Chemo-, Regio-, and Stereoselective Cyclizations of 1,3-Bis(trimethylsilyloxy)-1,3-butadienes with α-Chloroacetic Acid Chlorides and α-Chloroacetic Acetals

Peter Langer* and Thilo Krummel[a]

Abstract: Treatment of 1,3-bis(trimethylsilyloxy)-1,3-butadienes with α-chlorocarboxylic acid chlorides resulted in chemo- and regioselective formation of 6-chloro-3,5-dioxo esters, which were regioselectively converted into functionalised 3(2*H*)furanones. Chemo- and regioselective condensation of 1,3-bis(trimethylsilyloxy)-1,3-butadienes with α-chloroacetic dimethyl acetal afforded 6-chloro-5-methoxy-3-oxo esters, which could be regio- and stereoselectively transformed into 2-alkylidene-4-methoxytetrahydrofurans.

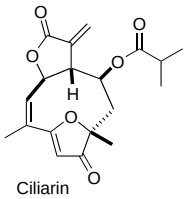
Keywords: chemoselectivity · cyclization · dianion equivalents · regioselectivity · stereoselective syntheses

Introduction

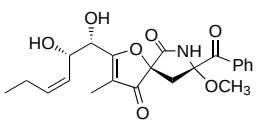
Domino reactions are of interest in organic chemistry since they enable the rapid assembly of complex products in one-pot processes.[1] Despite the simplicity of the idea, only a few reactions of 1,3-dianions[2] with 1,2-dielectrophiles have hitherto been reported.[3] These reactions may have associated drawbacks: on the one hand dianions are highly reactive compounds that can react both as nucleophiles and as bases; on the other hand 1,2-dielectrophiles are often rather labile compounds. Therefore, previous attention in dianion chemistry has been largely focused on reactions with monofunctional electrophiles, after which the resultant monoanion is simply quenched with water in a follow-up reaction. In the course of our investigations concerning cyclisation reactions of dianions[4] and dianion equivalents,[5] we have developed the first cyclisation reactions of 1,3-dicarbonyl dianions with oxalic acid dielectrophiles to give γ-alkylidenebutenolides.[4a, 5a]

We have recently reported cyclisation reactions of 1,3-bis(trimethylsilyloxy)-1,3-butadienes with α-chlorocarboxylic acid chlorides,[5b] which, to the best of our knowledge, represent the first such reactions of these electroneutral 1,3-dianion equivalents.[6] Herein, we wish to report full details and studies related to the preparative scope of this cyclisation reaction, which provides a convenient, chemo- and regioselective access to a variety of functionalised 3(2*H*)furanones. In addition, we show that this methodology may be successfully extended to the use of α-chloroacetic dimethyl acetal as the dielectrophile. Treatment of 1,3-bis(trimethylsilyloxy)-1,3-butadienes with α-chloroacetic dimethyl acetal allows a direct, regio- and stereoselective synthesis of 2-alkylidene-4-methoxytetrahydrofurans.

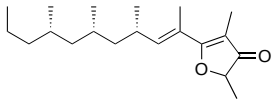
Both 3(2*H*)furanones and 2-alkylidenetetrahydrofurans are of pharmacological significance and represent important building blocks for natural product syntheses. A large number of natural products and pharmacologically important compounds belong to the 3(2*H*)furanone group: prominent examples include polyketides from *siphonaria pectinata*,[7a] the antitumour active trachyspic acid,[7b] antiallergic 4,5-dihydro-4-oxo-2-amino-3-furancarboxylic acids,[7c] the mutagenic furaneols,[7d] pseurotin A,[7e] the antitumour active sesquiterpenes eremantholides A – C,[7f] lychnophorolide A,[7g] ciliarin[7h] and the recently reported metabolite longianone.[7i,j]



Ciliarin



Pseurotin A



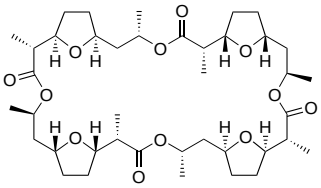
2-Deoxysiphonarienfuranone

Nonactates are subunits of the nactins, a biologically important class of macrotetrolide antibiotics isolated from a variety of *Streptomyces* cultures.[8, 9] 2-Alkylidene-4-alkoxy-

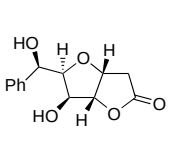
[a] Dr. P. Langer, T. Krummel
Institut für Organische Chemie
der Georg-August-Universität Göttingen
Tammannstrasse 2, 37077 Göttingen (Germany)
Fax: (+49) 551-399475
E-mail: planger@gwdg.de

0947-6539/01/0708-1720 $ 17.50+.50/0

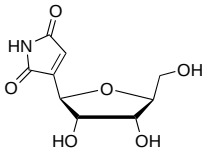
tetrahydrofurans can be considered as isononactinic acid derivatives. Due to their alkoxy ester functionality, they represent direct precursors for the synthesis of isonactins, related macrotetrolides and tetrahydrofuryl-based amino acids. These target molecules are of interest for biological reasons and also with regard to applications as potential ion channels.[10] 2-Alkylidene-4-alkoxytetrahydrofurans[11] represent important intermediates in the synthesis of natural products such as goniofufurone,[12a,b] a styryl lactone which proved cytotoxic towards human tumour cells, the pharmacologically important zaragozic acids,[12c] aplasmomycin,[12d] boromycin,[12e] muscarine,[12f,g] palytoxin,[12h] *C*-glycosides,[12i,j] erythroskyrine[12k] and the antitumour agent showdomycin.[12l,m]



Nonactin



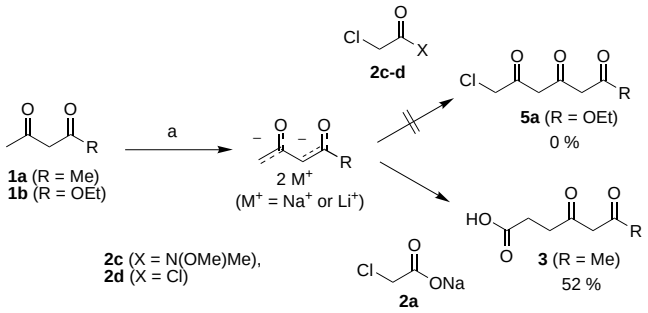
Goniofufurone



Showdomycin

Results and Discussion

A variety of products can conceivably be produced in the reaction of 1,3-dicarbonyl dianions with α-chloroacetic acid derivatives. Both the initial attack of the dianion on the dielectrophile and the subsequent cyclisation can proceed with different chemo- and regioselectivities. The reaction of the disodium salt of acetylacetone **1a** with the sodium salt of chloroacetic acid **2a** has been reported to give 4,6-dioxoheptanoic acid **3** by attack of the terminal carbon of the dianion on the carbon attached to the chlorine atom.[13] Two examples of condensation reactions of 1,3-dicarbonyl dianions with ethyl chloroacetate **2b** have been previously reported.[14] However, this approach is limited to sterically unhindered and unfunctionalised substrates. All attempts to induce a chemoselective attack of the dianion of ethyl acetoacetate **1b** on the carbonyl group of *N*-methyl-*N*-methoxy-chloroacetic acid amide **2c** and chloroacetyl chloride **2d** resulted only in the formation of complex mixtures (Scheme 1).



