and the mixture was stirred at −60°C for 21 h. Et_3N (1.1 cm^3) was added, and the flask was allowed to warm to room temperature slowly with stirring. The reaction was quenched by the addition of water (30 cm^3) followed by extraction with CH_2Cl_2 and drying. Evaporation of the solvent afforded an oily residue, which was dissolved in a mixed solvent prepared from *t*BuOH (15 cm^3) and H_2O (4 cm^3). To this was added 2-methyl-2-butene (0.65 cm^3) and $NaH_2PO_4{\cdot}2H_2O$ (182.8 mg) with stirring at room temperature. After 20 min of stirring, $NaClO_2$ (415.0 mg) was added, and the stirring was continued for an additional 1 h. The reaction was quenched by the addition of HCl aq (20 cm^3; ca. 1 mol/l), and the mixture was extracted with CH_2Cl_2 and dried. Evaporation of the solvent followed by silica gel (20 g) column chromatography using hexane–AcOEt (99:5, 90:10, 85:15, and 80:20) as eluent yielded **15** (150.3 mg, 94% from **13**).

Starting from a mixture of **13** and **14** (29.7 mg, 0.117 mmol) a mixture of **15** and **22** (30.3 mg, 96%) was obtained.

Compounds **21** was obtained from **19** in a 89% yield. For the synthesis of **31a**, **b** and **39a**, **b**, intermediate aldehydes **29a**, **b** and **37a**, **b** were isolated for the separation purpose from their isomers **30a**, **b** and **38a**, **b**, respectively. Namely, a mixture of **27a/28a** afforded **29a** and **30a** in 56 and 35% yields, respectively, after separation by silica-gel column chromatography. A mixture of **27b/28b** afforded **29b** and **30b** in 54, and 41% yields. The carboxylic acids **31a** and **31b** were then synthesized from **29a** and **29b** in 93 and 80% yields, respectively. In the same way, a crude mixture of **35a**, **b/36a**, **b** were oxidized to yield a mixture of **37a**, **b/38a**, **b** (75% from **34a**, **b**), which were separated from each other. The carboxylic acids **39a** and **39b** were then obtained from **37a** and **37b** in 96 and 82% yields, respectively.

3.6.1. 1-[1-(Pivaloyloxymethyl)ethenyl]cyclohexanecarboxylic acid (15). An oil; IR (neat) 2400–3600 (OH), 1733 (C=O), 1700 (C=O), 1640 (C=C), 1282, and 1148 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.19 (9H, s, *t*Bu), 1.42–1.67 (8H, m), 2.11–2.19 (2H, m), 4.62 (2H, d, *J*=0.7 Hz, C*H*$_2$OPiv), 5.29 (1H, br s, C=C*H*H), and 5.35 (1H, t, *J*=0.7 Hz, C=CH*H*); ^{13}C NMR ($CDCl_3$) δ=23.00 (2C), 25.52, 27.14 (3C), 32.54 (2C), 38.76, 50.52, 64.66, 115.90, 144.34, 178.08, and 180.95; MS *m*/*z* 268 (M^+, 82%), 256 (94), 200 (97), 182 (94), 147 (100), and 100 (99); HRMS [Found: *m*/*z* 268.1724 (M^+). Calcd for $C_{15}H_{24}O_4$: *M*, 268.1675].

3.6.2. 1-[1-(Pivaloyloxymethyl)ethenyl]cyclopentanecarboxylic acid (21). An oil; IR (neat) 2400–3600 (OH), 1733 (C=O), 1701 (C=O), 1647 (C=C), 1282, and 1147 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.21 (9H, s, *t*Bu), 1.68–1.85 (6H, m), 2.26–2.34 (2H, m), 4.63 (2H, dd, *J*=0.6, 1.2 Hz, C*H*$_2$OPiv), 5.25 (1H, br s, C=C*H*H), 5.27 (1H, t, *J*=1.2 Hz, C=CH*H*), 9.7–11.2 (1H, very br, CO_2H); ^{13}C NMR ($CDCl_3$) δ=23.47 (2C), 27.11 (3C), 34.66 (2C), 38.75, 58.05, 65.37, 114.23, 144.24, 178.08, and 180.37; MS *m*/*z* 254 (M^+, 100%), 214 (96), 209 (97), 135 (90), and 114 (95); HRMS [Found: *m*/*z* 254.1539 (M^+). Calcd for $C_{14}H_{22}O_4$: *M*, 254.1519].

