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One-carbon homologation of unsymmetrical ketones through magnesium β-oxido carbenoid rearrangement and trapping the enolate intermediates with electrophiles

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ABSTRACT

A procedure for one-carbon homologation of unsymmetrical ketones, including one-carbon ring-expansion of 2-substituted cyclohexanones, through magnesium β-oxido carbenoid rearrangement as the key reaction is described. Addition of the α-sulfinyl carbanion of 1-chloroethyl *p*-tolyl sulfoxide to an unsymmetrical ketone gave two diastereomers as adducts in good yields. The adducts were treated with a base to give alkoxides, which were treated with a Grignard reagent to give magnesium β-oxido carbenoids. The β-oxido carbenoid rearrangement then took place to afford one-carbon homologated ketones having a methyl group at the α-position. Remarkable specificity or selectivity was observed in the rearrangement. The magnesium enolate intermediates of this reaction were found to be able to get trapped with several electrophiles to give one-carbon homologated α,α-disubstituted ketones. Origin of the specificity and selectivity is also discussed.

1. Introduction

Homologation of carbonyl compounds from lower carbonyl compounds by carbon–carbon coupling is a very useful procedure for obtaining the desired carbonyl compounds.[1] If the homologation reactions are applied to cyclic carbonyl compounds, ring-expanded carbonyl compounds will be obtained.[2] The β-oxido carbenoid rearrangement is reported to be one of the most reliable reactions for one-carbon homologation of carbonyl compounds including one-carbon ring-expansion of cyclic ketones. The methods reported from Villieras and Normant,[3] Korbrich,[4] and Nozaki et al.[5] are based on the lithium β-oxido carbenoid rearrangement of the adduct of carbonyl compounds with dichloromethyllithium or dibromomethyllithium. A similar reaction using the adduct of cyclic ketones with bis(phenylthio)methyllithium was reported by Cohen.[6]

We have also been interested in the homologation of carbonyl compounds with the β-oxido carbenoid rearrangement as the key reaction for a long time. Our previous method was based on the rearrangement of lithium β-oxido carbenoids derived from adducts of carbonyl compounds with the lithium α-sulfinyl carbanion of aryl 1-chloroalkyl sulfoxides.[7] Recently, magnesium β-oxido carbenoid rearrangement was found to be better reaction for our homologation and a versatile procedure for homologation of ketones and aldehydes was established.[8] In all of our investigations mentioned above, we mainly used symmetrical ketones and aldehydes as carbonyl compounds.

In continuation of our interest in the homologation of carbonyl compounds via the magnesium β-oxido carbenoid rearrangement, we recently studied the homologation by using *unsymmetrical ketones* and interesting specificity or selectivity was observed in the rearrangement. Thus, as shown in Scheme 1, an unsymmetrical ketone **1** was treated with the lithium α-sulfinyl carbanion of 1-chloroethyl *p*-tolyl sulfoxide to afford adduct **2** as a mixture of separable two diastereomers. The adducts **2** were separated and each isomer was treated with *t*-BuMgCl (to form magnesium alkoxide) followed by alkylmetal (Grignard reagent or in some cases *t*-BuLi) to give magnesium β-oxido carbenoid **3**. Stereospecific or stereoselective magnesium β-oxido carbenoid rearrangement took place to give one-carbon elongated enolate **4** and/or **5**. Finally, the enolate intermediates were treated with electrophiles to give one-carbon homologated α,α-disubstituted ketones **6** and/or **7** in good overall yields from the adduct **2**. Details of this procedure and discussion of the origin of the specificity and selectivity are described hereinafter.[8d]

2. Results and discussion

2.1. One-carbon homologation of unsymmetrical acyclic ketones and trapping the enolate intermedates

At first, lithium α-sulfinyl carbanion of 1-chloroethyl *p*-tolyl sulfoxide was reacted with acetophenone, as an unsymmetrical

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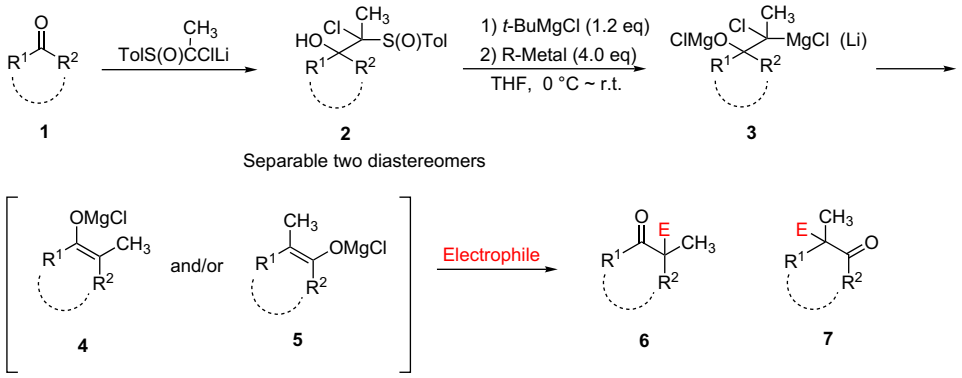
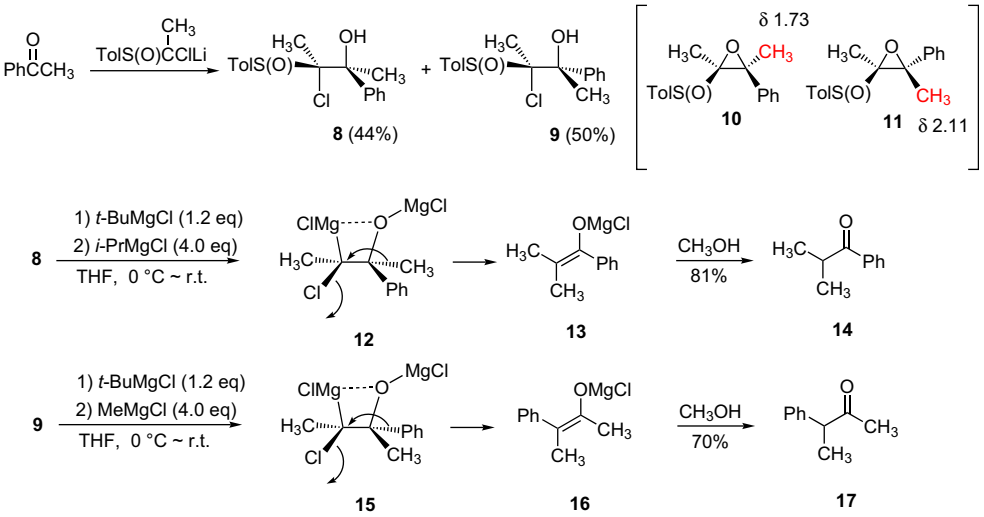


Scheme 1.



Scheme 2.

ketone, to give adducts as a mixture of separable two diastereomers (less polar adduct **8** and more polar adduct **9** on a silica gel plate) in a quantitative yield (Scheme 2). The configuration of each isomer **8** and **9** was determined as shown in Scheme 2 by using the previously reported method.[9a] Thus, each adduct **8** and **9** were converted to sulfinyloxiranes **10** and **11**,[9b] respectively, in high yields by treatment with *t*-BuOK. The configuration of the sulfinyloxiranes was easily determined from their ^{1}H NMR (this case, the chemical shift of the methyl groups mentioned in Scheme 2).[9a] As the epoxidation is the intramolecular S_N2 reaction, the configuration of **8** and **9** is easily determined from the structure of the corresponding sulfinyloxiranes **10** and **11**.

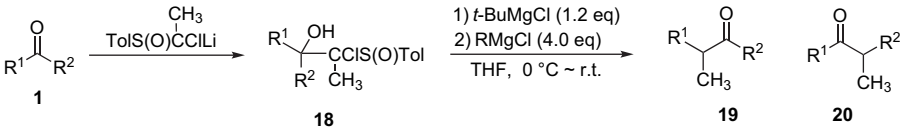
The adduct **8** was treated with *t*-BuMgCl followed by *i*-PrMgCl in THF at 0 °C and the reaction mixture was slowly allowed to warm to room temperature. From this treatment, we obtained isopropyl phenyl ketone **14** in 81% yield and isopropyl *p*-tolyl sulfoxide as the product from the sulfoxide–magnesium exchange reaction in a quantitative yield. Quite interestingly, the same treatment of **9** with *i*-PrMgCl did not give the desired ketone but a complex mixture. In this case, methylmagnesium chloride was found to be the best Grignard reagent to the reaction to afford 3-phenyl-2-butanone **17** as a sole product in 70% yield. It is worth noting that these magnesium β-oxido carbenoid rearrangements are highly stereospecific.

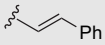
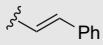
These specificities are explained as follows (see Scheme 2). The sulfoxide–magnesium exchange reaction[10] of the magnesium alkoxide of **8** gives β-oxido carbenoid **12**, whose conformation must be fixed by formation of a chelate ring as shown in Scheme 2. β-Oxido carbenoid rearrangement would take place from back side of the chlorine atom,[5c] in this case the methyl group, to give magnesium enolate **13**, from which ketone **14** is produced by the protonation with methanol. The situation must be quite similar in the case of the reaction with **9** (this case the phenyl group was migrated) to give **17** via β-oxido carbenoid intermediate **15** and enolate **16**.

Next, generality of this reaction was investigated with valerophenone, 3-methyl-1-phenyl-2-buten-1-one, *trans*-chalcone, 2-decanone, and 3-undecanone as representative unsymmetrical ketones and the results are summarized in Table 1. The addition reaction of the lithium α-sulfinyl carbanion of 1-chloroethyl *p*-tolyl sulfoxide with valerophenone resulted in the formation of adducts **18a-L** and **18a-P** in good yield. The magnesium β-oxido carbenoid rearrangement reaction starting from **18a-L** gave homologated ketones (**19a** and **20a**) in high yield; however, the product was a mixture of separable two isomers and the specificity was found to be somewhat low (entry 1).

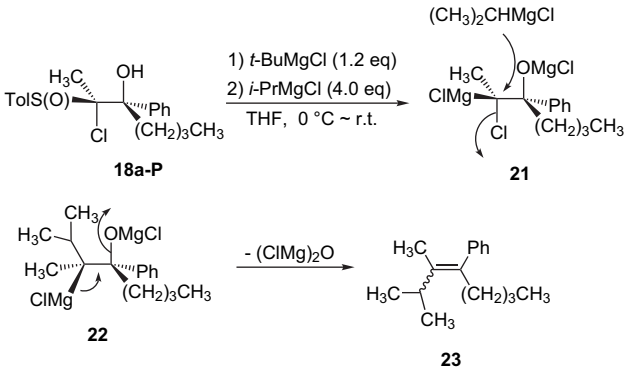
The reaction of **18a-P** with *i*-PrMgCl gave the desired homologated ketone **19a** in low yield (28%) with isopropylated olefin **23** as a product in 43% yield (Scheme 3; the configuration not determined). The mechanism of this olefin formation is expected to be as follows. First, reaction of **18a-P** with *t*-BuMgCl followed by *i*-PrMgCl gives magnesium β-oxido carbenoid **21**. In this particular case, *i*-PrMgCl attacks the carbenoid carbon to give isopropylated alkylmagnesium compound **22**. Finally, elimination of the magnesium oxide derivative from **22** affords an olefin with an isopropyl group **23**.

Table 1
One-carbon homologation of unsymmetrical ketones through magnesium β-oxido carbenoid



Entry	1		18[a] (Yield, %)	RMgCl	Time (h)	19	20
	R^1	R^2				Yield (%)	Yield (%)
1	Ph	$CH_2CH_2CH_2CH_3$	**18a-L** (28)	*i*-PrMgCl	0.5	29	60
2	Ph	$CH_2CH_2CH_2CH_3$	**18a-P** (48)	MeMgCl	1.0	69	0
3	Ph		**18b-L** (23)	*i*-PrMgCl	0.5	0	74
4	Ph		**18b-P** (52)	MeMgCl	1.0	75	0
5	CH_3		**18c-L** (57)	*i*-PrMgCl	0.5	0	93
6	CH_3		**18c-P** (33)	*i*-PrMgCl	0.5	19	19
7	CH_3	$CH_2(CH_2)_6CH_3$	**18d**[b] (85)	*i*-PrMgCl	0.5	31	35
8	CH_2CH_3	$CH_2(CH_2)_6CH_3$	**18e-L** (38)	*i*-PrMgCl	0.5	33	8
9	CH_2CH_3	$CH_2(CH_2)_6CH_3$	**18e-P** (43)	*i*-PrMgCl	0.5	15	49

[a] The letters **L** and **P** refer to less polar and more polar products, respectively, on a silica gel plate using a mixture of hexane and ethyl acetate as a developing solvent.
[b] A mixture of inseparable two diastereomers.