Scheme 1. Reactions of 1,3-dicarbonyl dianions with chloroacetic acid derivatives: a) 2 equiv LDA or $NaNH_2$, THF.

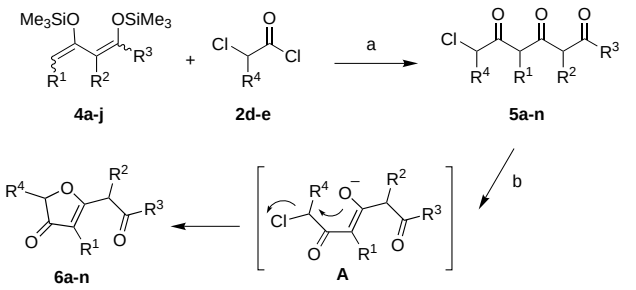
In order to overcome these problems, we decided to study the Lewis acid catalysed reaction of 1,3-bis(trimethylsilyloxy)-1,3-butadienes, electroneutral equivalents of 1,3-dicarbonyl dianions, with chloroacetyl chloride **2d**. Our initial attempts to realize the envisaged reaction were unsuccessful. Treatment of **2d** with the diene **4a** in the presence of stoichiometric amounts of $BF_3 \cdot OEt_2$ or $TiCl_4$ resulted in the formation of complex mixtures. Much to our satisfaction, however, the use of catalytic amounts of Me_3SiOTf resulted in chemo- and regioselective formation of the desired 6-chloro-3,5-dioxo ester **5a** (Scheme 2). Optimal yields (up to 71%) were obtained when the reaction was started at $-78\,^{\circ}C$ and the mixture was slowly allowed to warm to ambient temperature over a period of 12 h (Table 1). Treatment of **5a** with base resulted in regioselective cyclisation[14] through the oxygen atom of intermediate **A** to give the 3(2*H*)furanone **6a**. The use of KO*t*Bu resulted in the formation of a complex mixture, from which **6a** could be isolated in only 23% yield. Optimal yields (up to 91%) were obtained by using two equivalents of DBU as the base. It is noteworthy that isolation of **5a** was not necessary; crude **5a** could be directly transformed into **6a**, which was isolated in 65% overall yield (based on **4a**; Scheme 2). In order to study the preparative scope of the new methodology for the synthesis of 3(2*H*)furanones, the substituents of the 1,3-bis(trimethylsilyloxy)-1,3-butadienes were systematically varied (Table 2). Reaction of chloroacetyl

Table 1. Optimisation of the condensation of bis(silyl) enol ether **4a** with **2d**.

entry	Lewis acid	equiv	conditions (CH_2Cl_2)	Yield [%][a]
1	–	–	$-78 \rightarrow 20\,^{\circ}C$, 12 h	17
2	$BF_3 \cdot Et_2O$	1.0	$-78 \rightarrow 20\,^{\circ}C$, 12 h	0
3	$TiCl_4$	1.0	$-78 \rightarrow 20\,^{\circ}C$, 12 h	0
4	Me_3SiOTf	1.0	$-78 \rightarrow 20\,^{\circ}C$, 12 h	71
5	Me_3SiOTf	0.3	$-78 \rightarrow 20\,^{\circ}C$, 12 h	71
6	Me_3SiOTf	0.3	$-78 \rightarrow -40\,^{\circ}C$, 4 h	12

[a] Isolated yields of **5a**.

Abstract in German: *Die Reaktion von 1,3-Bis(trimethylsilyloxy)-1,3-butadienen mit α-Chlorcarbonsäurechloriden führt zur chemo- und regioselektiven Bildung von 6-Chlor-3,5-dioxoestern, die durch basenvermittelte regioselektive Cyclisierung in funktionalisierte 3(2H)Furanone überführt werden konnten. Die chemo- und regioselektive Kondensation von 1,3-Bis(trimethylsilyloxy)-1,3-butadienen mit α-Chloracetaldehyd-dimethylacetal liefert 6-Chlor-5-methoxy-3-oxoester, die durch basenvermittelte regio- und E-diastereoselektive Cyclisierung in 2-Alkyliden-4-methoxytetrahydrofurane umgewandelt werden konnten.*



Scheme 2. Synthesis of 3(2*H*)furanones **6a**–**n**: *a*) 1.0 equiv Me_3SiOTf, CH_2Cl_2, $-78 \rightarrow 20\,^{\circ}C$; b) 2.0 equiv DBU, THF, 2 h.

Table 2. Synthesis of 3(2*H*)furanones **6a**–**n**.

6	R^1	R^2	R^3	R^4	Yield [%] (**6**)[a]
a	H	H	OCH_2CH_3	H	65
b	H	H	OCH_3	H	70
c	H	H	$OCH(CH_3)_2$	H	63
d	CH_3	H	OCH_3	H	54
e	CH_2CH_3	H	OCH_2CH_3	H	53
f	$(CH_2)_3CH_3$	H	OCH_2CH_3	H	40
g	$CH_2CH=CH_2$	H	OCH_2CH_3	H	54
h	OCH_3	H	OCH_3	H	56
i	H	CH_3	OCH_2CH_3	H	54
j	$-CH_2CH_2CH_2-$		OCH_2CH_3	H	40
k	H	H	OCH_2CH_3	CH_3	56
l	OCH_3	H	OCH_3	CH_3	45
m	CH_2CH_3	H	OCH_2CH_3	CH_3	38
n	$-CH_2CH_2CH_2-$		OCH_2CH_3	CH_3	31

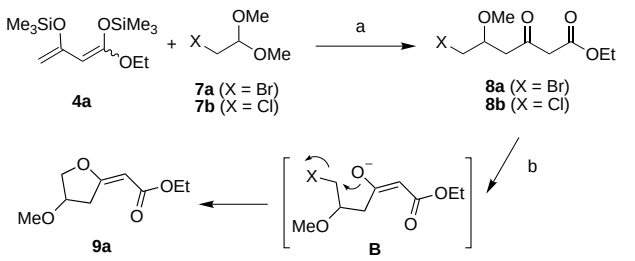
[a] Isolated yields of **6a**–**n** over two steps.

chloride **2d** with the dienes derived from methyl and isopropyl acetoacetate and subsequent cyclisation afforded the 3(2*H*)furanones **6b** and **6c**, respectively, in 70% and 63% overall yields. Reactions of **2d** with 1,3-bis(trimethylsilyloxy)-1,3-butadienes **4d**–**g**, bearing a methyl, ethyl, butyl or allyl group, respectively, on the terminal carbon atom, afforded the 4-alkyl-3(2*H*)furanones **6d**–**g** in good yields and with very good chemo- and regioselectivities.

A variety of naturally occuring 3(2*H*)furanones contain an oxygen atom at carbon C-4.[15] The synthesis of 3(2*H*)furanone **6h**, which contains a methoxy group in the C-4 position, was therefore of special interest. Dianions cannot be used for the synthesis of **6h**, since, besides the severe selectivity problems discussed above, dianions of methyl 4-methoxyacetoacetate and related substrates cannot be generated. This is presumably due to the fact that the dianion is destabilised by lone pair–lone pair interactions and by the π-donor effect of the oxygen atom.[16] Much to our satisfaction, reaction of **2d** with 4-methoxy-1,3-bis(trimethylsilyloxy)-1,3-diene (**4h**)[17] afforded the 4-methoxy-3(2*H*)furanone **6h** in good yield and with very good chemo- and regioselectivity. Starting from 1,3-bis(trimethylsilyloxy)-1,3-diene (**4i**), which bears a methyl substituent at the central carbon atom, the 3(2*H*)furanone **6i** was isolated. Reaction of **2d** with the cyclic diene **4j**, which is derived from ethyl cyclohexanone-2-carboxylate, afforded the interesting bicyclic 3(2*H*)furanone **6j**.