3.6.3. *trans*-4-*t*Butyl-1-[1-(pivaloyloxymethyl)ethenyl]cyclohexanecarbaldehyde (29a). An oil; IR (neat) 2697 (CHO), 1730 (C=O), 1637 (C=C), 1479, 1458, 1365, 1281, and 1146 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.82 (9H, s, *t*Bu), 0.97–1.18 (3H, m), 1.17 (9H, s, *t*Bu), 1.46 (2H, dt, *J*=2.3, 13.3 Hz), 1.69 (2H, dm, *J*=ca. 13 Hz), 2.09 (2H, dm, *J*=ca. 14 Hz), 4.49 (2H, s, C*H*$_2$OPiv), 5.33 (1H, s, C=C*H*H), 5.61 (1H, s, C=CH*H*), and 9.25 (1H, s, CHO); ^{13}C NMR ($CDCl_3$) δ=22.29 (2C), 27.09 (3C), 27.42 (3C), 28.69 (2C), 32.39, 38.76, 47.84, 54.88, 65.77, 119.75, 139.83, 178.02, and 202.25; MS *m*/*z* 207 (M^+−PivO, 0.8%), 178 (4), 135 (5), 121 (10), 107 (13), and 57 (100); HRMS [Found: *m*/*z* 206.1571 (M^+−PivOH). Calcd for $C_{14}H_{22}O$: *M*, 206.1672].

3.6.4. *cis*-4-*t*Butyl-1-[1-(pivaloyloxymethyl)ethenyl]cyclohexanecarbaldehyde (29b). Mp 74–76°C; IR (CH_2Cl_2) 2705 (CHO), 1724 (C=O), 1719 (C=O), 1636 (C=C), 1479, 1365, and 1152 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.80 (9H, s, *t*Bu), 0.88–1.09 (3H, m), 1.20 (9H, s, *t*Bu), 1.44 (2H, dt, *J*=3.2, 13.3 Hz), 1.73 (2H, dm, *J*=ca. 13 Hz), 2.34 (2H, dm, *J*=ca. 13 Hz), 4.49 (2H, br s, CH_2OPiv), 5.17 (1H, s, C=C*H*H), 5.32 (1H, s, C=CH*H*), and 9.25 (1H, s, CHO); ^{13}C NMR ($CDCl_3$) δ=23.89 (2C), 27.13 (3C), 27.37 (3C), 30.46 (2C), 32.30, 38.76, 47.27, 54.30, 64.10, 116.41, 143.22, 177.86, and 201.84; MS *m*/*z* 207 (M^+−PivO, 2%), 178 (5), 163 (2), 149 (2), 135 (5), 121 (11), 107 (12), and 57 (100); Analysis [Found: C, 73.63; H, 10.29%. Calcd for $C_{19}H_{32}O_3$: C, 73.98; H, 10.46%].