Scheme 3.

Using MeMgCl instead of *i*-PrMgCl was again found to be effective in this case and **19a** was obtained in 69% yield as a sole product (entry 2). The reaction starting from 3-methyl-1-phenyl-2-buten-1-one was found to be highly stereospecific and the homologated ketones **19b** and **20b** were obtained in good yields (entries 3 and 4). Highly specific rearrangement reaction of **18c-L**, derived from *trans*-chalcone, was observed to afford **20c** in 93% yield (entry 5). However, the reaction with isomer **18c-P** gave quite low yield of ketones **19c** and **20c** with almost no specificity (entry 6). Entries 7–9 show the results with aliphatic unsymmetrical ketones. As shown in the table, the rearrangement shows some stereospecificities; however, the ratios of **19** and **20** are not high.

As shown in Scheme 1, the product of the β-oxido carbenoid rearrangement is known to be an enolate[4–6] and in our previous paper we established a versatile new method for a synthesis of α,α-disubstituted carbonyl compounds with one-carbon homologation in one pot by trapping of the enolate intermediates with several electrophiles.[8c] As an extension of the presented reaction, we investigated trapping the magnesium enolate intermediates with aldehydes, acid chlorides, and allyl iodide starting from the selected adducts (see Table 2).

Representative reaction is as follows (entry 1). Adduct **8** was treated with *t*-BuMgCl followed by *i*-PrMgCl in THF at 0 °C and the reaction mixture was allowed to warm to room temperature. The temperature of the reaction mixture was then cooled to −70 °C, and propionaldehyde (4 equiv) was added. The temperature of the reaction mixture was slowly allowed to warm to room temperature for 2 h to give 3-hydroxy-2,2-dimethyl-1-phenyl-1-pentanone **24a** in 54% yield. The reaction starting from **9** (entry 4) gave 4-hydroxy-3-methyl-3-phenyl-2-hexanone **25a**, which is a structural isomer of **24a**; however, the yield was not satisfactory.

Trapping of the magnesium enolate intermediates with acid chlorides gave the desired β-diketone derivatives in good to high yields (entries 2, 5, 9, and 11). The allylation of the magnesium enolate intermediates with allyl iodide proceeds in the presence of HMPA (4 equiv) to afford the desired allylated ketones in moderate to good yields (entries 3, 7, 10, and 12).

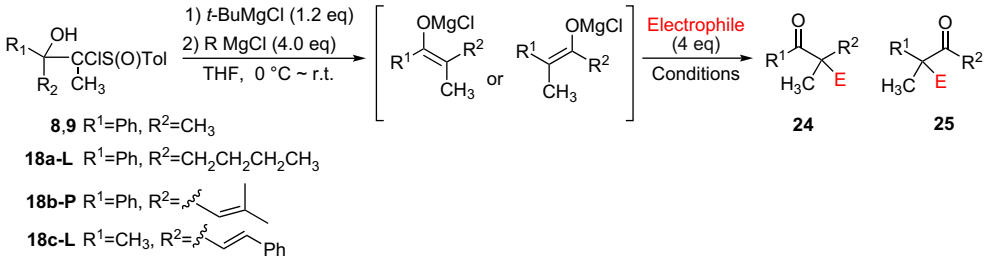
2.2. One-carbon homologation of 2-substituted cyclohexanones and trapping the enolate intermediates

Next, the presented homologation was applied to 2-methylcyclohexanone derivative **26** as an example of unsymmetrical cyclic ketones (Scheme 4). Thus, the reaction of the lithium α-sulfinyl carbanion of 1-chloroethyl *p*-tolyl sulfoxide with cyclohexanone derivative **26** gave two adducts **27** (60%) and **28** (35%) as easily separable two diastereomers. The stereochemistry of each adduct was determined by X-ray crystallographic analysis as shown in Figure 1 (vide infra).[11] Main adduct **27** was treated with *t*-BuMgCl (1.2 equiv) followed by *i*-PrMgCl (4 equiv) in THF at 0 °C. The sulfoxide–magnesium exchange reaction took place smoothly to give ring-expanded product **29** in 83% yield with trace amount of isomer **30**. The cycloheptanone derivative **29** was obtained as a mixture of separable two diastereomers (ratio about 10:1) and the main product, 1,7-*cis*-dimethyl product, is shown in Scheme 4.

Significant difference in the reactivity of **27** and **28** with *i*-PrMgCl was observed. Thus, when the minor adduct **28** was treated with *t*-BuMgCl (1.2 equiv) followed by *i*-PrMgCl (4 equiv) in THF, the reaction was rather slow and significant amount of starting material **28** was recovered. Increasing of the amount of *i*-PrMgCl (8 equiv) and prolonging the reaction time gave completed reaction and the same cycloheptanone **29** was obtained in 64% yield. Namely, these two reactions are highly selective.

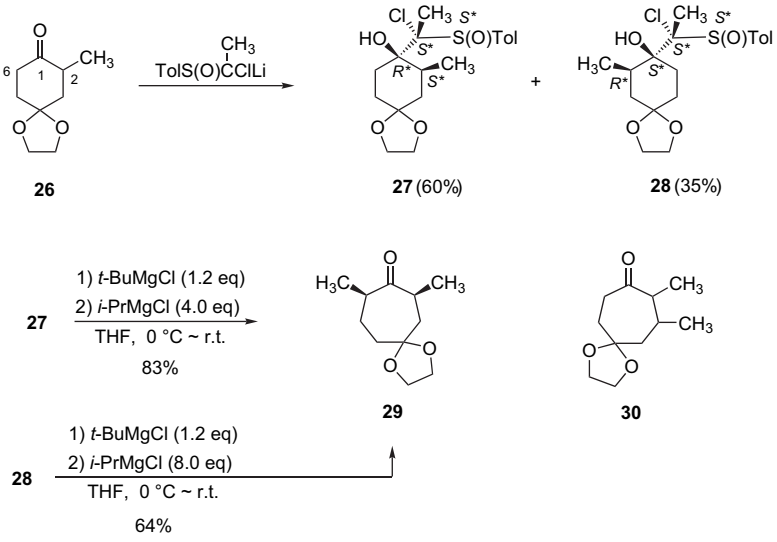
Obviously, the product **29** was derived from the one-carbon insertion between C_1 and C_6 carbons of adduct **27** by the β-oxido carbenoid rearrangement (less substituted carbon was migrated).

Table 2
Generation of the magnesium β-oxido carbenoids from adducts **8**, **9**, and **18** with a Grignard reagent and trapping the magnesium enolate intermediated with electrophiles to give α,α-disubstituted ketones **24** or **25**



Entry	Adduct	R-metal	Electrophile	Conditions	E	Product **24** or **25**	Yield (%)
1	**8**	*i*-PrMgCl	CH_3CH_2CHO	−70 °C to rt, 2 h	$CH_3CH_2CH(OH)$	**24a**	54
2			PhCOCl	rt, 1 h	PhCO	**24b**	77
3			 [a]	rt, 15 h		**24c**	64
4	**9**	MeMgCl	CH_3CH_2CHO	−70 °C, 1 h	$CH_3CH_2CH(OH)$	**25a**	24[b]
5			CH_3COCl	rt, 0.5 h	CH_3CO	**25b**	51
6	**18a-P**	MeMgCl	PhCHO	−70 °C, 1 h	PhCH(OH)	**25c**	62[c]
7			 [a]	rt, 15 h		**25d**	72
8	**18b-P**	MeMgCl	PhCHO	−70 °C, 1 h	PhCH(OH)	**25e**	53[d]
9			CH_3COCl	rt, 0.5 h	CH_3CO	**25f**	75
10			 [a]	rt, 18 h		**25g**	72
11	**18c-L**	*i*-PrMgCl	PhCOCl	rt, 0.5 h	PhCO	**24d**	99
12			 [a]	rt, 18 h		**24e**	56

[a] HMPA (4 equiv) was added as an additive.
[b] A mixture of two diastereomers (2.4:1).
[c] A mixture of two diastereomers (1.7:1).
[d] A mixture of two diastereomers (2.5:1).



Scheme 4.

As the β-oxido carbenoid rearrangement is classified as nucleophilic rearrangement similar to the Baeyer–Villiger oxidation,[12] it was expected that a more substituted carbon should be migrated. In fact, Hiyama reported selective olefinic carbon migration in his synthesis of nootkatone using β-oxido carbenoid rearrangement as the key reaction.[13] Cohen also reported the migration of a more highly substituted alkyl group in his carbenoid-type base-induced ring-expansion.[6] It is worth noting that the rearrangement observed in our study is in reverse direction to that of Hiyama's and Cohen's results.

This very interesting selectivity could be explained as follows (Scheme 5). As mentioned above, the structure of **27** was determined by X-ray analysis (see Fig. 1).[11] As the sulfinyl group is not sterically hindered, the sulfoxide–magnesium exchange reaction of **27** with *i*-PrMgCl is expected to proceed smoothly to give magnesium carbenoid **A**. Migration of the less substituted carbon would occur from back side of the chlorine atom to give enolate **31**. Conformer **B**, from which more substituted carbon migrated, is thought to be quite unfavorable because of the steric repulsion of two methyl groups depicted in **B**.

As already mentioned, the reactivity of **28** with *i*-PrMgCl was found to be far low compared with that of **27**. This phenomenon could be explained by the steric hindrance of the sulfinyl group of **28** by the methyl group on the cyclohexane ring as depicted (see Scheme 5). In this case, rotation of the bond between the carbon bearing the hydroxyl group and the carbon bearing the sulfinyl

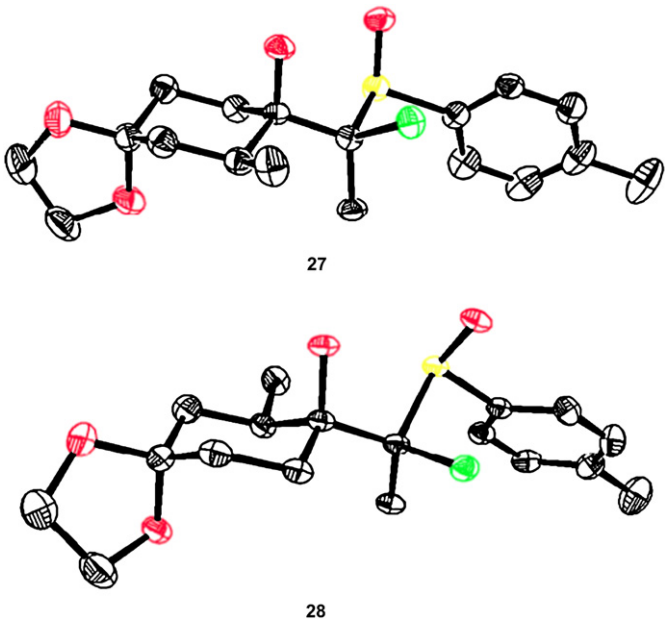


Figure 1. Crystal structure of the adducts **27** and **28**.

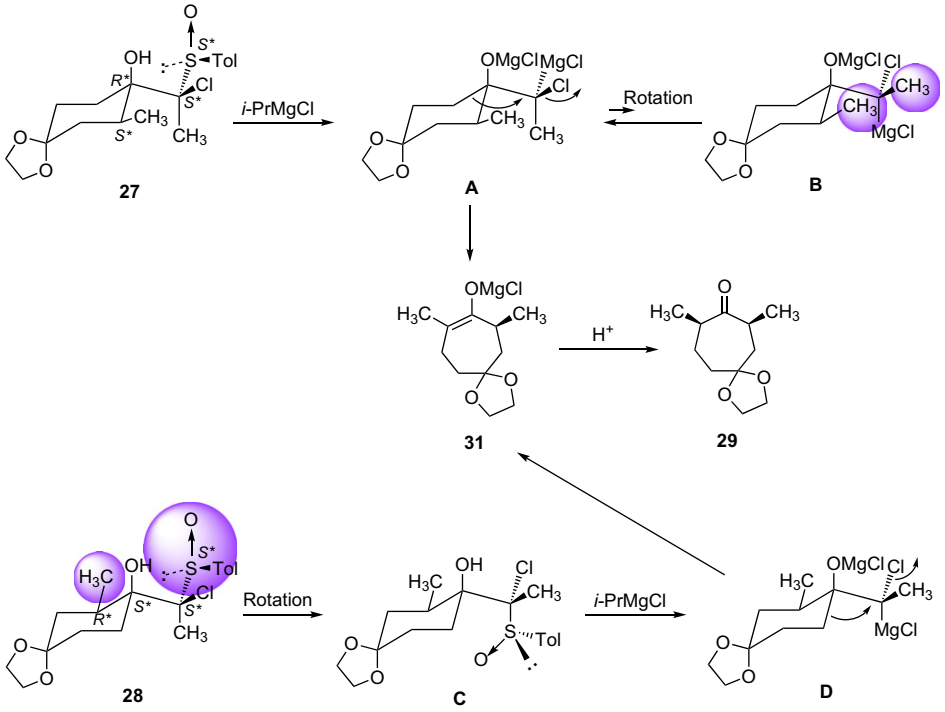
group would give conformer **C**. The sulfoxide–magnesium exchange reaction must occur from this conformer to give magnesium β-oxido carbenoid **D**, from which the less substituted carbon was migrated to afford the same enolate **31**.