Next, we studied variation of the substituents on the dielectrophile. Reaction of diene **4a** with 2-chloropropionyl chloride (**2e**) afforded the 6-chloro-3,5-dioxo ester **5k**, which was transformed into the 2-methyl-3(2*H*)furanone **6k**. Reactions of 2-chloropropionyl chloride with the methyl- and ethyl-substituted dienes **4d** and **4e** afforded the 2-methyl-3(2*H*)furanones **6l** and **6m**, respectively, in good yields and with very good chemo- and regioselectivities. Reaction of **2e** with the diene derived from ethyl cyclohexanone-2-carboxylate (**4j**) afforded the bicyclic 2-methyl-3(2*H*)furanone **6n** as a 1:1 mixture of diastereomers.

The Lewis acid catalysed reaction of 1-methoxy-3-trimethylsilyloxy-1,3-butadienes with monofunctional aldehydes has been reported to result in [4+2]-cycloaddition to give 4-pyranones.[18] The Ti^{IV}-mediated attack of simple silyl enol ethers on 1,2-dielectrophilic glyoxylates has been reported to proceed with high chemoselectivity at the aldehyde function.[19] The $TiCl_4$-mediated reaction of silyl enol ethers with α-bromo acetals has been reported to give β-alkoxy-γ-bromo ketones, which could be transformed into substituted furans.[20] Reactions of dianions or dianion equivalents with α-haloaldehyde derivatives have not been reported previously to the best of our knowledge.[21] Since anhydrous bromo- and chloroacetaldehyde represent rather labile compounds, we studied reactions of 1,3-bis(trimethylsilyloxy)-1,3-butadienes with the corresponding acetals (Scheme 3). Our first attempts



Scheme 3. Synthesis of 4-methoxy-2-alkylidenetetrahydrofuran **9a**: a) 1.0 equiv Me_3SiOTf, CH_2Cl_2, $-78 \rightarrow 20\,^{\circ}C$; b) 2.0 equiv DBU, THF, 2 h.

to realize the envisaged reaction were disappointing: treatment of the diene **4a**, derived from ethyl acetoacetate, with α-bromoacetic dimethyl acetal **7a** in the presence of $TiCl_4$ resulted in the formation of a complex mixture, from which the desired open-chain condensation product **8a** could be isolated in just 14% yield (Scheme 3, Table 3). Fortunately, the use of catalytic amounts of Me_3SiOTf[22] facilitated the formation of **8a** in 41% yield. Treatment of 6-bromo-5-methoxy-3-oxo ester **8a** with DBU afforded the 2-alkylidene-4-methoxytetrahydrofuran **9a** in 92% yield with very good

Table 3. Optimisation of the condensation of diene **4a** with acetals **7a** and **7b**.

entry	X	Lewis acid	equiv	conditions (CH_2Cl_2)	Yield [%] [a]
1	Cl	–	–	$-78 \rightarrow 20\,^{\circ}C$, 12 h	0
2	Br	$TiCl_4$	1.0	$-78 \rightarrow 20\,^{\circ}C$, 12 h	14
3	Br	Me_3SiOTf	0.3	$-78 \rightarrow 20\,^{\circ}C$, 12 h	41
4	Cl	Me_3SiOTf	0.3	$-78 \rightarrow 20\,^{\circ}C$, 12 h	71
5	Cl	Me_3SiOTf	1.0	$-78 \rightarrow 20\,^{\circ}C$, 12 h	72
6	Cl	Me_3SiOTf	0.3	$0 \rightarrow 20\,^{\circ}C$, 4 h	13
7	Cl	Me_3SiOTf	0.3	$-78 \rightarrow -40\,^{\circ}C$, 4 h	38

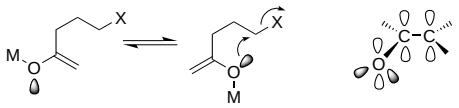
[a] Isolated yields of **8a** and **8b**.

0947-6539/01/0708-1722 $ 17.50+.50/0 *Chem. Eur. J.* **2001**, *7*, No. 8

regio- and *E*-selectivity. With a view to optimizing the yield of the first condensation step, the use of 2-chloroacetic dimethyl acetal **7b** was studied: reaction of diene **4a** with **7b** afforded the 6-chloro-5-methoxy-3-oxo ester **8b** in 71% yield. The improved yield suggests that this reaction proceeds with better chemoselectivity than the reaction of **4a** with the bromo acetal **7a**. Moreover, **7a** is more labile and prone to decomposition than **7b**. Much to our satisfaction, the alkyl chloride function of 6-chloro-5-methoxy-3-oxo ester **8b** proved to be sufficiently electrophilic to allow cyclisation: treatment of **8b** with DBU afforded the 2-alkylidene-4-methoxytetrahydrofuran **9a** in 89% yield with very good regio- and *E*-selectivity. It is noteworthy that crude **8b** could be directly transformed into **9a**, which was isolated in 64% overall yield (based on **4a**).

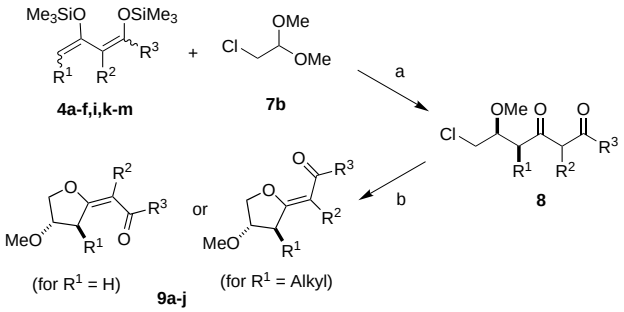
The Me_3SiOTf-catalysed condensation of diene **4a** with acetal **7b** proceeds by electrophilic attack of the silyl triflate on an oxygen atom of the acetal to generate a reactive oxonium intermediate,[23] which is in resonance with a methylcarboxonium ion/methoxytrimethylsilane contact pair. Subsequent nucleophilic displacement by the 1,3-bis(trimethylsilyloxy)-1,3-diene gives rise to the condensation product **8b** and methoxytrimethylsilane, with concomitant regeneration of the catalyst Me_3SiOTf.

The cyclisation step (**8b** → **9a**) proceeds by regioselective attack of the oxygen atom on the alkyl chloride group. This selectivity can be explained in terms of stereoelectronic considerations:[24] the formation of a five-membered ring by carbon alkylation of an enolate requires a perpendicular approach of the electrophile in relation to the plane of the enolate, whereas oxygen alkylation requires an approach in the plane of the enolate. Consequently, in the case of a five-membered ring, approach of the alkylating centre to the carbon site in the *O*-metallated enolate is more sterically hindered as compared with its approach in the plane to the oxygen site yielding the observed enol ether moiety (Scheme 4). The stereoselectivity in favour of the *E*-configured exocyclic double bond can be explained by the W-shaped configuration of intermediate **B**, in which the dipole–dipole repulsion between the oxygen atoms is minimised.[25]



Scheme 4. Stereoelectronic rationalisation of the regioselectivity of five-membered ring formation.