3.6.5. *trans*-4-*t*Butyl-1-(1-methyl-2-pivaloyloxyethenyl)cyclohexanecarbaldehyde (30a). An oil; IR (neat) 1745 (C=O), 1725 (C=O), 1479, 1457, 1365, 1279, and 1136 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.81 (9H, s, *t*Bu), 1.01 (1H, m), 1.14 (2H, dq, *J*=2.6, 12.7 Hz), 1.28 (9H, s, *t*Bu), 1.40 (2H, dt, *J*=2.6, 13.5 Hz), 1.59 (3H, d, *J*=1.5 Hz, Me), 1.68 (2H, dm, *J*=ca. 13 Hz), 2.13 (2H, dm, *J*=ca. 14 Hz), 7.17 (1H, q, *J*=1.5 Hz, C=CH), and 9.17 (1H, s, CHO); ^{13}C NMR ($CDCl_3$) δ=11.14, 22.17 (2C), 27.06 (3C), 27.48 (3C), 28.41 (2C), 32.41, 38.94, 48.07, 53.61, 116.77, 136.26, 175.44, and 201.75; MS *m*/*z* 308 (M^+, 0.3%), 279 (1), 195 (5), 83 (11), and 57 (100); HRMS (FAB) [Found: *m*/*z* 331.2247 (M^++Na). Calcd for $C_{19}H_{32}O_3Na$: *M*, 331.2250].

3.6.6. *cis*-4-*t*Butyl-1-(1-methyl-2-pivaloyloxyethenyl)cyclohexanecarbaldehyde (30b). Mp 74–76°C; IR (CH_2Cl_2) 2698 (CHO), 1744 (C=O), 1723 (C=O), 1662 (C=C), 1480, 1366, 1278, and 1072 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.80 (9H, s, *t*Bu), 0.88–1.04 (3H, m), 1.25 (9H, s, *t*Bu), 1.36 (2H, br t, *J*=ca. 13 Hz), 1.56 (3H, d, *J*=1.4 Hz, Me), 1.73 (2H, m), 2.34 (2H, dm, *J*=ca. 13 Hz), 7.11 (1H, q, *J*=1.4 Hz, C=CH), and 9.13 (1H, s, CHO); ^{13}C NMR ($CDCl_3$) δ=10.34, 23.96 (2C), 27.03 (3C), 27.40 (3C), 30.07 (2C), 32.31, 38.93, 47.45, 53.41, 120.90, 133.88, 175.40, and 201.54; MS *m*/*z* 308 (M^+, 0.4%), 279 (1), 195 (5), 85 (10), and 57 (100); Analysis [Found: C, 73.70; H, 10.27%. Calcd for $C_{19}H_{32}O_3$: C, 73.98; H, 10.46%].

3.6.7. *trans*-4-*t*Butyl-1-[1-(pivaloyloxymethyl)ethenyl]-cyclohexanecarboxylic acid (31a). Mp 135–138°C; IR (CH_2Cl_2) 3420 (OH), 1720 (C=O), 1699 (C=O), 1638 (C=C), and 1154 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.81 (9H, s, *t*Bu), 0.99–1.18 (3H, m), 1.18 (9H, s, *t*Bu), 1.60–1.74 (4H, m), 2.26 (2H, br d, *J*=ca. 13 Hz), 4.59 (2H, s, CH_2OPiv), 5.34 (1H, s, C=C*H*H), and 5.54 (1H, s, C=CH*H*); ^{13}C NMR ($CDCl_3$) δ=22.70 (2C), 27.02 (3C), 27.40 (3C), 31.58 (2C), 32.33, 38.73, 47.64, 49.33, 65.72, 118.75, 140.52, 178.15, and 181.83; MS *m*/*z* 267 (M^+−*t*Bu, 0.8%), 222 (2), 194 (2), 165 (4), 57 (100), and 41 (40); Analysis [Found: C, 70.27; H, 9.69%. Calcd for $C_{19}H_{32}O_4$: C, 70.33; H, 9.94%].