We further investigated this chemistry by using 2-cyclohexylcyclohexanone and 2-phenylcyclohexanone with 1-chloroethyl *p*-tolyl sulfoxide and the results are summarized in Table 3. The addition reaction of the lithium α-sulfinyl carbanion of 1-chloroethyl *p*-tolyl sulfoxide with 2-cyclohexylcyclohexanone gave adduct **32a** in good yield as two diastereomers, **32a-L** (60%) and **32a-P** (20%). The main adduct was treated with *t*-BuMgCl followed by *i*-PrMgCl; however, the sulfoxide–magnesium exchange reaction did not take place. In this particular case, we used *t*-BuLi at −70 °C and the desired 2-cyclohexyl-7-methylcyclohepanone **33a** was obtained in 83% yield (entry 1). Again, one-carbon insertion took place between C_1 and C_6 carbons and no 2,3-disubstituted cycloheptanone was obtained.

The reaction of the isomer **32a-P** with *t*-BuMgCl followed by *t*-BuLi at −70 °C was again sluggish and only 14% of the desired **33a** was obtained (entry 2). The reactions starting from 2-phenylcyclohexanone showed quite similar results to afford 2-methyl-7-phenylcycloheptanone **33b** (in this cases, *i*-PrMgCl was effective; entries 3 and 4).

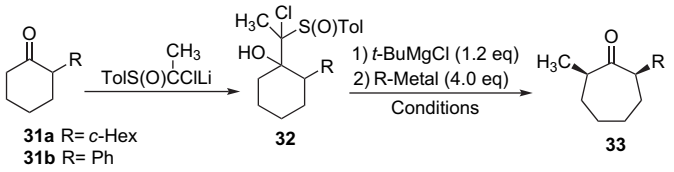
Finally, the trapping of the enolate intermediates of the above-mentioned reactions (**34**) with several electrophiles was investigated and a new method for a synthesis of 2,2,7-trisubstituted cycloheptanones from 2-substituted cyclohexanones was realized. The results are summarized in Table 4.

As shown in entry 1, **27** was treated with *t*-BuMgCl followed by *i*-PrMgCl at room temperature for 5 min. The reaction was quenched by adding excess CH_3OD to give 7-deuterated ketone **35a** in 82% yield with 93% deuterium incorporation (entry 1). Quenching of the reaction with benzaldehyde resulted in the formation of alcohol **35b** in 75% yield (entry 2). In a similar way, the reaction with benzoyl chloride gave diketone **35c** in 73% yield (entry 3). When the trapping was carried out with iodomethane, addition of HMPA as an additive was found to be effective to give 2,2,7-trimethylcycloheptanone **35d** in 73% yield (entry 4). The same reaction was carried out starting from **32a-L** with *t*-BuLi and the results are shown in entries 5–8. By this method, regioselectively substituted cycloheptanone derivatives having multi substituents can be synthesized. Structures of the trisubstituted cycloheptanones **35** and **36** were easily anticipated from the structure of the enolate intermediate. Observation of NOE between the two hydrogen on the carbon bearing the cyclohexyl group and that on the carbon bearing the hydroxyl group in **36b** is an evidence for the stereochemistry of the final products (see the footnote d in Table 4).



Scheme 5.

Table 3
One-carbon ring-expansion of 2-substituted cyclohexanones **31** to 2,7-disubstituted cycloheptanones **33** through the magnesium β-oxido carbenoid rearrangement



Entry	**31** (R)	**32**[a] (Yield, %)	R-metal	Conditions	**33**	Yield (%)
1	*c*-Hex	**32a-L** (60)	*t*-BuLi	−70 °C, 30 min	**33a**	83[b]
2	*c*-Hex	**32a-P** (20)	*t*-BuLi	−70 °C, 30 min	**33a**	14[c]
3	Ph	**32b-L** (54)	*i*-PrMgCl	0 °C to rt, 30 min	**33b**	84[d,e]
4	Ph	**32-P** (30)	*i*-PrMgCl	0 °C to rt, 30 min	**33b**	10[f]

[a] The letters **L** and **P** refer to less polar and more polar products, respectively, on a silica gel plate using a mixture of hexane and ethyl acetate as a developing solvent.
[b] A 10:1 mixture of separable two diastereomers.
[c] About 30% of the starting material was recovered.
[d] About 5% of 2-methyl-3-phenycycloheptanone was obtained.
[e] A 13:1 mixture of two inseparable diastereomers.
[f] About 20% of the starting material was recovered.

3. Experimental

3.1. General

All melting points were measured on a Yanaco MP-S3 apparatus and are uncorrected. ^{1}H NMR spectra were measured in a $CDCl_3$ solution with JEOL JNM-LA 300, 500, BRUKER DPX 400, and AV 600 spectrometer. Electron-impact mass spectra (MS) were obtained at 70 eV by direct insertion by HITACHI M-80B mass spectrometer. IR spectra were recorded on a Perkin–Elmer Spectrum One FT-IR instrument. Silica gel 60N containing 0.5% fluorescence reagent 254 and a quartz column were used for column chromatography and the products having UV absorption were detected by UV irradiation. In experiment requiring a dry solvent and reagent, HMPA and diisopropylamine were distilled from CaH_2 and THF was distilled from diphenylketyl. Compounds **14**,[14] **17**,[15] **19a**,[16] **19b**,[17] **19c**,[18] **20a**,[19] **20b**,[20] **20c**,[21] **20d**,[22] **24b**,[23] and **24c**[24] are known.

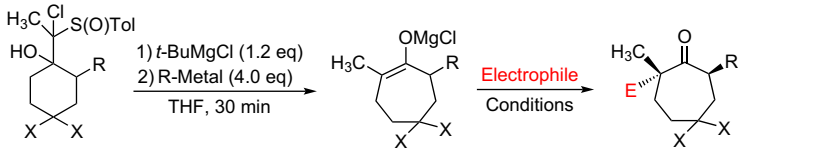
3.2. 3-Chloro-2-phenyl-3-(toluene-4-sulfinyl)butan-2-ol (8 and 9)

To a solution of LDA (3.96 mmol) in 5 mL of dry THF in a flame-dried flask at −70 °C under argon atmosphere was added a solution of 1-chloroethyl *p*-tolyl sulfoxide (669 mg, 3.3 mmol) in 5 mL of dry THF dropwise with stirring and the solution was stirred at −70 °C for 10 min. To this reaction mixture was added a solution of acetophenone (360 mg, 3 mmol) in 5 mL of THF dropwise with stirring. The reaction mixture was stirred at −70 °C for 30 min. The reaction was quenched with satd aq NH_4Cl. The whole was extracted with $CHCl_3$ and the organic layer was dried over $MgSO_4$. The product was purified by silica gel column chromatography to afford **8** (426 mg, 44%) and **9** (484 mg, 50%) as colorless crystals. Compound **8**: colorless crystals; mp 166.5–167.5 °C (hexane–AcOEt); IR (KBr) 3373 (OH), 3031, 2990, 1596, 1446, 1407, 1083, 1050, 1025 (SO), 1011, 699, 506 cm^{-1}; ^{1}H NMR δ 1.34 (3H, s), 2.18 (3H, s), 2.43 (3H, s), 4.71 (1H, s), 7.30–7.39 (5H, m), 7.58 (2H, d, J=8.3 Hz), 7.64–7.66 (2H, m). Anal. Calcd for $C_{17}H_{19}ClO_2S$: C, 63.24; H, 5.93; Cl, 10.98; S, 9.93. Found: C, 63.14; H, 5.94; Cl, 10.93; S, 9.84. Compound **9**: colorless crystals; mp 165–166 °C (hexane–AcOEt); IR (KBr) 3246 (OH), 3060, 2945, 1596, 1445, 1370, 1081, 1029 (SO), 816, 765, 702, 511 cm^{-1}; ^{1}H NMR δ 1.48 (3H, s), 1.82 (3H, s), 2.42 (3H, s), 5.70 (1H, s), 7.29 (2H, d, J=8.0 Hz), 7.37–7.50 (5H, m), 7.71–7.73 (2H, m). Anal. Calcd for $C_{17}H_{19}ClO_2S$: C, 63.24; H, 5.93; Cl, 10.98; S, 9.93. Found: C, 63.07; H, 5.94; Cl, 10.89; S, 9.79.

3.3. Sulfinyloxiranes 10 and 11

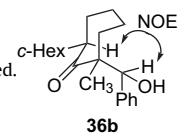
To a solution of adduct **8** (179 mg, 0.5 mmol) in 5 mL of a 1:1 mixture of *t*-BuOH and THF at 0 °C was added a suspension of *t*-BuOK (0.6 mmol) in 2 mL of *t*-BuOH dropwise with stirring. The reaction mixture was stirred at 0 °C for 20 min. The reaction was quenched with satd aq NH_4Cl and the whole mixture was extracted with $CHCl_3$. The product was purified by silica gel column chromatography to give sulfinyloxirane **10** (136 mg, 95%) as colorless crystals; mp 101–102 °C (AcOEt–hexane). Spectral data see literature 9b. The similar treatment of **9** with *t*-BuOK gave **11** as colorless crystals in 93% yield; mp 82–84 °C (AcOEt–hexane). Spectral data see literature 9b.

Table 4
One-carbon ring-expansion of 2-substitued cyclohexanones to 2,2,7-trisubstituted cycloheptanones **35** and **36** through the adducts **27** and **32-L**



Entry	**27** or **32-L**	R-metal	Electrophile	Conditions	E	**35** or **36**	Yield (%)
1	**27**	*i*-PrMgCl	CH_3OD	rt, 5 min	D	**35a**	82[a]
2	**27**	*i*-PrMgCl	PhCHO	rt, 30 min	PhCH(OH)	**35b**	75[b]
3	**27**	*i*-PrMgCl	PhCOCl	rt, 30 min	PhCO	**35c**	73[b]
4	**27**	*t*-BuLi	CH_3I	rt, 15 h	CH_3	**35d**	73[c]
5	**32a-L**	*t*-BuLi	CH_3OD	−70 °C, 5 min	D	**35d**	87[a]
6	**32a-L**	*t*-BuLi	PhCHO	−70 °C, 30 min	PhCH(OH)	**36b**	82[d]
7	**32a-L**	*t*-BuLi	PhCOCl	−70 °C, 30 min	PhCO	**36c**	62[b]
8	**32a-L**	*t*-BuLi	CH_3I	−70 °C to rt, 15 h	CH_3	**36d**	49[c]

[a] Deuterium content 93%.
[b] Single product.
[c] HMPA (4 equiv) was added as an additive.
[d] A 7:1 mixture of two diastereomers. NOE was observed between the two hydrogens depicted.



36b

3.4. Isopropyl phenyl ketone (14)

To a solution of *t*-BuMgCl (0.24 mmol) in 2 mL of dry THF in a flame-dried flask at 0 °C under argon atmosphere was added a solution of adduct **8** (64.6 mg, 0.2 mmol) in 2 mL of dry THF dropwise with stirring. The reaction mixture was stirred at 0 °C for 10 min. To the solution of the magnesium alkoxide was added *i*-PrMgCl (0.8 mmol) dropwise with stirring. The reaction mixture was slowly allowed to warm to room temperature for 30 min. The reaction was quenched with MeOH. The whole was extracted with $CHCl_3$. The organic layer was dried over $MgSO_4$ and the product was purified by silica gel column chromatography to afford **14** (24 mg, 81%) as colorless oil. The spectral data of this product is identical to that reported in literature 14.