In order to study the preparative scope of the new cyclisation reaction for the synthesis of 2-alkylidene-4-methoxytetrahydrofurans, the substituents on the 1,3-bis(trimethylsilyloxy)-1,3-butadienes were systematically varied (Scheme 5, Table 4). Reactions of the dienes derived from ethyl, methyl, isopropyl, methoxyethyl, benzyl and isobutyl acetoacetates (**4a–c**, **4k–m**, respectively) afforded the corresponding *E*-configured 2-alkylidene-4-methoxytetrahydrofurans **9a–f** in good yields and with very good regio- and stereoselectivities. Starting with the dienes derived from methyl 3-oxopentanoate, ethyl 3-oxohexanoate and ethyl 3-oxooctanoate (**4d–f**, respectively), the tetrahydrofurans **9g–i** were obtained with very good regioselectivities and with good 1,2-diastereoselectivities. Tetrahydrofuran **9g** was formed with complete *E* selectivity. The *Z* configuration of the exocyclic double bond of **9h** can be explained by the steric influence of the ethyl group. The *E* configuration of tetrahydrofuran **9i** can be explained in terms of a $Z \rightarrow E$ isomerisation occurring during the isolation process, which proved to be difficult and rather time-consuming in this case. Treatment of **7b** with the diene derived from ethyl 2-methylacetoacetate (**4i**) resulted in the formation of the 2-alkylidenetetrahydrofuran **9j** in good yield. Despite the presence of an additional substituent at the exocyclic double bond, the product was formed with excellent *E* selectivity.



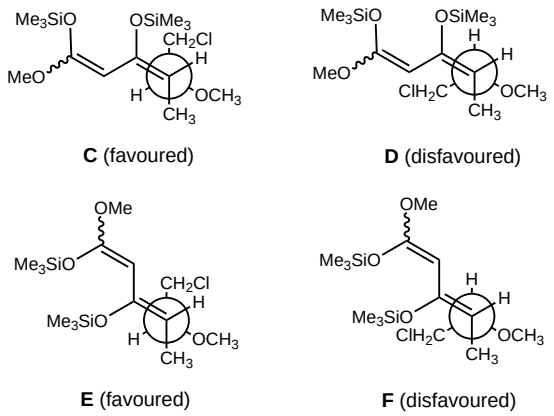
Scheme 5. Synthesis of 4-methoxy-2-alkylidenetetrahydrofurans **9a–j**; a) 1.0 equiv Me_3SiOTf, CH_2Cl_2, $-78 \rightarrow 20\,^{\circ}C$; b) 2.0 equiv DBU, THF.

Table 4. Synthesis of 4-methoxy-2-alkylidenetetrahydrofurans **9a–j**.

9	R^1	R^2	R^3	Yield [%][a]	*E*:*Z*	*ds*[b]
a	H	H	OCH_2CH_3	64	>98:2	–
b	H	H	OCH_3	60	>98:2	–
c	H	H	$OCH(CH_3)_2$	53	>98:2	–
d	H	H	$OCH_2CH_2OCH_3$	56	>98:2	–
e	H	H	OCH_2Ph	62	>98:2	–
f	H	H	$OCH_2CH(CH_3)_2$	60	>98:2	–
g	CH_3	H	OCH_3	52	>98:2	10:1
h	CH_2CH_3	H	OCH_2CH_3	50	<2:98	6:1
i	$(CH_2)_3CH_3$	H	OCH_2CH_3	32	>98:2	10:1
j	H	CH_3	OCH_2CH_3	58	>98:2	–

[a] Isolated yields of **9a–j** over the two steps. [b] Selectivity in favour of the isomer depicted.

The good 1,2-diastereoselectivities observed in the formation of tetrahydrofurans **9g–j** can best be explained by the acyclic extended transition states **C–F**, in which electrostatic repulsion is minimised (Scheme 6).[19, 22] In the reaction of a diene with *E* configuration of the terminal double bond, the transition state **C**, which leads to the *erythro* isomer, is sterically favoured over the diastereomeric transition state **D**, which affords the *threo* product, in agreement with the experimental findings. Likewise, the *erythro* transition state **E** resulting from the *Z*-configured diene is preferred to the alternative *threo* transition state **F**. It is noteworthy that, according to this mechanism, the configuration of the terminal double bond has no consequence for the stereoselection.



Scheme 6. Transition states in the reaction of the bis-silyl enol ether of methyl 3-oxopentanoate with **7b**.

In conclusion, we have developed a new approach for the synthesis of a wide range of functionalised 3(2*H*)furanones by the cyclisation of 1,3-bis(trimethylsilyloxy)-1,3-butadienes with α-chloroacetic acid chlorides. This methodology could be successfully extended to the use of α-chloroacetic dimethyl acetal as the dielectrophile, which allowed a convenient synthesis of 2-alkylidene-4-methoxytetrahydrofurans. The five-membered oxacycles prepared are of pharmacological relevance and represent useful building blocks for the synthesis of natural products.

Experimental Section

General: Compounds **2d**, **7a**,**b** and TMSOTf were bought from Aldrich. Compounds **4** were prepared by a literature procedure.[6b] ^{1}H and ^{13}C NMR spectra were measured on Bruker AM250 and Bruker AMX300 spectrometers (^{1}H: 250, 300 MHz respectively; ^{13}C 75.5, 50.3 MHz, respectively). In the ^{13}C NMR spectra signals labeled "+" are attributed to either CH_3 or CH groups and those labeled "−" to CH_2 or C groups. IR spectra were measured on a Finnigan MAT95 spectrometer. Mass spectra were recorded with Varian MAT CH7 and MAT731 spectrometers. Elemental analyses were measured with a Leco CHN2000 analyser (Heraeus).

General procedure for the preparation of 3(2*H*)furanones 6 with the preparation of 6a as an example: Me_3SiOTf (5.5 mmol, 1.20 g) was added to a solution of **2d** (5.5 mmol, 0.62 g) and **4a** (5.5 mmol, 1.51 g) in CH_2Cl_2 (70 mL) at −78 °C. Catalytic amounts of Me_3SiOTf (0.3 equiv.) could also be successfully used in the reaction. The reaction mixture was allowed to warm to 20 °C over a period of 12 h. After stirring for 2 h at 20 °C, a saturated solution of $NaHCO_3$ was added, the organic layer was separated and the aqueous layer was repeatedly extracted with diethyl ether. The combined organic extracts were dried ($MgSO_4$) and filtered, and the filtrate was concentrated to dryness in vacuo. The residue was purified by column chromatography (silica gel, diethyl ether/petroleum ether) to give **5a** as a colourless oil (805 mg, 71%). DBU (1.28 mmol, 195 mg) was added to a solution of **5a** (0.64 mmol, 132 mg) in THF (5 mL). After stirring for 2.5 h, glacial acetic acid (0.4 mL) was added. The solvent was removed in vacuo and the residue was purified by chromatography to give **6a** as a colourless oil (100 mg, 91%). Due to their instability, the open-chain intermediates **5** had to be used for the cyclisation reaction within one day.