3.6.8. *cis*-4-*t*Butyl-1-[1-(pivaloyloxymethyl)ethenyl]-cyclohexanecarboxylic acid (31b). Mp 88–92°C; IR (Nujol) 2300–3400 (OH), 1740 (C=O), 1697 (C=O), 1643 (C=C), and 1142 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.68 (9H, s, *t*Bu), 0.83 (1H, m), 1.02 (2H, m), 1.07 (9H, s, *t*Bu), 1.25 (2H, dt, *J*=2.5, 12.7 Hz), 1.61 (2H, br d, *J*=ca. 13 Hz), 2.30 (2H, br d, *J*=ca. 13 Hz), 4.50 (2H, s, CH_2OPiv), 5.11 (1H, s, C=C*H*H), and 5.13 (1H, s, C=CH*H*); ^{13}C NMR ($CDCl_3$) δ=24.52 (2C), 27.14 (3C), 27.40 (3C), 32.28, 33.37 (2C), 38.75, 47.24, 50.71, 64.14, 114.37, 145.89, 178.02, and 179.78; MS *m*/*z* 222 (M^+−PivOH, 2%), 207 (2), 165 (5), 57 (100), and 41 (44); HRMS [Found: *m*/*z* 222.1629 (M^+−PivOH). Calcd for $C_{14}H_{22}O_2$: *M*, 222.1621].

3.6.9. *trans*-4-Benzyloxy-1-[1-(pivaloyloxymethyl)ethenyl]-cyclohexanecarbaldehyde (37a). An oil; IR (CH_2Cl_2) 2697 (CHO), 1728 (C=O), 1637 (C=C), 1457, 1281, and 1148 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.18 (9H, s, *t*Bu), 1.65–2.04 (8H, m), 3.51 (1H, quint, *J*=4.7 Hz, C*H*OBn), 4.51 (4H, s, CH_2OPiv and OCH_2Ph), 5.28 (1H, s, C=C*H*H), 5.49 (1H, s, C=CH*H*), 7.24–7.37 (5H, m, Ph), and 9.28 (1H, s, CHO); ^{13}C NMR ($CDCl_3$) δ=25.01 (2C), 26.82 (2C), 27.06 (3C), 38.73, 54.27, 64.77, 69.85, 73.7 (br), 118.7 (br), 127.38, 127.40 (2C), 128.31 (2C), 138.78, 141.33, 177.87, and 201.51; MS *m*/*z* 228 (M^+−PivO–CHO, 1%), 210 (1), 150 (3), 91 (100), 57 (77), and 41 (48); HRMS (FAB) [Found: *m*/*z* 381.2012 (M^++Na). Calcd for $C_{22}H_{30}O_4Na$: *M*, 381.2043].

3.6.10. *cis*-4-Benzyloxy-1-[1-(pivaloyloxymethyl)ethenyl]-cyclohexanecarbaldehyde (37b). An oil; IR (CH_2Cl_2) 2704 (CHO), 1727 (C=O), 1637 (C=C), 1456, and 1149 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.19 (9H, s, *t*Bu), 1.45–2.28 (8H, m), 3.39 (1H, tt, *J*=3.7, 8.5 Hz, C*H*OBn), 4.48 (2H, s, CH_2OPiv), 4.52 (2H, s, OCH_2Ph), 5.23 (1H, br s, C=C*H*H), 5.42 (1H, br s, C=CH*H*), 7.24–7.36 (5H, m, Ph), and 9.26 (1H, s, CHO); ^{13}C NMR ($CDCl_3$) δ=26.54 (2C), 27.10 (3C), 27.77 (2C), 38.74, 54.10, 64.44, 69.82, 75.06, 117.73, 127.41 (3C), 128.33 (2C), 138.76, 141.53, 177.86, and 201.02; MS *m*/*z* 165 (M^+−PivOH–Bn, 2%), 120 (7), 91 (100), 57 (78), and 41 (50); HRMS (FAB) [Found: *m*/*z* 381.2071 (M^++Na). Calcd for $C_{22}H_{30}O_4Na$: *M*, 381.2043].