3.5. 3-Phenyl-2-butanone (17)

To a solution of *t*-BuMgCl (0.24 mmol) in 2 mL of dry THF in a flame-dried flask at 0 °C under argon atmosphere was added a solution of adduct **9** (64.6 mg, 0.2 mmol) in 2 mL of dry THF dropwise with stirring. The reaction mixture was stirred at 0 °C for 10 min. To the solution of the magnesium alkoxide was added MeMgCl (0.8 mmol) dropwise with stirring. The reaction mixture was slowly allowed to warm to room temperature for 60 min. The reaction was quenched with MeOH. The whole was extracted with $CHCl_3$ and the organic layer was dried over $MgSO_4$. The product was purified by silica gel column chromatography to afford **17** (20.7 mg, 70%) as colorless oil. The spectral data of this product is identical to that reported in the literature 15.

3.6. 2-Chloro-3-phenyl-2-(toluene-4-sulfinyl)heptan-3-ol (18a-L and 18a-P)

Compound **18a-L**: colorless crystals; mp 132–133 °C (hexane–AcOEt); IR (KBr) 3364 (OH), 2953, 2869, 1449, 1367, 1082, 1049 (SO), 817, 703, 510 cm^{-1}; ^1H NMR δ 0.87 (3H, t, J=7.3 Hz), 0.97–1.08 (1H, m), 1.31–1.43 (2H, m), 1.35 (3H, s), 1.45–1.55 (1H, m), 2.45 (1H, ddd, J=13.8, 11.5, 4.3 Hz), 2.42 (3H, s), 2.63 (1H, ddd, J=13.7, 11.4, 4.3 Hz), 4.53 (1H, br s), 7.29–7.39 (5H, m), 7.57–7.60 (4H, m). Anal. Calcd for $C_{20}H_{25}ClO_2S$: C, 65.83; H, 6.91; Cl, 9.71; S, 8.79. Found: C, 65.80; H, 6.88; Cl, 9.62; S, 8.68. Compound **18a-P**: colorless crystals; mp 122–123 °C (hexane–AcOEt); IR (KBr) 3319 (OH), 2962, 2872, 1447, 1424, 1149, 1061, 1030 (SO), 1010, 815, 711 cm^{-1}; ^1H NMR δ 0.74–0.83 (1H, m), 0.82 (3H, t, J=7.3 Hz), 1.18–1.35 (2H, m), 1.37–1.48 (1H, m), 1.50 (3H, s), 2.16 (1H, dddd, J=13.4, 12.0, 4.3, 2.0 Hz), 2.28 (1H, ddd, J=13.2, 12.2, 4.5 Hz), 2.41 (3H, s), 5.68 (1H, d, J=1.9 Hz), 7.28 (2H, d, J=7.9 Hz), 7.39 (1H, tt, J=7.2, 1.1 Hz), 7.44–7.48 (4H, m), 7.61–7.74 (2H, m). Anal. Calcd for $C_{20}H_{25}ClO_2S$: C, 65.83; H, 6.91; Cl, 9.71; S, 8.79. Found: C, 65.80; H, 6.92; Cl, 9.61; S, 8.65.

3.7. 2-Chloro-5-methyl-3-phenyl-2-(toluene-4-sulfinyl)hex-4-en-3-ol (18b-L and 18b-P)

Compound **18b-L**: colorless crystals; mp 151–152 °C (hexane–AcOEt); IR (KBr) 3343 (OH), 2983, 2919, 1660, 1449, 1050, 1025 (SO), 808, 701, 507 cm^{-1}; ^1H NMR δ 1.32 (3H, s), 1.52 (3H, s), 1.90 (3H, d, J=0.9 Hz), 2.42 (3H, s), 4.91 (1H, br s), 6.50 (1H, s), 7.28–7.34 (5H, m), 7.59 (2H, d, J=8.0 Hz), 7.64 (2H, d, J=6.9 Hz). Anal. Calcd for $C_{20}H_{23}ClO_2S$: C, 66.19; H, 6.39; Cl, 9.77; S, 8.83. Found: C, 66.09; H, 6.40; Cl, 9.67; S, 8.74. Compound **18b-P**: colorless crystals; mp 164–165 °C (hexane–AcOEt); IR (KBr) 3231 (OH), 3061, 2911, 1662, 1595, 1447, 1385, 1078, 1045, 1034 (SO), 816, 701 cm^{-1}; ^1H NMR δ 1.32 (3H, d, J=1.2 Hz), 1.43 (3H, s), 1.76 (3H, d, J=1.3 Hz), 2.42 (3H, s), 5.22 (1H, s), 6.13 (1H, s), 7.29 (2H, d, J=8.0 Hz), 7.33–7.39 (3H, m), 7.53 (2H, d, J=8.3 Hz), 7.67–7.69 (2H, m,). Anal. Calcd for $C_{20}H_{23}ClO_2S$: C, 66.19; H, 6.39; Cl, 9.77; S, 8.83. Found: C, 66.16; H, 6.38; Cl, 9.68; S, 8.77.

3.8. 4-Chloro-3-methyl-1-phenyl-4-(toluene-4-sulfinyl)pent-1-en-3-ol (18c-L and 18c-P)

Compound **18c-L**: colorless crystals; mp 94–95 °C (hexane–AcOEt); IR (KBr) 3324 (OH), 2989, 1596, 1419, 1054, 1022 (SO), 752 cm^{-1}; ^1H NMR δ 1.55 (3H, d, J=1.2 Hz), 1.56 (3H, s), 2.44 (3H, s), 5.16 (1H, s), 6.62 (1H, d, J=15.7 Hz), 7.10 (1H, d, J=15.7 Hz), 7.29 (1H, tt, J=7.4, 1.5 Hz), 7.34–7.39 (4H, m), 7.50–7.51 (2H, m), 7.58 (2H, d, J=8.3 Hz). Anal. Calcd for $C_{19}H_{21}ClO_2S$: C, 65.41; H, 6.07; Cl, 10.16; S, 8.60. Found: C, 65.25; H, 5.89; Cl, 9.98; S, 9.03. Compound **18c-P**: colorless crystals; mp 82–83 °C (hexane–AcOEt); IR (KBr) 3282 (OH), 3026, 1597, 1494, 1445, 1369, 1034 (SO) cm^{-1}; ^1H NMR δ 1.56 (3H, s), 1.86 (3H, s), 2.42 (3H, s), 4.28 (1H, s), 6.40 (1H, d, J=15.0 Hz), 6.79 (1H, d, J=16.0 Hz), 7.24–7.28 (1H, m), 7.30–7.34 (4H, m), 7.39–7.41 (2H, m), 7.61 (2H, d, J=7.9 Hz). Anal. Calcd for $C_{19}H_{21}ClO_2S$: C, 65.41; H, 6.07; Cl, 10.16; S, 8.60. Found: C, 65.32; H, 5.97; Cl, 10.06; S, 9.04.

3.9. 2-Chloro-3-methyl-2-(toluene-4-sulfinyl)undecan-3-ol (18d)

A mixture of 1:1 inseparable two diastereomers; colorless crystals; mp 84–86 °C (hexane–AcOEt); IR (KBr) 3349 (OH), 2925, 1598, 1466, 1377, 1036 (SO), 812 cm^{-1}; ^1H NMR δ 0.86–0.91 (3H, m), 1.25–1.53 (16H, m), 1.67 (2H, s), 1.71–1.78 (0.5H, m), 1.84–1.91 (1H, m), 2.12–2.19 (0.5H, m), 2.44 (3H, s), 3.98 (0.5H, s), 4.00 (0.5H, s), 7.34 (2H, d, J=10.1 Hz), 7.61 (2H, dd, J=10.3, 1.8 Hz). Anal. Calcd for $C_{19}H_{31}ClO_2S$: C, 63.57; H, 8.70; Cl, 9.88; S, 8.93. Found: C, 63.54; H, 8.65; Cl, 9.73; S, 8.93.

3.10. 2-Chloro-3-ethyl-2-(toluene-4-sulfinyl)undecan-3-ol (18e-L and 18e-P)

Compound **18e-L**: colorless crystals; mp 56–57 °C (hexane); IR (KBr) 3316 (OH), 2923, 1598, 1401, 1039 (SO), 809 cm^{-1}; ^1H NMR δ 0.88 (3H, t, J=6.8 Hz), 1.12 (3H, t, J=7.5 Hz), 1.21–1.34 (10H, m), 1.41–1.56 (2H, m), 1.46 (3H, s), 1.70–1.87 (2H, m), 2.04 (1H, dq, J=14.6, 7.4 Hz), 2.19 (1H, dq, J=14.8, 7.4 Hz), 2.43 (3H, s), 3.96 (1H, s), 7.33 (2H, d, J=8.2 Hz), 7.60 (2H, d, J=8.2 Hz). Anal. Calcd for $C_{20}H_{33}ClO_2S$: C, 64.40; H, 8.92; Cl, 9.50; S, 8.60. Found: C, 64.46; H, 8.85; Cl, 9.41; S, 8.67. Compound **18e-P**: colorless crystals; mp 63–64 °C (hexane); IR (KBr) 3344 (OH), 2923, 1598, 1466, 1400, 1379, 1031 (SO), 811 cm^{-1}; ^1H NMR δ 0.89 (3H, t, J=6.9 Hz), 1.02 (3H, t, J=7.5 Hz), 1.24–1.40 (10H, m), 1.46 (3H, s), 1.48–1.53 (1H, m), 1.58–1.65 (1H, m), 1.81 (1H, dq, J=14.5, 7.2 Hz), 1.92 (1H, dq, J=14.6, 7.4 Hz), 1.99 (1H, ddd, J=14.1, 12.0, 5.0 Hz), 2.10 (1H, ddd, J=14.2, 12.3, 4.3 Hz), 2.44 (3H, s), 4.01 (1H, s), 7.34 (2H, d, J=8.3 Hz), 7.60 (2H, d, J=8.3 Hz). Anal. Calcd for $C_{20}H_{33}ClO_2S$: C, 64.40; H, 8.92; Cl, 9.50; S, 8.60. Found: C, 64.48; H, 8.85; Cl, 9.40; S, 8.67.

3.11. 2-Methylundecan-3-one (19d)

Colorless oil; IR (neat) 2925, 1715 (CO), 1465 cm^{-1}; ^1H NMR δ 0.88 (3H, t, J=6.9 Hz), 1.09 (6H, d, J=6.8 Hz), 1.21–1.32 (10H, m), 1.52–1.59 (2H, m), 2.43 (2H, t, J=7.4 Hz), 2.59 (1H, septet, J=6.9 Hz). MS m/z (%) 184 (M^+, 23), 141 (100), 99 (5), 86 (33), 71 (56), 43 (47). Calcd for $C_{12}H_{24}O$: M, 184.1827. Found: m/z 184.1828.

3.12. 3-Methyldodecan-4-one (19e)

Colorless oil; IR (neat) 2928, 1713 (CO), 1461, 1379, 1072 cm^{-1}; ^1H NMR δ 0.85–0.89 (6H, m), 1.05 (3H, d, J=6.9 Hz), 1.20–1.32 (10H, m), 1.37 (1H, double quintet, J=14.1, 7.1 Hz), 1.52–1.58 (2H, m), 1.67 (1H, double quintet, J=14.2, 7.1 Hz), 2.37–2.49 (3H, m). MS m/z (%) 198 (M^+, 15), 141 (68), 85 (23), 72 (42), 57 (100). Calcd for $C_{13}H_{26}O$: M, 198.1982. Found: m/z 198.1988.

3.13. 4-Methyldodecan-3-one (20e)

Colorless oil; IR (neat) 2927, 1717 (CO), 1460, 1377, 1106, 1026 cm^{-1}; ^1H NMR δ 0.88 (3H, t, J=6.9 Hz), 1.04 (3H, t, J=7.3 Hz), 1.06 (3H, d, J=6.9 Hz), 1.17–1.36 (13H, m), 1.58–1.67 (1H, m), 2.44 (2H, dq, J=7.3, 2.4 Hz), 2.52 (1H, sextet, J=6.9 Hz). MS m/z (%) 198 (M^+, 3), 169 (2), 141 (2), 99 (10), 86 (100), 71 (20), 57 (76). Calcd for $C_{13}H_{26}O$: M, 198.1982. Found: m/z 198.1975.