5-Ethoxycarbonylmethyl-3(2*H*)furanone (6a): Yield: 100 mg, 65%; ^{1}H NMR ($CDCl_3$, 250 MHz): $\delta = 1.22$ (t, 8 Hz, 3H; CH_3), 3.55 (s, 2H; CH_2), 4.18 (q, $J = 8$ Hz, 2H; OCH_2CH_3), 4.48 (s, 2H; OCH_2), 5.66 (s, 1H; CH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 13.79$ (+), 36.46 (−), 61.57 (−), 75.10 (−), 106.13 (+), 166.39 (−), 185.95 (−), 202.15 (−); MS (70 eV): *m*/*z* (%): 170 (20) $[M]^+$; the exact molecular mass $m/z = 170.0579 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_8H_{10}O_4$: C 56.47, H 5.92; found C 56.35, H 6.08.

5-Methoxycarbonylmethyl-3(2*H*)furanone (6b): Preparation from diene **4b** (208 mg, 0.80 mmol) gave compound **6b** in two steps. Yield: 88 mg, 70%; ^{1}H NMR ($CDCl_3$, 250 MHz): $\delta = 3.48$ (s, 2H; CH_2), 3.63 (s, 3H; OCH_3), 4.42 (s, 2H; OCH_2), 5.60 (s, 1H; CH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 36.11$ (+), 52.40 (−), 75.07 (+), 106.15 (−), 166.84 (−), 185.65 (−), 202.03 (−); MS (70 eV): *m*/*z* (%): 156 (100) $[M]^+$, 128 (28); the exact molecular mass $m/z = 156.0422 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_7H_8O_4$: C 53.85, H 5.16; found C 53.51, H 5.35.

5-Isopropoxycarbonylmethyl-3(2*H*)furanone (6c): Preparation from diene **4c** (158 mg, 0.55 mmol) gave compound **6c** in two steps. Yield: 64 mg, 63%; ^{1}H NMR ($CDCl_3$, 250 MHz): $\delta = 1.25$ (d, 6H; CH_3), 3.52 (s, 2H; CH_2), 4.53 (s, 2H; OCH_2), 5.02 (sept, 1H; CH), 5.68 (s, 1H; CH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 21.57$ (+), 37.03 (−), 69.58 (+), 75.25 (−), 106.23 (+), 166.03 (−), 186.27 (−), 202.31 (−); MS (70 eV): *m*/*z* (%): 184 (42) $[M]^+$, 125 (36), 43 (100); the exact molecular mass $m/z = 184.0735 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_9H_{12}O_4$: C 58.69, H 6.57; found C 58.32, H 6.28.

5-Methoxycarbonylmethyl-4-methyl-3(2*H*)furanone (6d): Preparation from diene **4d** (214 mg, 0.78 mmol) gave compound **6d** in two steps. Yield: 72 mg, 54%; ^{1}H NMR ($CDCl_3$, 250 MHz): $\delta = 1.72$ (s, 3H; CH_3), 3.58 (s, 2H; CH_2), 3.75 (s, 3H; OCH_3), 4.52 (s, 2H; OCH_2); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 5.24$ (+), 34.95 (−), 52.64 (−), 74.00 (+), 113.68 (−), 167.21 (−), 180.22 (−), 203.14 (−); MS (70 eV): *m*/*z* (%): 170 (100) $[M]^+$, 110 (44); the exact molecular mass $m/z = 170.0579 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_8H_{10}O_4$: C 56.47, H 5.92; found: C 56.35, H 6.08.

5-Ethoxycarbonylmethyl-4-ethyl-3(2*H*)furanone (6e): Preparation from diene **4e** (158 mg, 0.52 mmol) gave compound **6e** in two steps. Yield: 55 mg, 53%; ^{1}H NMR ($CDCl_3$, 250 MHz): $\delta = 1.05$ (t, $J = 7$ Hz, 3H; CH_3), 1.27 (t, $J = 7$ Hz, 3H; CH_3), 2.18 (q, $J = 7$ Hz, 2H; CH_2), 3.55 (s, 2H; CH_2), 4.18 (q, $J = 7$ Hz, 2H; OCH_2), 4.45 (s, 2H; OCH_2); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 12.31$ (+), 13.19 (+), 13.56 (−), 34.32 (−), 60.80 (−), 73.17 (−), 118.29 (−), 166.16 (−), 179.58 (−), 201.90 (−); IR (neat): $\tilde{\nu} = 2975$ (m), 2937 (m), 1739 (s), 1700 (s), 1627 (s), 1424 (m), 1190 (s), 1026 cm^{-1} (m); MS (70 eV): *m*/*z* (%): 198 (100) $[M]^+$, 183 (8), 169 (39), 153 (25), 124 (74); the exact molecular mass $m/z = 198.0892 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_{10}H_{14}O_4$: C 60.59, H 7.12; found C 60.20, H 7.22.

5-Ethoxycarbonylmethyl-4-butyl-3(2*H*)furanone (6f): Preparation from diene **4f** (254 mg, 0.77 mmol) gave compound **6f** in two steps. Yield: 70 mg, 40%; ^{1}H NMR ($CDCl_3$, 250 MHz): $\delta = 0.82$ (t, $J = 7$ Hz, 3H; CH_3), 1.20 (t, $J = 7$ Hz, 3H; CH_3), 1.20–1.40 (m, 4H; CH_2), 2.08 (t, $J = 7$ Hz, 2H; CH_2), 3.52 (s, 2H; CH_2), 4.15 (q, $J = 7$ Hz, 2H; OCH_2), 4.42 (s, 2H; OCH_2); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 13.65$ (+), 13.91 (+), 20.63 (−), 22.30 (−), 30.49 (−), 35.13 (−), 61.68 (−), 73.89 (−), 117.93 (−), 166.80 (−), 180.47 (−), 203.00 (−); MS (70 eV): *m*/*z* (%): 226 (76) $[M]^+$, 208 (24), 197 (40), 184 (66), 138 (95), 110 (100); the exact molecular mass $m/z = 226.1205 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV).

4-Allyl-5-ethoxycarbonylmethyl-3(2*H*)furanone (6g): Preparation from diene **4g** (198 mg, 0.63 mmol) gave compound **6g** in two steps. Yield: 72 mg, 54%; ^{1}H NMR ($CDCl_3$, 250 MHz): $\delta = 1.13$ (t, $J = 7$ Hz, 3H; CH_3), 2.78 (m, 2H; $CH_2CH{=}CH_2$), 2.08 (t, $J = 7$ Hz, 2H; CH_2), 3.42 (s, 2H; CH_2), 4.02 (q, $J = 7$ Hz, 2H; OCH_2), 4.38 (s, 2H; OCH_2), 4.90 (m, 2H; $CH{=}CH_2$), 5.61 (m, 2H; $CH{=}CH_2$); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 13.67$ (+), 24.35 (−), 34.96 (−), 61.35 (−), 73.73 (−), 115.13 (−), 115.44 (−), 133.78 (+), 166.36 (−), 181.18 (−), 201.69 (−); IR (neat): $\tilde{\nu} = 3081$ (w), 2982 (m), 2938 (m), 2907 (w), 1740 (s), 1701 (s), 1633 (s), 1427 (s), 1390 (s), 1256 (s), 1188 (s), 1028 cm^{-1} (s); MS (70 eV): *m*/*z* (%): 210 (88) $[M]^+$, 122 (100); the exact molecular mass $m/z = 210.0892 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_{11}H_{14}O_4$: C 62.85, H 6.71; found C 63.10, H 7.02.