3.6.11. *trans*-4-Benzyloxy-1-(1-methyl-2-pivaloyloxyethenyl)cyclohexanecarbaldehyde (38a). An oil; IR (CH_2Cl_2) 2694 (CHO), 1741 (C=O), 1456, 1279, and 1143 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.26 (9H, s, *t*Bu), 1.56–2.00 (8H, m), 1.58 (3H, d, *J*=1.5 Hz, Me), 3.53 (1H, br tt, *J*=2.9, 5.2 Hz, C*H*OBn), 4.50 (2H, s, OCH_2Ph), 7.19 (1H, q, *J*=1.5 Hz, C=CH), 7.24–7.36 (5H, m, Ph), and 9.18 (1H, s, CHO); ^{13}C NMR ($CDCl_3$) δ=10.55, 24.50 (2C), 26.73 (2C), 27.02 (3C), 38.92, 53.28, 69.87, 73.6 (br), 118.7 (br), 127.40 (3C), 128.33 (2C), 134.95, 138.82, 175.24, and 201.16; MS *m*/*z* 137 (M^+−PivO–CHO–Bn, 3%), 91 (31), 57 (100), and 41 (24); HRMS [Found: *m*/*z* 137.0880 (M^+−PivO–CHO–Bn). Calcd for $C_9H_{13}O$: *M*, 137.0967].

3.6.12. *cis*-4-Benzyloxy-1-(1-methyl-2-pivaloyloxyethenyl)-cyclohexanecarbaldehyde (38b). An oil; IR (CH_2Cl_2) 2695 (CHO), 1742 (C=O), 1724 (C=O), 1637 (C=C), 1456, 1279, and 1140 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.26 (9H, s, *t*Bu), 1.37–2.30 (8H, m), 1.58 (3H, d, *J*=1.1 Hz, Me), 3.36 (1H, tt, *J*=3.7, 8.9 Hz, C*H*OBn), 4.52 (2H, s, OCH_2Ph), 7.13 (1H, q, *J*=1.1 Hz, C=CH), 7.23–7.35 (5H, m, Ph), and 9.15 (1H, s, CHO); ^{13}C NMR ($CDCl_3$) δ=10.60, 26.58 (2C), 27.01 (3C), 28.07 (2C), 38.92, 53.15, 69.87, 75.66, 119.33, 127.46 (3C), 128.34 (2C), 134.47, 138.80, 175.37, and 200.66; MS *m*/*z* 166 (M^+−PivO–Bn, 1%), 137 (4), 91 (32), 57 (100), and 41 (24); HRMS [Found: *m*/*z* 137.0867 (M^+−PivO–CHO–Bn). Calcd for $C_9H_{13}O$: *M*, 137.0967].

3.6.13. *trans*-4-Benzyloxy-1-[1-(pivaloyloxymethyl)-ethenyl]cyclohexanecarboxylic acid (39a). Mp 90–92°C; IR (CH_2Cl_2) 2400–3400 (OH), 1724 (C=O), 1700 (C=O), 1641 (C=C), 1455, 1154, and 702 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.19 (9H, s, *t*Bu), 1.71–1.80 (4H, m), 1.94–2.09 (4H, m), 3.55 (1H, quint, *J*=4.8 Hz, C*H*OBn), 4.51 (2H, s, OCH_2Ph), 4.63 (2H, s, CH_2OPiv), 5.34 (1H, s, C=C*H*H), 5.41 (1H, br s, C=CH*H*), and 7.24–7.36 (5H, m, Ph); ^{13}C NMR ($CDCl_3$) δ=27.08 (3C), 27.42 (2C), 27.99 (2C), 38.72, 49.90, 64.72, 69.87, 75.6 (br), 116.7 (br), 127.40 (3C), 128.32 (2C), 138.84, 143.2 (br), 178.03 and 180.67; MS *m*/*z* 181 (M^+−PivOH–Bn, 39%), 152 (1), 111 (5), and 91 (100); HRMS [Found: *m*/*z* 181.0868 (M^+−PivOH–Bn). Calcd for $C_{10}H_{13}O_3$: *M*, 181.0865].