3.14. 2,3-Dimethyl-4-phenyl-3-octene (23)

To a solution of *t*-BuMgCl (0.24 mmol) in 2 mL of dry THF in a flame-dried flask at 0 °C under argon atmosphere was added a solution of adduct **18a-P** (730 mg, 0.2 mmol) in 2 mL of dry THF dropwise with stirring. The reaction mixture was stirred at 0 °C for 10 min. *i*-PrMgCl (0.8 mmol) was added to the solution of the magnesium alkoxide dropwise with stirring. The reaction mixture was slowly allowed to warm to room temperature for 30 min. The reaction was quenched with MeOH and the whole was extracted with $CHCl_3$. The organic layer was dried over $MgSO_4$ and the product was purified by silica gel column chromatography to afford **19a** (10.7 mg, 28%) and olefin **23** (18.7 mg, 43%). Olefin **23**: colorless oil; IR (neat) 2961, 1600, 1467, 704 cm^{-1}; ^1H NMR δ 0.83 (3H, t, J=6.9 Hz), 1.04 (6H, d, J=6.8 Hz), 1.19–1.28 (4H, m), 1.37 (3H, s), 2.31–2.36 (2H, m), 2.99 (1H, septet, J=6.9 Hz), 7.06 (2H, d, J=7.6 Hz), 7.14–7.21 (1H, m), 7.29 (2H, t, J=7.6 Hz). MS m/z (%) 216 (M^+, 66), 201 (26), 173 (8), 159 (100), 145 (41), 131 (45), 117 (49). Calcd for $C_{16}H_{24}$: M, 216.1876. Found: m/z 216.1876.

3.15. 3-Hydroxy-2,2-dimethyl-1-phenyl-1-pentanone (24a)

To a solution of *t*-BuMgCl (0.24 mmol) in 2 mL of dry THF in a flame-dried flask at 0 °C under argon atmosphere was added a solution of adduct **8** (64.6 mg, 0.2 mmol) in 2 mL of dry THF dropwise with stirring. The reaction mixture was stirred at 0 °C for 10 min. To the solution of the magnesium alkoxide was added *i*-PrMgCl (0.8 mmol) dropwise with stirring. The reaction mixture was slowly allowed to warm to room temperature for 30 min. The reaction mixture was cooled to −70 °C and propionaldehyde (0.8 mmol) was added with stirring. The temperature of the reaction mixture was slowly allowed to warm to room temperature for 2 h. The reaction was quenched with MeOH and the whole was extracted with $CHCl_3$. The organic layer was dried over $MgSO_4$. The product was purified by silica gel column chromatography to afford **24a** (22.3 mg, 54%) as colorless oil; IR (neat) 3484 (OH), 2971, 1671 (CO), 1598, 1466, 1263, 979 cm^{-1}; ^1H NMR δ 1.03 (3H, t, J=7.4 Hz), 1.31 (3H, s), 1.33 (3H, s), 1.38 (1H, double quintet, J=10.5, 7.1 Hz), 1.56 (1H, ddq, J=13.8, 7.5, 2.0 Hz), 2.48 (1H, d, J=6.2 Hz), 3.78 (1H, ddd, J=14.6, 6.0, 1.8 Hz), 7.38–7.42 (2H, m), 7.44–7.49 (1H, m), 7.61–7.64 (2H, m). MS m/z (%) 206 (M^+, 2), 188 (6), 148 (49), 105 (100), 84 (48), 77 (40).

3.16. 2,2-Dimethyl-1,3-diphenylpropane-1,3-dione (24b)

After generation of the enolate in a similar way as described above, benzoyl chloride (0.8 mmol) was added dropwise to the reaction mixture and the solution was stirred at room temperature for 1 h. The reaction was quenched with MeOH. The whole was extracted with $CHCl_3$. The organic layer was dried over $MgSO_4$. The product was purified by silica gel column chromatography to afford **24b** (38.8 mg, 77%) as colorless oil. The spectral data of this compound are identical to that reported in the literature 23.

3.17. 2,2-Dimethyl-1-phenylpent-4-en-1-one (24c)

After generation of the enolate in a similar way as described above, HMPA (0.14 ml) was added to the solution of the enolate and stirred for 10 min. Allyl iodide (0.8 mmol) was added dropwise to the reaction mixture and the solution was stirred at room temperature for 15 h. The reaction was quenched with MeOH and the whole was extracted with $CHCl_3$. The organic layer was dried over $MgSO_4$. The product was purified by silica gel column chromatography to afford **24c** (24.1 mg, 64%) as colorless oil. The spectral data of this compound are identical to that reported in the literature 24.

3.18. 4-Hydroxy-3-methyl-3-phenylhexan-2-one (25a)

About 2.4:1 mixture of separable two diastereomers. Main product: colorless oil; IR (neat) 3547 (OH), 2964, 1699 (CO), 1600, 1446, 1354, 1228, 978 cm^{-1}; ^1H NMR δ 0.83–0.98 (4H, m), 1.37–1.43 (1H, m), 1.54 (3H, s), 1.95 (3H, s), 2.71 (1H, dd, J=1.8, 3.8 Hz), 3.98–4.02 (1H, m), 7.28–7.32 (3H, m), 7.35–7.39 (2H, m). MS m/z (%) 205 ($[M-H]^+$, 5), 163 (6), 148 (100), 131 (16), 105 (46), 91 (12). Minor product: colorless oil; IR (neat) 3567 (OH), 2930, 1699 (CO), 1353, 1223, 976 cm^{-1}; ^1H NMR δ 0.76–0.89 (4H, m), 1.16–1.23 (1H, m), 1.56 (3H, s), 1.90 (3H, s), 3.30 (1H, s), 4.17 (1H, d, J=11.6 Hz), 7.21 (2H, d, J=7.8 Hz), 7.28–7.38 (3H, m). MS m/z (%) 205 ($[M-H]^+$, 3), 163 (3), 148 (100), 131 (30), 105 (36), 91 (12).

3.19. 3-Methyl-3-phenylpentane-2,4-dione (25b)

Colorless oil; IR (neat) 2923, 1756, 1747 (CO), 1602, 1368, 1226, 1173 cm^{-1}; ^1H NMR δ 1.86 (3H, s), 2.01 (3H, s), 2.03 (3H, s), 7.17–7.22 (3H, m), 7.29 (2H, t, J=7.5 Hz). MS m/z (%) 190 (M^+, 6), 148 (100), 133 (12), 115 (8), 105 (46), 91 (20). Calcd for $C_{12}H_{14}O_2$: M, 190.0992. Found: m/z 190.0983.

3.20. 1-Hydroxy-2-methyl-1,2-diphenylheptan-3-one (25c)

About 1.7:1 mixture of separable two diastereomers. Main product: colorless crystals; mp 40–41 °C (pentane); IR (KBr) 3513 (OH), 2929, 1695 (CO), 1453, 1373, 1042 cm^{-1}; ^1H NMR δ 0.80 (3H, t, J=7.3 Hz), 1.12–1.26 (2H, m), 1.42–1.59 (2H, m), 1.51 (3H, s), 2.17–2.36 (2H, m), 3.97 (1H, d, J=2.4 Hz), 5.44 (1H, d, J=1.9 Hz), 6.67 (2H, d, J=7.5 Hz), 6.98–7.04 (4H, m), 7.09 (1H, t, J=7.1 Hz), 7.26–7.28 (3H, m). Anal. Calcd for $C_{20}H_{24}O_2$: C, 81.04; H, 8.16. Found: C, 81.05; H, 8.04.

Minor product: colorless oil; IR (neat) 3546 (OH), 2917, 1694 (CO), 1454, 1028 cm^{-1}; ^1H NMR δ 0.82 (3H, t, J=7.3 Hz), 1.14–1.25 (2H, m), 1.41 (3H, s), 1.45–1.59 (2H, m), 2.22–2.34 (2H, m), 3.76 (1H, d, J=2.7 Hz), 5.26 (1H, d, J=2.7 Hz), 6.73 (2H, d, J=7.6 Hz), 7.01–7.11 (4H, m), 7.16 (1H, t, J=7.6 Hz), 7.25–7.33 (3H, m). MS m/z (%) 296 (M^+, trace), 295 ($[M-H]^+$, 3), 278 (8), 190 (87), 148 (12), 105 (100), 85 (72).

3.21. 4-Methyl-4-phenylnon-1-en-5-one (25d)

Colorless oil; IR (neat) 2959, 1709 (CO), 1600, 1446, 916, 703 cm^{-1}; ^1H NMR δ 0.77 (3H, t, J=7.3 Hz), 1.08–1.17 (2H, m), 1.37–1.49 (2H, m), 1.47 (3H, s), 2.15 (1H, ddd, J=17.0, 8.2, 6.6 Hz), 2.22 (1H, ddd, J=17.0, 8.2, 6.5 Hz), 2.67 (2H, d, J=7.2 Hz), 4.97–5.04 (2H, m), 5.47 (1H, ddt, J=17.2, 10.0, 7.2 Hz), 7.19–7.24 (2H, m), 7.25–7.27 (1H, m), 7.32–7.36 (2H, m). MS m/z (%) 230 (M^+, 4), 145 (100), 129 (10), 117 (16), 85 (22). Calcd for $C_{16}H_{22}O$: M, 230.1668. Found: m/z 230.1664.

3.22. 1-Hydroxy-2,5-dimethyl-1,2-diphenylhex-4-en-3-one (25e)

About 2.5:1 mixture of separable two diastereomers. Main product: colorless crystals; mp 106–107 °C (pentane); IR (KBr) 3539 (OH), 2981, 1667 (CO), 1604, 1446, 1043, 1027, 700 cm^{-1}; ^1H NMR δ 1.49 (3H, s), 1.76 (3H, d, J=1.1 Hz), 2.22 (3H, d, J=1.1 Hz), 4.51 (1H,

d, J=2.5 Hz), 5.41(1H, d, J=2.3 Hz), 5.71 (1H, t, J=1.3 Hz), 6.67 (2H, d, J=7.1 Hz), 6.95–7.04 (4H, m), 7.06–7.10 (1H, m), 7.22–7.27 (3H, m). Anal. Calcd for $C_{20}H_{22}O_2$: C, 81.60; H, 7.53. Found: C, 81.60; H, 7.45. Minor product: colorless oil; IR (neat) 3534 (OH), 2933, 1670 (CO), 1613, 1445, 1381, 1022, 701 cm^{-1}; ^1H NMR δ 1.40 (3H, s), 1.77 (3H, d, J=1.0 Hz), 2.23 (3H, d, J=1.0 Hz), 4.07 (1H, d, J=3.3 Hz), 5.26 (1H, d, J=3.0 Hz), 5.76 (1H, t, J=3.0 Hz), 6.68 (2H, d, J=7.2 Hz), 6.99–7.02 (2H, m), 7.07 (2H, t, J=7.4 Hz), 7.13–7.17 (1H, m), 7.23–7.32 (3H, m). MS m/z (%) 293 ([M−H]$^+$, 5), 188 (100), 173 (57), 105 (36), 83 (89), 77 (32). Calcd for $C_{20}H_{21}O_2$: [M−H]$^+$, 293.1542. Found: m/z 293.1542.

3.23. 3,6-Dimethyl-3-phenylhept-5-ene-2,4-dione (25f)

Colorless oil; IR (neat) 2915, 1755 (CO), 1660 (CO), 1600, 1493, 1443, 1368, 1225, 1200 cm^{-1}; ^1H NMR δ 1.81 (3H, s), 1.85 (3H, s), 1.86 (3H, d, J=0.9 Hz), 2.01 (3H, s), 5.89 (1H, s), 7.20–7.25 (3H, m), 7.29–7.32 (2H, m). MS m/z (%) 230 (M$^+$, 28), 188 (100), 173 (85), 159 (21), 145 (18), 129 (18), 83 (85). Calcd for $C_{15}H_{18}O_2$: M, 230.1305. Found: m/z 230.1304.

3.24. 2,5-Dimethyl-5-phenylocta-2,7-dien-4-one (25g)

Colorless oil; IR (neat) 2978, 1682 (CO), 1621, 1496, 1446, 1378, 1020, 701 cm^{-1}; ^1H NMR δ 1.43 (3H, s), 1.73 (3H, d, J=1.1 Hz), 2.13 (3H, d, J=1.1 Hz), 2.62–2.72 (2H, m), 4.96–5.02 (2H, m), 5.49 (1H, ddt, J=17.4, 10.4, 7.1 Hz), 5.76 (1H, quintet, J=1.3 Hz), 7.20–7.26 (3H, m), 7.31–7.35 (2H, m). MS m/z (%) 228 (M$^+$, 3), 145 (15), 129 (8), 117 (8), 91 (10), 83 (100). Calcd for $C_{16}H_{20}O$: M, 228.1513. Found: m/z 228.1504.