5-Methoxycarbonylmethyl-4-methoxy-3(2*H*)furanone (6h): Preparation from diene **4h** (145 mg, 0.50 mmol) gave compound **6h** in two steps. Yield: 52 mg, 56%; ^{1}H NMR ($CDCl_3$, 250 MHz): $\delta = 3.52$ (s, 2H; CH_2), 3.68, 3.75 (2 × s, 2 × 3H; OCH_3), 4.42 (s, 2H; OCH_2); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 33.23$ (−), 52.44 (+), 59.44 (+), 73.51 (−), 138.38 (−), 167.02 (−), 173.13 (−), 195.56 (−); IR (neat): $\tilde{\nu} = 2957$ (w), 1740 (s), 1634 (m), 1440 (m), 1210 (s), 1041 cm^{-1} (m); MS (70 eV): *m*/*z* (%): 186 (100) $[M]^+$, 171 (6), 144 (12); the exact molecular mass $m/z = 186.0528 \pm 2$ mD $[M]^+$ was confirmed by

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HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_8H_{10}O_5$: C 51.61, H 5.41; found C 51.35, H 5.70.

5-(Ethoxycarbonyl-1′-ethyl)-3(2*H*)furanone (6i): Preparation from diene **4i** (160 mg, 0.55 mmol) gave compound **6i** in two steps. Yield: 55 mg, 54%; ^{1}H NMR ($CDCl_3$, 250 MHz): $\delta = 1.25$ (t, $J = 8$ Hz, 3H; CH_3), 1.40 (d, $J =$ 7 Hz, 3H; $CHCH_3$), 3.41 (q, $J = 7$ Hz, 1H; $CHCH_3$), 4.07 (s, 2H; OCH_2), 4.22 (q, $J = 8$ Hz, 2H; OCH_2), 5.95 (s, 1H; CH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 13.71$ (+), 13.91 (+), 43.84 (+), 48.95 (+), 61.40 (−), 97.32 (−), 170.18 (−), 185.62 (−), 192.03 (−); IR (neat): $\tilde{\nu} = 2986$ (m), 2943 (m), 1738 (s), 1602 (s), 1453 (m), 1190 (s), 1128 (m), 1083 (m), 1032 cm^{-1} (m); MS (70 eV): m/z (%): 184 (2) $[M]^+$; the exact molecular mass $m/z =$ 184.0736 ± 2 mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_9H_{12}O_4$: C 58.69, H 6.57; found C 58.45, H 6.38.

7-Ethoxycarbonyl-4,5,6,7-tetrahydrobenzo[*b*]furan-3-one (6j): Preparation from diene **4j** (179 mg, 0.57 mmol) gave compound **6j** in two steps. Yield: 48 mg, 40%; ^{1}H NMR ($CDCl_3$, 250 MHz): $\delta = 1.25$ (t, $J = 7$ Hz, 3H; CH_3), 1.55 – 1.90 (m, 2H; CH_2), 2.05 (m, 2H; CH_2), 2.22 (m, 2H; CH_2), 3.52 (t, $J = 6$ Hz, 1H; $CHCH_2$), 4.20 (q, $J = 7$ Hz, 2H; OCH_2), 4.21 (s, 2H; OCH_2), 4.51 (s, 2H; OCH_2); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 13.50$ (+), 17.26 (−), 19.08 (−), 25.72 (−), 42.15 (+), 60.93 (−), 74.16 (−), 114.49 (−), 169.53 (−), 183.56 (−), 200.55 (−); IR (neat): $\tilde{\nu} = 2940$ (m), 2866 (m), 1734 (s), 1700 (s), 1635 (s), 1427 (m), 1179 (s), 1133 (m) cm^{-1}; MS (70 eV): m/z (%): 210 (76) $[M]^+$, 137 (100); the exact molecular mass $m/z = 210.0892 \pm$ 2 mD $[M]^+$ was confirmed by HRMS (EI, 70 eV).

5-Ethoxycarbonylmethyl-2-methyl-3(2*H*)furanone (6k): Preparation from diene **4a** (181 mg, 0.66 mmol) gave compound **6k** in two steps. Yield: 68 mg, 56%; ^{1}H NMR ($CDCl_3$, 250 MHz): $\delta = 1.30$ (t, $J = 7$ Hz, 3H; CH_2CH_3), 1.45 (d, $J = 8$ Hz, 3H; $CHCH_3$), 3.55 (s, 2H; CH_2), 4.22 (q, $J =$ 7 Hz, 2H; OCH_2), 4.55 (q, $J = 8$ Hz, 1H; OCH), 5.62 (s, 1H; CH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 14.00$, 16.14, 36.81, 61.78, 82.79, 104.92, 166.65, 184.36, 205.11; IR (neat): $\tilde{\nu} = 3117$ (m), 2981 (m), 2937 (m), 2873 (m), 1739 (s), 1596 (s), 1526 (m), 1370 (s), 1184 (br), 1028 cm^{-1} (s); MS (70 eV): m/z (%): 184 (100) $[M]^+$, 112 (68); the exact molecular mass $m/z = 184.0735 \pm$ 2 mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_9H_{12}O_4$: C 58.69, H 6.57; found C 58.35, H 6.39.

5-Methoxycarbonylmethyl-2,4-dimethyl-3(2*H*)furanone (6l): Preparation from diene **4h** (173 mg, 0.63 mmol) gave compound **6l** in two steps. Yield: 52 mg, 45%; ^{1}H NMR ($CDCl_3$, 250 MHz): $\delta = 1.39$ (d, $J = 8$ Hz, 3H; $CHCH_3$), 1.65 (s, 3H; CH_3), 3.55 (s, 2H; CH_2), 3.72 (s, 3H; OCH_3), 4.45 (q, $J = 8$ Hz, 1H; OCH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 5.44$ (+), 16.22 (+), 34.94 (−), 52.62 (+), 81.13 (+), 112.15 (−), 167.35 (−), 178.59 (−), 205.68 (−); MS (70 eV): m/z (%): 184 (100) $[M]^+$, 124 (46); the exact molecular mass $m/z = 184.0735 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_9H_{12}O_4$: C 58.69, H 6.57; found C 58.42, H 6.48.

5-Ethoxycarbonylmethyl-4-ethyl-2-methyl-3(2*H*)furanone (6m): Preparation from diene **4e** (175 mg, 0.58 mmol) gave compound **6m** in two steps. Yield: 47 mg, 38%; ^{1}H NMR ($CDCl_3$, 250 MHz): $\delta = 1.03$ (t, $J = 7$ Hz, 3H; CH_3), 1.26 (t, $J = 8$ Hz, 3H; CH_3), 1.45 (d, $J = 8$ Hz, 3H; $CHCH_3$), 2.15 (q, $J = 8$ Hz, 2H; CH_2), 3.52 (s, 2H; CH_2), 4.22 (q, $J = 7$ Hz, 2H; OCH_2), 4.43 (q, $J = 8$ Hz, 1H; OCH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 13.32$, 14.04, 14.51, 16.28, 35.21, 61.77, 81.09, 117.84, 167.03, 178.66, 205.57; MS (70 eV): m/z (%): 212 (48) $[M]^+$, 185 (100); the exact molecular mass $m/z =$ 212.1049 ± 2 mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_{11}H_{16}O_4$: C 62.25, H 7.60; found C 62.22, H 7.71.