3.6.14. *cis*-4-Benzyloxy-1-[1-(pivaloyloxymethyl)ethenyl]-cyclohexanecarboxylic acid (39b). Mp 82–84°C; IR (CH_2Cl_2) 2600–3600 (OH), 1730 (C=O), 1702 (C=O), 1637 (C=C), 1455, 1282, and 1154 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.20 (9H, s, *t*Bu), 1.48–1.63 (4H, m), 1.93–2.04 (2H, m), 2.36–2.44 (2H, m), 3.35–3.43 (1H, m, C*H*OBn), 4.56 (2H, s, OCH_2Ph), 4.62 (2H, br s, CH_2OPiv), 5.28 (1H, s, C=C*H*H), 5.32 (1H, s, C=CH*H*), and 7.24–7.35 (5H, m, Ph); ^{13}C NMR ($CDCl_3$) δ=27.11 (3C), 28.77 (2C), 30.13 (2C), 38.74, 50.14, 64.33, 69.87, 75.6 (br), 115.62, 127.48, 127.57 (2C), 128.34 (2C), 138.60, 144.1 (br), 178.05 and 179.09; MS *m*/*z* 166 (M^+−PivO–BnO, 18%), 138 (14), 121 (7), 107 (11), and 91 (100); HRMS [Found: *m*/*z* 166.0954 (M^+−PivO–BnO). Calcd for $C_{10}H_{14}O_2$: *M*, 166.0994].

3.7. Lactonization

To a stirred solution of **15** (93.0 mg, 0.347 mmol) in THF (10 cm^3) was added an aqueous solution of NaOH (15 cm^3; 2 mol/l) and water (20 cm^3). After being stirred for 26 h at room temperature, HCl aq (20 cm^3; 2 mol/l) was added, and the mixture was extracted with CH_2Cl_2 followed by

drying. The solvent was evaporated to give an oily residue, which was chromatographed on silica gel (18 g) using hexane–AcOEt (85:15) as eluent to afford **4** (48.9 mg, 85%).

A mixture of **15** and **22** (30.2 mg, 0.113 mmol) afforded **15** (10.9 mg, 58%) and **23** (5.7 mg, 27%).

Compounds **5**, **6a**, **6b**, **7a** and **7b** were obtained in 88, 96, 93, 94, 94% yields, respectively, from corresponding carboxylic acids.

3.7.1. 4-Methylene-2-oxaspiro[4.5]decan-1-one (4). An oil; IR (neat) 1776 (C=O), 1669 (C=C), 1449, 1351, 1171, 1116, 1031, and 901 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.38–1.96 (10H, m), 4.77 (2H, t, J=2.2 Hz, CH_2O), 5.08 (1H, dt, J=0.7, 2.2 Hz, C=C*H*H), and 5.17 (1H, dt, J=0.7, 2.2 Hz, C=CH*H*); ^{13}C NMR ($CDCl_3$) δ=21.03 ($2CH_2$), 25.10 (CH_2), 33.37 ($2CH_2$), 44.70 (C), 69.34 (CH_2), 107.24 (CH_2), 149.33 (C), and 179.89 (CO); MS m/z 166 (M^+, 93%), 121 (16), 111 (9), 78 (93), and 66 (100); HRMS [Found: m/z 166.1018 (M^+). Calcd for $C_{10}H_{14}O_2$: M, 166.0994].

3.7.2. 4-Methylene-2-oxaspiro[4.4]nonan-1-one (5). An oil; IR (neat) 1782 (C=O), 1671 (C=C), 1466, 1139, and 1028 cm^{-1}; ^1H NMR ($CDCl_3$, TMS=0.00) δ=1.75–2.18 (8H, m), 4.81 (2H, dd, J=2.0, 2.4 Hz, CH_2O), 5.02 (1H, dt, J=0.6, 2.0 Hz, C=C*H*H), and 5.04 (1H, dt, J=0.6, 2.4 Hz, C=CH*H*); ^{13}C NMR ($CDCl_3$) δ=26.05 (2C), 38.41 (2C), 51.80, 70.14, 105.89, 150.12, and 182.02; MS m/z 152 (M^+, 13%), 124 (6), 111 (24), 93 (94), and 79 (100); HRMS [Found: m/z 152.0820 (M^+). Calcd for $C_9H_{12}O_2$: M, 152.0838].