3.25. 2-Methyl-1-phenyl-2-styrylbutane-1,3-dione (24d)

Colorless oil; IR (neat) 3027, 1716 (CO), 1683 (CO), 1597, 1448, 1243, 970, 749 cm^{-1}; ^1H NMR δ 1.69 (3H, s), 2.08 (3H, s), 6.34 (1H, d, J=16.7 Hz), 7.22–7.31 (4H, m), 7.36–7.41 (4H, m), 7.50 (1H, tt, J=7.4, 1.5 Hz), 7.85–7.87 (2H, m). MS m/z (%) 278 (M$^+$, 7), 236 (35), 221 (7), 129 (7), 115 (7), 105 (100), 77 (33). Calcd for $C_{19}H_{18}O_2$: M, 278.1305. Found: m/z 278.1312.

3.26. 3-Methyl-3-styrylhex-5-en-2-one (24e)

Colorless oil; IR (neat) 2978, 1707 (CO), 1639, 1448, 1353, 972 cm^{-1}; ^1H NMR δ 1.33 (3H, s), 2.15 (3H, s), 2.44–2.55 (2H, m), 5.06–5.12 (2H, m), 5.70 (1H, ddt, J=17.3, 10.0, 7.2 Hz), 6.26 (1H, d, J=16.3 Hz), 6.46 (1H, d, J=16.0 Hz), 7.22–7.26 (1H, m), 7.30–7.38 (4H, m). MS m/z (%) 214 (M$^+$, 5), 171 (81), 143 (19), 129 (53), 115 (26), 91 (100), 77 (15). Calcd for $C_{15}H_{18}O$: M, 214.1356. Found: m/z 214.1351.

3.27. 8-[1-Chloro-1-(toluene-4-sulfinyl)ethyl]-7-methyl-1,4-dioxaspiro[4.5]decan-8-ol (27 and 28)

To a solution of LDA (3.96 mmol) in 5 mL of dry THF in a flame-dried flask at −70 °C under argon atmosphere was added a solution of 1-chloroethyl p-tolyl sulfoxide (669 mg, 3.3 mmol) in 5 mL of dry THF dropwise with stirring and the solution was stirred at −70 °C for 10 min. To the reaction mixture was added **26** (510 mg, 3 mmol) dissolved in 5 mL THF dropwise with stirring. The reaction mixture was stirred at −70 °C for 30 min. The reaction was quenched with satd aq NH_4Cl. The whole was extracted with $CHCl_3$ and the organic layer was dried over $MgSO_4$. The product was purified by silica gel column chromatography to afford **27** (671 mg, 60%) and **28** (391 mg, 35%) both as colorless crystals. Compound **27**: colorless crystals; mp 139–140 °C (hexane–AcOEt); IR (KBr) 3373 (OH), 2933, 1598, 1459, 1404, 1242, 1140, 1055 (SO), 973, 815 cm^{-1}; ^1H NMR δ 1.09 (3H, d, J=6.6 Hz), 1.41 (1H, dt, J=13.0, 3.1 Hz), 1.55 (3H, s), 1.74–1.81 (1H, m), 2.01 (1H, t, J=12.8 Hz), 2.11–2.21 (3H, m), 2.45 (3H, s), 2.58–2.63 (1H, m), 3.92 (1H, s), 3.94–4.01 (4H, m), 7.35 (2H, d, J=8.1 Hz), 7.56 (2H, d, J=8.1 Hz). Anal. Calcd for $C_{18}H_{25}ClO_4S$: C, 57.98; H, 6.76; Cl, 9.51; S, 8.60. Found: C, 58.11; H, 6.71; Cl, 9.56; S, 8.73. Compound **28**: colorless crystals; mp 126–127 °C (hexane–AcOEt); IR (KBr) 3371 (OH), 2960, 1596, 1440, 1361, 1097, 1048 (SO), 976 cm^{-1}; ^1H NMR δ 1.34 (3H, d, J=6.7 Hz), 1.43 (3H, s), 1.49 (1H, dt, J=13.1, 3.4 Hz), 1.61 (1H, dq, J=12.9, 3.4 Hz), 1.83 (1H, ddt, J=13.6, 4.0, 1.2 Hz), 1.95–2.02 (2H, m), 2.23 (1H, ddd, J=13.3, 3.9, 3.3 Hz), 2.27–2.34 (1H, m), 2.44 (3H, s), 3.80 (1H, s), 3.92–3.99 (4H, m), 7.33 (2H, d, J=7.8 Hz), 7.61 (2H, d, J=8.3 Hz). Anal. Calcd for $C_{18}H_{25}ClO_4S$: C, 57.98; H, 6.76; Cl, 9.51; S, 8.60. Found: C, 57.85; H, 6.72; Cl, 9.38; S, 8.47.

3.28. 7,9-Dimethyl-1,4-dioxaspiro[4.6]undecan-8-one (29)

To a solution of t-BuMgCl (0.36 mmol) in 3 mL of dry THF in a flame-dried flask at 0 °C under argon atmosphere was added a solution of **27** (112 mg, 0.3 mmol) in 2 mL of dry THF dropwise with stirring. The reaction mixture was stirred at 0 °C for 10 min. To the solution of the magnesium alkoxide was added i-PrMgCl (1.2 mmol) dropwise. The reaction mixture was slowly allowed to warm to room temperature for 30 min. The reaction mixture was quenched with satd aq NH_4Cl and the whole was extracted with $CHCl_3$. The organic layer was dried over $MgSO_4$ and the product was purified by silica gel column chromatography to afford **29** (49 mg, 83%) as a mixture of separable cis/trans isomers. cis-Isomer: colorless oil; IR (neat) 2934, 1705 (CO), 1463, 1377, 1114, 1059 cm^{-1}; ^1H NMR δ 1.06 (3H, d, J=6.7 Hz), 1.11 (3H, d, J=7.0 Hz), 1.55 (1H, dddd, J=15.0, 8.7, 4.5, 1.8 Hz), 1.61 (1H, dd, J=14.1, 10.9 Hz), 1.62 (1H, dd, J=14.3, 11.1 Hz), 1.75–1.81 (2H, m), 2.30 (1H, dddd, J=15.5, 10.3, 5.3, 1.7 Hz), 2.61 (1H, sextet, J=6.2 Hz), 2.96 (1H, ddq, J=11.2, 6.7, 2.9 Hz), 3.88–3.99 (4H, m). MS m/z (%) 198 (M$^+$, 10), 170 (21), 155 (5), 127 (14), 113 (59), 99 (76), 86 (100). Calcd for $C_{11}H_{18}O_3$: M, 198.1254. Found: m/z 198.1248. trans-Isomer: colorless oil; IR (neat) 2932, 1705 (CO), 1456, 1376, 1112, 1082 cm^{-1}; ^1H NMR δ 1.06 (3H, d, J=6.9 Hz), 1.08 (3H, d, J=7.0 Hz), 1.58–1.65 (1H, m), 1.66–1.81 (4H, m), 1.88 (1H, ddt, J=13.3, 6.2, 2.0 Hz), 2.56 (1H, m), 2.90 (1H, ddq, J=10.8, 6.8, 4.3 Hz), 3.92–3.97 (4H, m). MS m/z (%) 198 (M$^+$, 14), 170 (35), 155 (12), 127 (18), 113 (72), 99 (80), 86 (100). Calcd for $C_{11}H_{18}O_3$: M, 198.1255. Found: m/z 198.1259.

3.29. 9,10-Dimethyl-1,4-dioxaspiro[4.6]undecan-8-one (30)

Colorless oil; IR (neat) 2927, 1731 (CO), 1456, 1363, 1086, 965 cm^{-1}; ^1H NMR δ 0.96 (3H, d, J=7.3 Hz), 1.08 (3H, d, J=7.0 Hz), 1.68–1.75 (1H, m), 1.80–1.87 (2H, m), 2.00 (1H, dddd, J=14.5, 9.2, 3.2, 1.7 Hz), 2.29–2.37 (1H, m), 2.42 (1H, ddd, J=16.0, 9.2, 3.0 Hz), 2.64–2.74 (2H, m), 3.91–3.98 (4H, m). MS m/z (%) 198 (M$^+$, 3), 156 (45), 113 (40), 99 (78), 86 (100), 55 (23). Calcd for $C_{11}H_{18}O_3$: M, 198.1255. Found: m/z 198.1255.

3.30. 1-[1-Chloro-1-(toluene-4-sulfinyl)ethyl]-2-cyclohexylcyclohexanol (32a-L and 32a-P)

Compound **32a-L**: colorless crystals; mp 147–148 °C (hexane–AcOEt); IR (KBr) 3428 (OH), 2923, 1448, 1399, 1037 (SO), 807 cm^{-1}; ^1H NMR δ 0.93 (1H, dq, J=12.5, 3.0 Hz), 1.00–1.12 (2H, m), 1.14–1.33 (4H, m), 1.37 (1H, d, J=11.9 Hz), 1.51–1.59 (2H, m), 1.54 (3H, s), 1.63–1.74 (4H, m), 1.78–1.83 (2H, m), 1.92 (1H, tq, J=12.9, 3.8 Hz), 2.17–2.24 (2H, m), 2.44 (3H, s), 2.54 (1H, d, J=12.5 Hz), 3.72 (1H, s), 7.34 (2H, d, J=8.0 Hz), 7.57 (2H, d, J=8.2 Hz). Anal. Calcd for $C_{21}H_{31}ClO_2S$: C, 65.86; H, 8.16; Cl, 9.26; S, 8.37. Found: C, 66.03; H, 8.29; Cl, 9.30; S, 8.50. Compound **32a-P**: colorless crystals; mp 125–126 °C (hexane–AcOEt); IR (KBr) 3368 (OH), 2927, 1450, 1384, 1055 (SO), 812 cm^{-1}; ^1H NMR δ 1.10–1.20 (3H, m), 1.25–1.45 (6H, m), 1.35 (3H, s), 1.58–1.86 (8H, m), 2.16 (1H, d, J=13.4 Hz), 2.22–2.28 (2H, m), 2.43 (3H, s), 2.67 (1H, s), 7.33 (2H, d, J=8.3 Hz), 7.64 (2H, d, J=8.3 Hz).

Anal. Calcd for $C_{21}H_{31}ClO_2S$: C, 65.86; H, 8.16; Cl, 9.26; S, 8.37. Found: C, 65.68; H, 8.11; Cl, 9.43; S, 8.30.

3.31. 1-[1-Chloro-1-(toluene-4-sulfinyl)ethyl]-2-phenylcyclohexanol (32b-L and 32b-P)

Compound **32b-L**: colorless crystals; mp 151–152 °C (hexane–AcOEt); IR (KBr) 3418 (OH), 2940, 1596, 1453, 1398, 1084, 1036 (SO), 822, 707 cm^{-1}; ^1H NMR δ 1.19 (3H, s), 1.43 (1H, tq, J=13.3, 4.0 Hz), 1.63 (1H, d, J=13.3 Hz), 1.78–1.83 (2H, m), 2.0 (1H, q, J=12.8 Hz), 2.11–2.24 (2H, m), 2.37 (3H, s), 2.54 (1H, d, J=13.1 Hz), 3.00 (1H, d, J=11.2 Hz), 3.39 (1H, br s), 7.15–7.25 (5H, m), 7.28–7.66 (4H, m). Anal. Calcd for $C_{21}H_{25}ClO_2S$: C, 66.91; H, 6.69; Cl, 9.41; S, 8.51. Found: C, 67.02; H, 6.60; Cl, 9.42; S, 8.62. Compound **32b-P**: colorless crystals; mp 124–125 °C (hexane–AcOEt); IR (KBr) 3403 (OH), 2937, 1492, 1448, 1406, 1080, 1031 (SO), 807, 702 cm^{-1}; ^1H NMR δ 1.24–1.38 (1H, m), 1.41 (3H, s), 1.55–1.72 (3H, m), 1.75–1.95 (2H, m), 2.23 (1H, dq, J=13.0, 3.7 Hz), 2.36 (3H, s), 2.38–2.43 (1H, m), 2.85 (1H, dd, J=12.4, 3.4 Hz), 4.54 (1H, s), 7.19 (2H, d, J=7.8 Hz), 7.23–7.62 (7H, m). Anal. Calcd for $C_{21}H_{25}ClO_2S$: C, 66.91; H, 6.69; Cl, 9.41; S, 8.51. Found: C, 66.90; H, 6.62; Cl, 9.32; S, 8.46.