7-Ethoxycarbonyl-2-methyl-4,5,6,7-tetrahydrobenzo[*b*]furan-3-one (6n): Preparation from diene **4j** (198 mg, 0.63 mmol) gave compound **6b** in two steps. Yield: 44 mg, 31%; ^{1}H NMR ($CDCl_3$, 250 MHz): $\delta = 1.22$ (m, 3H; CH_3), 1.39 (d, $J = 8$ Hz, 3H; CH_3), 1.70 (m, 2H; CH_2), 2.00 – 2.30 (m, 4H; CH_2), 3.45 (t, $J = 5$ Hz, 1H; $CHCH_2$), 4.18 (m, 2H; OCH_2), 4.45 (m, 1H; $OCHCH_3$), the product was isolated as a 1:1 mixture of diastereomers; ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 14.28$, 14.32 (+), 16.38, 16.50 (+), 18.16 (−), 19.88, 19.96 (−), 26.53, 26.60 (−), 42.93, 43.06 (+), 61.74, 61.81 (−), 82.29, 82.37 (+), 113.82, 113.94 (−), 170.43, 170.56 (−), 182.75, 182.96 (−), 204.26, 204.35 (−); IR (neat): $\tilde{\nu} = 2979$ (m), 2938 (m), 2872 (m), 1734 (s), 1636 (s), 1446 (m), 1371 (m), 1233 (s), 1126 cm^{-1} (s); MS (70 eV): m/z (%): 224 (100) $[M]^+$, 195 (26), 170 (50), 151 (86); the exact molecular mass $m/z = 224.1048 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV).

General procedure for the preparation of 2-alkylidene-4-methoxytetrahydrofurans 9, with the preparation of 9a given as an example: Me_3SiOTf (5.5 mmol, 1.15 g) was added to a solution of **7b** (685 mg, 5.5 mmol) and **4a** (5.5 mmol) in CH_2Cl_2 (70 mL) at −78 °C. Catalytic amounts of Me_3SiOTf (0.3 equiv) could also be successfully used in the reaction. The reaction mixture was allowed to warm to 20 °C over a period of 12 h. After stirring for 2 h at 20 °C, a saturated solution of $NaHCO_3$ was added, the organic layer was separated and the aqueous layer was repeatedly extracted with diethyl ether. The combined organic extracts were dried ($MgSO_4$) and filtered, and the filtrate was concentrated to dryness in vacuo. The residue was purified by column chromatography (silica gel, diethyl ether/petroleum ether) to give **8b** as a colourless oil (882 mg, 72%). DBU (4.5 mmol) was added to a solution of **8b** (2.25 mmol, 500 mg) in THF (5 mL). After stirring for 2.5 h, glacial acetic acid (1.5 mL) was added. The solvent was removed in vacuo and the residue was purified by chromatography to give **9a** as a colourless oil (370 mg, 89%). Overall yield: 64%. Due to their instability, the open-chain intermediates **8** had to be used for the cyclisation reaction within one day.

2-(*E*)-(Ethoxycarbonylmethylidene)-4-methoxytetrahydrofuran (9a): Yield: 370 mg, 64%; ^{1}H NMR ($CDCl_3$, 250 MHz, $E:Z > 98:2$): $\delta = 1.22$ (t, $J = 8$ Hz, 3H; CH_3), 2.92 (ddd, $J = 14$, 7, 2 Hz, 1H; CH_2), 3.28 (s, 3H; OCH_3), 3.45 (dd, $J = 14$, 2 Hz, 1H; CH_2), 4.10 (q, $J = 8$ Hz, 2H; OCH_2CH_3), 4.10 – 4.20 (m, 2H; CH, OCH_2), 4.30 (dd, $J = 10$, 2 Hz, 1H; OCH_2), 5.35 (t, $J = 2$ Hz, 1H; CH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 14.34$ (+), 36.34, (−), 56.38 (+), 59.22 (−), 75.47 (−), 77.92 (+), 90.85 (+), 168.32 (−), 174.47 (−); IR (neat): $\tilde{\nu} = 2982$ (m), 2934 (m), 2904 (m), 2827 (w), 1701 (s), 1644 (s), 1465 (m), 1121 (s), 1096 cm^{-1} (s); MS (70 eV): m/z (%): 186 (28) $[M]^+$, 155 (100), 141 (68); the exact molecular mass $m/z = 186.0892 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_9H_{14}O_4$: C 58.05, H 7.58; found C 57.75, H 7.76.

2-(*E*)-(Methoxycarbonylmethylidene)-4-methoxytetrahydrofuran (9b): Preparation from diene **4b** (138 mg, 0.53 mmol) gave compound **9b** in two steps. Yield: 55 mg, 60%; ^{1}H NMR ($CDCl_3$, 250 MHz, $E:Z > 98:2$): $\delta = 2.89$ (ddd, $J = 15$, 7, 2 Hz, 1H; CH_2), 3.22 (s, 3H; OCH_3), 3.42 (dd, $J =$ 15, 2 Hz, 1H; CH_2), 3.60 (s, 3H; OCH_3), 4.10 (m, 2H; CH, OCH_2), 4.27 (dd, $J = 10$, 2 Hz, 1H; OCH_2), 5.30 (t, $J = 2$ Hz, 1H; CH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 36.30$ (−), 50.53 (+), 56.28 (+), 75.51 (−), 77.82 (+), 90.31 (+), 168.63 (−), 174.69 (−); IR (neat): $\tilde{\nu} = 3117$ (w), 2956 (m), 1724 (s), 1700 (s), 1603 (s), 1437 (s), 1175 (s), 1130 (s), 1017 cm^{-1} (s); MS (70 eV): m/z (%): 141 (80) $[M - OCH_3]^+$, 109 (100); elemental analysis calcd (%) for $C_8H_{12}O_4$: C 55.81, H 7.03; found C 56.25, H 6.88.

2-(*E*)-(Isopropoxycarbonylmethylidene)-4-methoxytetrahydrofuran (9c): Preparation from diene **4c** (127 mg, 0.44 mmol) gave compound **9c** in two steps. Yield: 47 mg, 53%; ^{1}H NMR ($CDCl_3$, 250 MHz, $E:Z > 98:2$): $\delta = 1.20$ (d, $J = 6$ Hz, 6H; CH_3), 2.93 (ddd, $J = 15$, 7, 2 Hz, 1H; CH_2), 3.30 (s, 3H; OCH_3), 3.49 (dd, $J = 15$, 2 Hz, 1H; CH_2), 4.13 (m, 2H; CH, OCH_2), 4.30 (dd, $J = 10$, 2 Hz, 1H; OCH_2), 4.98 (sept, $J = 6$ Hz, 1H; OCH), 5.30 (t, $J = 2$ Hz, 1H; CH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 21.96$ (+), 21.98 (+), 36.34 (−), 56.39 (+), 66.23 (+), 75.35 (−), 77.95 (+), 91.34 (+), 167.84 (−), 174.18 (−); IR (neat): $\tilde{\nu} = 2981$ (m), 2936 (m), 2828 (w), 1700 (s), 1646 (s), 1383 (m), 1289 (m), 1231 (m), 1129 (s), 826 cm^{-1} (m); MS (70 eV): m/z (%): 200 (26) $[M]^+$, 169 (18), 141 (100), 127 (72); the exact molecular mass $m/z = 200.1048 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_{10}H_{16}O_4$: C 59.98, H 8.05; found C 59.78, H 8.16.