3.7.3. *trans*-8-*t*Butyl-4-methylene-2-oxaspiro[4.5]decan-1-one (6a). Mp 74–76°C; IR (CH_2Cl_2) 1769 (C=O), 1670 (C=C), 1169, and 1025 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.88 (9H, s, *t*Bu), 1.14 (1H, tt, J=3.2, 12.2 Hz, 8-H), 1.33 (2H, ddt, J=7.4, 10.0, 12.6 Hz, 7_{ax}-H_2), 1.71–1.86 (6H, m, 6-H_4 and 7_{eq}-H_2), 4.72 (2H, t, J=2.2 Hz, 3-H_2), 5.11 (1H, t, J=2.0 Hz, C=C*H*H), and 5.34 (1H, t, J=2.4 Hz, C=CH*H*); ^{13}C NMR ($CDCl_3$) δ=21.88 (2C), 27.32 (3C), 32.38 (2C), 32.48, 45.34, 46.54, 69.63, 109.08, 147.89, and 181.30; MS m/z 207 (M^+−Me, 7%),194 (2), 177 (3), 165 (22), 93 (23), 79 (26), 57 (100), and 41 (82); HRMS [Found: m/z 207.1338 (M^+−Me). Calcd for $C_{13}H_{19}O_2$: M, 207.1386].

3.7.4. *cis*-8-*t*Butyl-4-methylene-2-oxaspiro[4.5]decan-1-one (6b). Mp 55–57°C; IR (CH_2Cl_2) 1763 (C=O), 1671 (C=C), 1110, and 1035 cm^{-1}; ^1H NMR ($CDCl_3$) δ=0.89 (9H, s, *t*Bu), 1.05 (1H, tt, J=3.3, 12.1 Hz, 8-H), 1.46 (2H, dt, J=3.9, 13.4 Hz, 6_{ax}-H_2), 1.64 (2H, dm, J=ca. 13 Hz, 7_{eq}-H_2), 1.78 (2H, dq, J=3.3, 12.9 Hz, 7_{ax}-H_2), 1.95 (2H, dm, J=ca. 13 Hz, 6_{eq}-H_2), 4.78 (2H, t, J=2.2 Hz, 3-H_2), 5.01 (1H, dt, J=0.5, 2.4 Hz, C=C*H*H), and 5.03 (1H, dt, J=0.5, 2.0 Hz, C=CH*H*); ^{13}C NMR ($CDCl_3$) δ=22.18 (2C), 27.55 (3C), 32.50, 35.05 (2C), 43.95, 47.42, 69.18, 105.95, 150.06, and 179.21; MS m/z 207 (M^+−Me, 7%), 194 (7), 177 (12), 166 (45), 138 (40), 57 (64), and 41 (100); HRMS [Found: m/z 207.1333 (M^+−Me). Calcd for $C_{13}H_{19}O_2$: M, 207.1386].