3.32. 2-Cyclohexyl-7-methylcycloheptanone (33a)

To a solution of *t*-BuMgCl (0.36 mmol) in 3 mL of dry THF in a flame-dried flask at −70 °C under argon atmosphere was added a solution of **32a-L** (115 mg, 0.3 mmol) in 2 mL of dry THF dropwise with stirring. The reaction mixture was stirred at −70 °C for 10 min. To the solution of the magnesium alkoxide was added *t*-BuLi (1.2 mmol) dropwise with stirring and the mixture was stirred at −70 °C for 30 min. The reaction was quenched with satd aq NH_4Cl and the whole was extracted with $CHCl_3$. The organic layer was dried over $MgSO_4$. The product was purified by silica gel column chromatography to afford **33a** (52 mg, 83%) as a mixture of separable cis/trans isomers. cis-Isomer: colorless oil; IR (neat) 2924, 1707 (CO), 1449, 1376, 1150 cm^{-1}; ^1H NMR δ 0.85 (1H, ddd, J=16.3, 12.5, 3.6 Hz), 0.89 (1H, ddd, J=16.0, 12.5, 3.4 Hz), 1.03 (3H, d, J=6.7 Hz), 1.09–1.28 (4H, m), 1.32–1.39 (2H, m), 1.50–1.57 (3H, m), 1.60–1.66 (3H, m), 1.67–1.73 (2H, m), 1.77–1.82 (2H, m), 1.89–1.94 (1H, m), 2.47 (1H, ddd, J=10.4, 9.2, 4.6 Hz), 2.58 (1H, sextet, J=6.6 Hz). MS m/z (%) 208 (M^+, 9), 126 (100), 109 (17), 97 (12), 84 (44), 67 (38). Calcd for $C_{14}H_{24}O$: M, 208.1826. Found: m/z 208.1827. trans-Isomer: colorless oil; IR (neat) 2925, 1702 (CO), 1449, 1374, 1164, 938 cm^{-1}; ^1H NMR δ 0.90–1.00 (2H, m), 1.03 (3H, d, J=6.7 Hz), 1.08–1.15 (2H, m), 1.17–1.36 (5H, m), 1.50–1.55 (2H, m), 1.61–1.64 (1H, m), 1.66–1.76 (4H, m), 1.81–1.85 (1H, s), 1.87–1.91 (1H, m), 1.97–2.01 (1H, m), 2.22 (1H, ddd, J=11.4, 7.8, 5.1 Hz), 2.66 (1H, ddd, J=10.0, 6.7, 3.4 Hz). MS m/z (%) 208 (M^+, 9), 165 (7), 126 (100), 109 (13), 95 (12), 84 (43). Calcd for $C_{14}H_{24}O$: M, 208.1826. Found: m/z 208.1833.

3.33. 2-Methyl-7-phenylcycloheptanone (33b)

About 13:1 mixture of inseparable two diastereomers. Colorless oil; IR (neat) 2930, 1712 (CO), 1602, 1497, 1455, 1375, 1124, 698 cm^{-1}; ^1H NMR δ 1.08 (3H, d, J=6.8 Hz), 1.39–1.50 (1H, m), 1.54–1.64 (1H, m), 1.66–1.79 (3H, m), 1.84–1.93 (1H, m), 1.98–2.06 (2H, m), 2.84 (1H, sextet, J=6.4 Hz), 3.74 (0.07H, dd, J=12.0, 4.4 Hz), 3.98 (0.93H, dd, J=10.0, 4.2 Hz), 7.20–7.32 (5H, m). MS m/z (%) 202 (M^+, 39), 130 (7), 117 (54), 104 (100), 91 (48), 78 (8). Calcd for $C_{14}H_{18}O$: M, 202.1356. Found: m/z 202.1359.

3.34. 9-Deuterio-7,9-dimethyl-1,4-dioxaspiro[4.6]undecan-8-one (35a)

To a solution of *t*-BuMgCl (0.36 mmol) in 3 mL of dry THF in a flame-dried flask at 0 °C under argon atmosphere was added a solution of **27** (112 mg, 0.3 mmol) in 2 mL of dry THF dropwise with stirring. The reaction mixture was stirred at 0 °C for 10 min. To the solution of the magnesium alkoxide was added *i*-PrMgCl (1.2 mmol) dropwise with stirring. The reaction mixture was slowly allowed to warm to room temperature for 5 min. The reaction was quenched with CH_3OD and the whole was extracted with $CHCl_3$. The organic layer was dried over $MgSO_4$ and the product was purified by silica gel column chromatography to afford **35a** (49 mg, 82%) as colorless oil; IR (neat) 2934, 2879, 1707 (CO), 1460, 1376, 1261, 1117, 861 cm^{-1}; ^1H NMR δ 1.06 (3H, d, J=6.8 Hz), 1.10 (3H, s), 1.54 (1H, dd, J=15.1, 8.9 Hz), 1.60 (1H, d, J=11.5 Hz), 1.63 (1H, d, J=11.3 Hz), 1.76–1.81 (2H, m), 2.28 (1H, dd, J=14.3, 11.1 Hz), 2.95 (1H, ddq, J=10.9, 6.7, 3.0 Hz), 3.88–3.98 (4H, m). MS m/z (%) 199 (M^+, 6), 171 (21), 156 (6), 128 (6), 113 (58), 99 (75), 86 (100). Calcd for $C_{11}H_{17}DO_3$: M, 199.1318. Found: m/z 199.1319.

3.35. 9-[Hydroxy(phenyl)methyl]-7,9-dimethyl-1,4-dioxaspiro[4.6]undecan-8-one (35b)

After the enolate intermediate was generated in a similar way as described above, benzaldehyde (1.2 mmol) was added dropwise to the reaction mixture and the solution was stirred at room temperature for 30 min. The reaction was quenched with satd aq NH_4Cl and the whole was extracted with $CHCl_3$. The organic layer was dried over $MgSO_4$ and the product was purified by silica gel column chromatography to afford **35b** (68.5 mg, 75%) as colorless crystals; mp 120–121 °C (hexane–AcOEt); IR (KBr) 3348 (OH), 2974, 1698 (CO), 1454, 1375, 1093, 1044 cm^{-1}; ^1H NMR δ 1.02 (3H, d, J=6.6 Hz), 1.05 (3H, s), 1.20 (1H, ddd, J=14.9, 7.9, 0.9 Hz), 1.53 (1H, dd, J=14.2, 12.1 Hz), 1.59–1.64 (2H, m), 1.73–1.78 (1H, m), 2.52 (1H, t, J=13.7 Hz), 2.61 (1H, dd, J=4.2, 2.1 Hz), 3.12 (1H, ddq, J=12.0, 6.6, 1.9 Hz), 3.89–3.96 (4H, m), 4.63 (1H, d, J=4.3 Hz), 7.26–7.32 (5H, m). MS m/z (%) 304 (M^+, trace), 198 (93), 170 (95), 155 (74), 127 (90), 113 (100), 99 (96), 86 (96). Calcd for $C_{18}H_{24}O_4$: M, 304.1675. Found: m/z 304.1678. Anal. Calcd for $C_{18}H_{24}O_4$: C, 71.03; H, 7.95. Found: C, 71.07; H, 7.93.

3.36. 9-Benzoyl-7,9-dimethyl-1,4-dioxaspiro[4.6]undecan-8-one (35c)

Colorless crystals; mp 69–70 °C (hexane); IR (KBr) 2932, 1719 (CO), 1672 (CO), 1459, 1448, 1231, 1119, 756 cm^{-1}; ^1H NMR δ 0.84 (3H, d, J=6.6 Hz), 1.50–1.55 (1H, m), 1.55 (3H, s), 1.69 (2H, d, J=8.5 Hz), 1.79–1.85 (2H, m), 2.78–2.91 (2H, m), 3.86–3.97 (4H, m), 7.41 (2H, t, J=7.9 Hz), 7.51 (1H, tt, J=7.5, 1.1 Hz), 7.77–7.79 (2H, m). MS m/z (%) 302 (M^+, 11), 180 (8), 149 (11), 113 (39), 105 (100), 86 (42). Calcd for $C_{18}H_{22}O_4$: M, 302.1519. Found: m/z 302.1515. Anal. Calcd for $C_{18}H_{22}O_4$: C, 71.50; H, 7.33. Found: C, 71.36; H, 7.30.

3.37. 7,9,9-Trimethyl-1,4-dioxaspiro[4.6]undecan-8-one (35d)

To a solution of *t*-BuMgCl (0.36 mmol) in 3 mL of dry THF in a flame-dried flask at 0 °C under argon atmosphere was added a solution of **27** (112 mg, 0.3 mmol) in 2 ml of dry THF dropwise with stirring. The reaction mixture was stirred at 0 °C for 10 min. To the solution of the magnesium alkoxide was added *i*-PrMgCl (1.2 mmol) dropwise with stirring. The reaction mixture was slowly allowed to warm to room temperature for 30 min. HMPA (0.21 mL) was added to a solution of the ring-expanded enolate intermediate and the reaction mixture was stirred for 10 min. Iodomethane (1.2 mmol) was added dropwise to the reaction mixture and the solution was stirred at room temperature for 15 h. The reaction was quenched with satd aq NH_4Cl and the whole was extracted with $CHCl_3$. The organic layer was dried over $MgSO_4$ and the product was purified by silica gel column chromatography to afford **35d** (47 mg, 73%) as colorless crystals; mp 36–37 °C (hexane–AcOEt); IR (KBr)

2965, 2875, 1705 (CO), 1458, 1120, 1096, 947, 860 cm^{-1}; ^1H NMR δ 1.04 (3H, d, J=6.6 Hz), 1.07 (3H, s), 1.11 (3H, s), 1.47–1.59 (3H, m), 1.65–1.78 (2H, m), 2.16 (1H, dd, J=13.5, 12.0 Hz), 3.16 (1H, ddq, J=12.2, 6.6, 2.3 Hz), 3.89–3.99 (4H, m). MS m/z (%) 212 (M^+, 6), 184 (36), 156 (12), 141 (11), 113 (87), 99 (75), 86 (100). Calcd for $C_{12}H_{20}O_3$: M, 212.1412. Found: m/z 212.1405. Anal. Calcd for $C_{12}H_{20}O_3$: C, 67.89; H, 9.50. Found: C, 68.06; H, 9.71.

3.38. 7-Cyclohexyl-2-deuterio-2-methylcycloheptanone (36a)

To a solution of *t*-BuMgCl (0.36 mmol) in 3 mL of dry THF in a flame-dried flask at −70 °C under argon atmosphere was added a solution of **32a-L** (115 mg, 0.3 mmol) in 2 mL of dry THF dropwise with stirring. The reaction mixture was stirred at −70 °C for 10 min. To the solution of the magnesium alkoxide was added *t*-BuLi (1.2 mmol) dropwise with stirring. The mixture was stirred at −70 °C for 5 min. The reaction was quenched with CH_3OD and the whole was extracted with $CHCl_3$. The organic layer was dried over $MgSO_4$ and the product was purified by silica gel column chromatography to afford **36a** (54.6 mg, 87%) as colorless oil; IR (neat) 2925, 1707 (CO), 1449, 1375, 996 cm^{-1}; ^1H NMR δ 0.81–0.92 (2H, m), 1.02 (3H, s), 1.08–1.29 (4H, m), 1.32–1.40 (2H, m), 1.47–1.59 (3H, m), 1.59–1.66 (3H, m), 1.67–1.75 (2H, m), 1.76–1.83 (2H, m), 1.91 (1H, ddd, J=14.1, 8.9, 2.8 Hz), 2.46 (1H, ddd, J=10.7, 9.0, 4.9 Hz). MS m/z (%) 209 (M^+, 12), 127 (100), 109 (12), 95 (11), 84 (32), 67 (26). Calcd for $C_{14}H_{23}DO$: M, 209.1889. Found: m/z 209.1890.

3.39. 7-Cyclohexyl-2-[hydroxyl(phenyl)methyl]-2-methylcycloheptanone (36b)

About 7:1 mixture of separable two diastereomers. Main product: colorless crystals; mp 70–71 °C (hexane–AcOEt); IR (KBr) 3480 (OH), 2924, 1695 (CO), 1451, 1378, 998, 703 cm^{-1}; ^1H NMR δ 0.89–0.99 (2H, m), 1.03 (3H, s), 1.04–1.17 (4H, m), 1.20–1.37 (3H, m), 1.64–1.71 (5H, m), 1.72–1.81 (3H, m), 1.93–2.00 (2H, m), 2.17 (1H, d, J=2.8 Hz), 2.72 (1H, ddd, J=11.0, 8.3, 2.5 Hz), 4.78 (1H, d, J=2.5 Hz), 7.27–7.36 (5H, m). MS m/z (%) 314 (M^+, trace), 208 (68), 126 (100), 109 (16), 105 (46), 84 (35), 77 (50). Calcd for $C_{21}H_{30}O_2$: M, 314.2244. Found: m/z 314.2245. Anal. Calcd for $C_{21}H_{30}O_2$: C, 80.21; H, 9.62. Found: C, 80.32; H, 9.51. Minor product: colorless crystals; mp 93–94 °C (hexane–AcOEt); IR (KBr) 3502 (OH), 2923, 1685 (CO), 1468, 1450, 1043, 704 cm^{-1}; ^1H NMR δ 0.87–1.16 (4H, m), 1.00 (3H, s), 1.22–1.41 (5H, m), 1.51 (1H, d, J=12.8 Hz), 1.64–1.94 (8H, m), 2.17 (1H, t, J=13.1 Hz), 2.38 (1H, d, J=4.0 Hz), 2.60 (1H, ddd, J=10.7, 6.1, 1.5 Hz), 4.60 (1H, d, J=4.0 Hz), 7.27–7.33 (5H, m). MS m/z (%) 314 (M^+, 2), 208 (86), 179 (11), 165 (47), 151 (33), 126 (100), 105 (85), 84 (85), 77 (81). Calcd for $C_{21}H_{30}O_2$: M, 314.2246. Found: m/z 314.2237.

3.40. 2-Benzoyl-7-cyclohexyl-2-methylcycloheptanone (36c)

Colorless crystals; mp 65–66 °C (hexane–AcOEt); IR (KBr) 2925, 1706 (CO), 1670 (CO), 1447, 1233, 952, 700 cm^{-1}; ^1H NMR δ 0.54 (1H, dq, J=12.1, 3.6 Hz), 0.79 (1H, dq, J=12.4, 3.6 Hz), 0.91–1.03 (2H, m), 1.06–1.16 (2H, m), 1.18–1.25 (2H, m), 1.36–1.54 (4H, m), 1.51 (3H, s), 1.61–1.65 (1H, m), 1.73 (1H, dd, J=14.6, 8.2 Hz), 1.79–1.87 (3H, m), 1.89–1.94 (1H, m), 2.57 (1H, ddd, J=11.6, 7.6, 2.6 Hz), 2.65 (1H, dd, J=14.5, 11.3 Hz), 7.37–7.40 (2H, m), 7.49 (1H, tt, J=7.4, 1.4 Hz), 7.79–7.81 (2H, m). MS m/z (%) 312 (M^+, 19), 207 (36), 178 (16), 159 (11), 147 (24), 134 (26), 105 (100). Calcd for $C_{21}H_{28}O_2$: M, 312.2087. Found: m/z 312.2091. Anal. Calcd for $C_{21}H_{28}O_2$: C, 80.73; H, 9.03. Found: C, 80.72; H, 9.00.

3.41. 7-Cyclohexyl-2,2-dimethylcycloheptanone (36d)

Colorless oil; IR (neat) 2926, 1704 (CO), 1471, 1449, 1384, 958 cm^{-1}; ^1H NMR δ 0.76–0.92 (2H, m), 0.98–1.37 (8H, m), 1.05 (6H, s), 1.52–1.82 (7H, m), 1.84–1.96 (2H, m), 2.57 (1H, ddd, J=11.3, 9.2, 2.5 Hz). MS m/z (%) 222 (M^+, 18), 140 (100), 125 (15), 109 (30), 96 (31), 81 (46), 55 (67). Calcd for $C_{15}H_{26}O$: M, 222.1983. Found: m/z 222.1983.

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References and notes

1. A monograph and some reviews concerning homologation of carbonyl compounds: (a) Hase, T. A. *Umpoled Synthons: A Survey of Sources and Uses in Synthesis*; John Wiley and Sons: New York, NY, 1987; (b) Martin, S. F. *Synthesis* **1979**, 633; (c) Hase, T. A.; Koskimies, J. K. *Aldrichimica Acta* **1981**, *14*, 73; (d) Stowell, J. C. *Chem. Rev.* **1984**, *84*, 409; (e) Badham, N. F. *Tetrahedron* **2004**, *60*, 11.
2. A monograph and some reviews concerning ring-expansion reactions: (a) Hesse, M. *Ring Enlargement in Organic Synthesis*; VCH: Weinheim, 1991; (b) Hiyama, T.; Nozaki, H. *J. Synth. Org. Chem. Jpn.* **1977**, *35*, 979; (c) Krow, G. R. *Tetrahedron* **1987**, *43*, 3; (d) Dowd, P.; Zhang, W. *Chem. Rev.* **1993**, *93*, 2091; (e) Roxburgh, C. J. *Tetrahedron* **1993**, *47*, 10749; (f) Tochtermann, W.; Kraft, P. *Synlett* **1996**, 1029.
3. (a) Villieras, J.; Bacquet, C.; Normant, J. F. *J. Organomet. Chem.* **1972**, *40*, C1; (b) Villieras, J.; Bacquet, C.; Masure, D.; Normant, J. F. *J. Organomet. Chem.* **1973**, *50*, C7; (c) Villieras, J.; Perriot, P.; Normant, J. F. *Synthesis* **1979**, 968.
4. (a) Kobrich, G.; Grosser, J. *Tetrahedron Lett.* **1972**, 4117; (b) Kobrich, G.; Grosser, J. *Chem. Ber.* **1973**, *106*, 2626.
5. (a) Taguchi, H.; Yamamoto, H.; Nozaki, H. *Tetrahedron Lett.* **1972**, 4661; (b) Taguchi, H.; Yamamoto, H.; Nozaki, H. *J. Am. Chem. Soc.* **1974**, *96*, 6510; (c) Taguchi, H.; Yamamoto, H.; Nozaki, H. *Tetrahedron Lett.* **1976**, 2617; (d) Taguchi, H.; Yamamoto, H.; Nozaki, H. *Bull. Chem. Soc. Jpn.* **1977**, *50*, 1592.
6. Abraham, W. D.; Bhupathy, M.; Cohen, T. *Tetrahedron Lett.* **1987**, *28*, 2203.
7. (a) Satoh, T.; Hayashi, Y.; Mizu, Y.; Yamakawa, K. *Tetrahedron Lett.* **1992**, *33*, 7181; (b) Satoh, T.; Itoh, N.; Gengyo, K.; Yamakawa, K. *Tetrahedron Lett.* **1992**, *33*, 7543; (c) Satoh, T.; Hayashi, Y.; Mizu, Y.; Yamakawa, K. *Bull. Chem. Soc. Jpn.* **1994**, *67*, 1412; (d) Satoh, T.; Itoh, N.; Gengyo, K.; Takada, S.; Asakawa, N.; Yamani, Y.; Yamakawa, K. *Tetrahedron* **1994**, *50*, 11839.
8. (a) Satoh, T.; Mizu, Y.; Kawashima, T.; Yamakawa, K. *Tetrahedron* **1995**, *51*, 703; (b) Satoh, T.; Miyashita, K. *Tetrahedron Lett.* **2004**, *45*, 4859; (c) Miyashita, K.; Satoh, T. *Tetrahedron* **2005**, *61*, 5067; (d) Preliminary results of this study were reported as a communication: Satoh, T.; Tanaka, S.; Asakawa, N. *Tetrahedron Lett.* **2006**, *47*, 6769; (e) Recent paper for a synthesis of bicyclo[*n*.1.0]alkanes by using chemistry of magnesium carbenoid: Ogata, S.; Saitoh, H.; Wakasugi, D.; Satoh, T. *Tetrahedron* **2008**, *62*, 5711.
9. (a) Satoh, T.; Hirano, M.; Kuroiwa, A.; Kaneko, Y. *Tetrahedron* **2006**, *62*, 9268; (b) Satoh, T.; Kobayashi, S.; Nakanishi, S.; Horiguchi, K.; Irisa, S. *Tetrahedron* **1999**, *55*, 2515.
10. (a) Satoh, T. *J. Synth. Org. Chem. Jpn.* **1996**, *54*, 481; (b) Hoffmann, R. W.; Nell, P. G. *Angew. Chem., Int. Ed.* **1999**, *38*, 338; (c) Satoh, T. *Chem. Soc. Rev.* **2007**, *36*, 1561.
11. Crystal data for alcohol **27**: $C_{18}H_{25}ClO_4S$, M=372.89, monoclinic, space group $P2_1/c$ (#14), a=14.7778(10) Å, b=12.2868(8) Å, c=20.2419(13) Å, β=100.0160(10)°, V=3619.3(4) $Å^3$, Z=8, $F(000)$=1584, D_{calcd}=1.369 g cm^{-3}, μ(Mo Kα)=3.45 cm^{-1}, T=173 K, radiation=0.71073 Å, R_1=0.0406 for $I>2.0\sigma(I)$, wR_2=0.1070 for all data (8321 reflections), GOF=0.954 (441 parameters), crystal dimensions 0.55×0.51×0.46 mm^3. Crystal data for alcohol **28**: $C_{18}H_{25}ClO_4S$, M=372.89, monoclinic, space group $P2_1/n$ (#14), a=13.6179(11) Å, b=9.1203(8) Å, c=15.9592(14) Å, β=113.8050(10)°, V=1813.5(3) $Å^3$, Z=4, $F(000)$=792, D_{calcd}=1.366 g cm^{-3}, μ(Mo Kα)=3.45 cm^{-1}, T=173 K, radiation=0.71073 Å, R_1=0.0381 for $I>2.0\sigma(I)$, wR_2=0.1088 for all data (4157 reflections), GOF=1.014 (221 parameters), crystal dimensions 0.45×0.41×0.06 mm^3. The single crystals of **27** and **28** were mounted on glass fibers. Diffraction data were measured on a Bruker APEX CCD-Detector X-ray diffractometer with monochromated Mo Kα radiation from a rotating anode source apparatus. The data reduction, structure solution and refinement, and all the necessary computational data processes were performed using APEX, SAINT, SHELXTL programs. Crystallographic data excluding structures have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 678426 for **27** and CCDC 678427 for **28**, respectively. A copy of the data can be obtained free of charge from CCDC, 12 Union road, Cambridge CB2 1EZ, UK [direct line: +44 1223 762910, fax: +44 (0) 1223 336033 or e-mail: deposit@ccdc.cam.ac.uk.
12. Smith, M. B.; March, J. *March's Advanced Organic Chemistry*, 5th ed.; John Wiley and Sons: New York, NY, 2001; pp 1377-1505.
13. Hiyama, T.; Shinoda, M.; Nozaki, H. *Tetrahedron Lett.* **1979**, 3529.
14. Ito, M.; Kitahara, S.; Ikariya, T. *J. Am. Chem. Soc.* **2005**, *127*, 6172.
15. Kosugi, M.; Hagiwara, I.; Sumiya, T.; Migita, T. *Bull. Chem. Soc. Jpn.* **1984**, *57*, 242.
16. Baigrie, M. L.; Seiklay, R. H.; Tidwell, T. T. *J. Am. Chem. Soc.* **1985**, *107*, 5391.

17. Hong, Y.-T.; Barchuk, A.; Krische, J. M. *Angew. Chem., Int. Ed* **2006**, *45*, 6885.
18. Peach, P.; Cross, J. D.; Kenny, A. J.; Mann, I.; Houson, I.; Campvell, L.; Walsgrove, T.; Wills, M. *Tetrahedron* **2006**, *62*, 1864.
19. Cho, C. S.; Kim, B. T.; Lee, M. J.; Kim, T.-J.; Shim, S. C. *Angew. Chem., Int. Ed.* **2001**, *40*, 958.
20. Jun, C.-H.; Koo, B.-T.; Kang, J.-B.; Kim, K.-J. *Bull. Korean Chem. Soc.* **1994**, *15*, 1064.
21. Ohe, T.; Ohse, T.; Mori, K.; Ohtaka, S.; Uemura, S. *Bull. Chem. Soc. Jpn.* **2003**, *76*, 1823.
22. Sakai, T.; Matsumoto, S.; Hidaka, S.; Imajo, N.; Tsuboi, S.; Utaka, M. *Bull. Chem. Soc. Jpn.* **1991**, *64*, 3473.
23. Choundhary, A.; Baumstark, L. A. *Synthesis* **1989**, *9*, 688.
24. Barentsen, M. H.; Sieval, B. A.; Cornelisse, J. *Tetrahedron* **1995**, *51*, 7495.