3.7.5. *trans*-8-Benzyloxy-4-methylene-2-oxaspiro[4.5]decan-1-one (7a). An oil; IR (neat) 1769 (C=O), 1670 (C=C), 1452, 1352, 1095, and 1029 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.70–1.85 (4H, m, 6_{eq}-H_2, 7_{eq}-H_2), 1.90 (2H, br ddd-like, J=3, 9, 13 Hz, 6_{ax}-H_2), 2.11–2.20 (2H, m, 7_{ax}-H_2), 3.66 (1H, tt, J=3.1, 6.0 Hz, 8-H), 4.55 (2H, s, OCH_2Ph), 4.78 (2H, dd, J=2.0, 2.4 Hz, 3-H_2), 5.10 (1H, dt, J=0.7, 2.0 Hz, C=C*H*H), 5.24 (1H, dt, J=0.7, 2.4 Hz, C=CH*H*), and 7.26–7.38 (5H, m, Ph); ^{13}C NMR ($CDCl_3$) δ=25.85 (2C), 29.22 (2C), 44.19, 69.48, 69.95, 73.35, 107.84, 127.42 (2C), 127.47, 128.38 (2C), 138.92, 148.70, and 179.85; MS m/z 181 (M^+−CH_2Ph, 26%), 111 (4), 91 (100), and 65 (14); MS (CI method) m/z 273 (M^++H, 66%), 181 (23), 165 (42), 85 (62), and 69 (100); HRMS [Found: m/z 181.0875 (M^+−CH_2Ph). Calcd for $C_{10}H_{13}O_3$: M, 181.0865].

3.7.6. *cis*-8-Benzyloxy-4-methylene-2-oxaspiro[4.5]decan-1-one (7b). An oil; IR (neat) 1765 (C=O), 1671 (C=C), 1450, 1350, 1097, and 1029 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.52 (2H, br ddd-like, J=4, 11, 14 Hz, 6_{ax}-H_2), 1.88–2.15 (6H, m, 7-H_4, 6_{eq}-H_2), 3.49 (1H, tt-like, J=3.9, 9.3 Hz, 8-H), 4.58 (2H, s, OCH_2Ph), 4.78 (2H, t, J=2.2 Hz, 3-H_2), 5.07 (1H, dt, J=0.7, 2.2 Hz, C=C*H*H), 5.08 (1H, dt, J=0.7, 2.2 Hz, C=CH*H*), and 7.25–7.38 (5H, m, Ph); ^{13}C NMR ($CDCl_3$) δ=26.62 (2C), 31.51 (2C), 43.80, 69.28, 69.71, 75.31, 106.87, 127.39, 127.46 (2C), 128.34 (2C), 138.96, 148.89, and 178.93; MS m/z 181 (M^+−CH_2Ph, 89%), 167 (99), 136 (100), 121 (99), and 107 (99); HRMS [Found: m/z 181.0842 (M^+−CH_2Ph). Calcd for $C_{10}H_{13}O_3$: M, 181.0865].

3.7.7. 3-Hydroxy-4-methyl-2-oxaspiro[4.5]decan-1-one (23). An oil; IR (neat) 3398 (OH), 1763 (C=O), 1743 (C=O), 1451, 1190, 1151, 1134, and 959 cm^{-1}; ^1H NMR ($CDCl_3$) δ=1.03 (3H×1/4, d, J=7.2 Hz, Me of the minor isomer), 1.06 (3H×3/4, d, J=7.2 Hz, Me of the major isomer), 1.22–2.09 (10H, m), 2.18 (1H×3/4, dq, J=3.9, 7.2 Hz, C*H*Me of the major isomer), 2.26 (1H×1/4, dq, J=5.3, 7.2 Hz, C*H*Me of the minor isomer), 3.9–4.6 (1H, very br, OH), 5.40 (1H×3/4, d, J=3.9 Hz, C*H*OH of the major isomer), 5.72 (1H×1/4, d, J=5.3 Hz, C*H*OH of the minor isomer); ^{13}C NMR ($CDCl_3$) assigned for the major isomer: δ=12.01, 21.78, 21.88, 25.20, 28.26, 33.81, 45.65, 46.37, 102.18, and 180.58; assigned for the minor isomer: δ=8.13, 21.32, 21.69, 25.26, 29.49, 33.26, 44.37, 45.65, 97.76, and 180.78; MS m/z 184 (M^+, 93%), 166 (86), 156 (100), 142 (91), 108 (93), 100 (99), and 78 (96); HRMS [Found: m/z 184.1069 (M^+). Calcd for $C_{10}H_{16}O_3$:, M, 184.1100].

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