2-(*E*)-(Methoxyethoxycarbonylmethylidene)-4-methoxytetrahydrofuran (9d): Preparation from diene **4k** (170 mg, 0.56 mmol) gave compound **9d** in two steps. Yield: 68 mg, 56%; ^{1}H NMR ($CDCl_3$, 250 MHz, $E:Z > 98:2$): $\delta = 2.89$ (ddd, $J = 15$, 7, 2 Hz, 1H; CH_2), 3.22, 3.30 (2 × s, 2 × 3H; OCH_3), 3.42 (dd, $J = 15$, 2 Hz, 1H; CH_2), 3.50 (t, $J = 6$ Hz, 2H; OCH_2), 4.13 (t, $J =$ 6 Hz, 2H; OCH_2), 4.00 – 4.20 (m, 2H; CH, OCH_2), 4.25 (dd, $J = 10$, 2 Hz, 1H; OCH_2), 5.33 (t, $J = 2$ Hz, 1H; CH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta =$ 36.31 (−), 56.20 (+), 58.70 (+), 62.19 (−), 70.53 (−), 75.48 (−), 77.73 (+), 90.32 (+), 168.02 (−), 174.95 (−); IR (neat): $\tilde{\nu} = 2936$ (m), 2826 (m), 1703 (s), 1645 (s), 1457 (m), 1384 (m), 1338 (m), 1120 (s), 1051 cm^{-1} (s); MS (70 eV): m/z (%): 216 (8) $[M]^+$, 158 (32), 141 (100); the exact molecular mass $m/z = 216.0997 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_{10}H_{16}O_5$: C 55.55, H 7.46; found C 55.45, H 7.28.

2-(*E*)-(Benzyloxycarbonylmethylidene)-4-methoxytetrahydrofuran (9e): Preparation from diene **4l** (131 mg, 0.39 mmol) gave compound **9e** in two steps. Yield: 60 mg, 62%; ^{1}H NMR ($CDCl_3$, 250 MHz, $E:Z > 98:2$):

$\delta = 2.98$ (ddd, $J = 15, 7, 2$ Hz, 1H; CH_2), 3.35 (s, 3H; OCH_3), 3.58 (dd, $J = 15, 2$ Hz, 1H; CH_2), 4.15 (m, 2H; CH, OCH_2), 4.35 (dd, $J = 10, 2$ Hz, 1H; OCH_2), 5.15 (s, 2H; OCH_2Ph), 5.42 (t, $J = 2$ Hz, 1H; CH), 7.35 (m, 5H; Ph); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 36.52$ (−), 56.47 (+), 65.21 (−), 75.69 (−), 77.92 (+), 90.62 (+), 127.87 (+), 127.94 (+), 128.43 (+), 136.69 (−), 168.16 (−), 175.11 (−); IR (neat): $\tilde{\nu} = 2936$ (m), 2827 (w), 1702 (s), 1645 (s), 1455 (m), 1230 (m), 1116 (s), 1043 cm^{-1} (s); MS (70 eV): m/z (%): 248 (1) $[M]^+$, 186 (18), 155 (100); the exact molecular mass $m/z = 248.1048 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_{14}H_{16}O_4$: C 67.73, H 6.50; found C 68.02, H 6.58.

2-(*E*)-(Isobutoxycarbonylmethylidene)-4-methoxytetrahydrofuran (9f): Preparation from diene **4m** (175 mg, 0.58 mmol) gave compound **9f** in two steps. Yield: 75 mg, 60%; ^{1}H NMR ($CDCl_3$, 250 MHz, $E:Z > 98:2$): $\delta = 0.90$ (d, $J = 8$ Hz, 6H; CH_3), 1.90 (sept, $J = 8$ Hz, 1H; CH_2CH), 2.93 (ddd, $J = 15, 7, 2$ Hz, 1H; CH_2), 3.30 (s, 3H; OCH_3), 3.49 (dd, $J = 15, 2$ Hz, 1H; CH_2), 3.82 (d, $J = 8$ Hz, 2H; CH_2CH), 4.15 (m, 2H; CH, OCH_2), 4.33 (dd, $J = 10, 2$ Hz, 1H; OCH_2), 5.38 (t, $J = 2$ Hz, 1H; CH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 19.12$ (+), 27.75 (+), 36.37 (−), 56.40 (+), 69.59 (−), 75.48 (−), 77.94 (+), 90.92 (+), 168.42 (−), 174.39 (−); MS (70 eV): m/z (%): 214 (12) $[M]^+$, 141 (100); the exact molecular mass $m/z = 214.1205 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_{11}H_{18}O_4$: C 61.66, H 8.47; found C 61.35, H 8.18.

2-(*E*)-(Methoxycarbonylmethylidene)-4-methoxy-3-methyltetrahydrofuran (9g): Preparation from diene **4d** (159 mg, 0.58 mmol) gave compound **9g** in two steps. Yield: 56 mg, 52%; ^{1}H NMR ($CDCl_3$, 200 MHz, inseparable mixture of diastereomers, *trans*:*cis* = 10:1, $E:Z > 98:2$): $\delta =$ 1.19 (d, $J = 7$ Hz, 3H; CH_3), 3.29 (s, 3H; OCH_3), 3.61 (s, 3H; OCH_3), 3.65 (m, 1H; CH), 3.78 (q, $J = 7$ Hz, 1H; CH), 4.28 (m, 2H; CH, OCH_2), 4.33 (dd, $J = 10, 2$ Hz, 1H; OCH_2), 5.28 (s, 1H; CH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 15.83$ (+), 41.96 (+), 50.64 (+), 56.24 (+), 73.96 (−), 84.86 (+), 90.01 (+), 168.28 (−), 179.64 (−); IR (neat): $\tilde{\nu} = 2932$ (m), 1739 (m), 1704 (s), 1647 (s), 1464 (m), 1388 (m), 1127 (s), 1098 cm^{-1} (s); MS (70 eV): m/z (%): 186 (20) $[M]^+$, 155 (100); the exact molecular mass $m/z = 186.0892 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV).

2-(*E*)-(Ethoxycarbonylmethylidene)-3-ethyl-4-methoxytetrahydrofuran (9h): Preparation from diene **4e** (145 mg, 0.48 mmol) gave compound **9h** in two steps. Yield: 52 mg, 50%; ^{1}H NMR ($CDCl_3$, 250 MHz, mixture of diastereomers, *trans*:*cis* = 6:1, $E:Z < 2:98$): $\delta = 1.02$ (m, 3H; CH_3), 1.25 (m, 3H; CH_3), 1.45–1.90 (m, 2H; CH_2), 2.72 (t, $J = 6$ Hz, 1H; $CHCH_2$), 3.32 (2 × s, 3H; OCH_3), 3.72 (m, 1H; $CHOCH_3$), 4.12 (q, 2H; OCH_2), 4.30–4.60 (m, 2H; OCH_2), 4.80, 4.88 (2 × s, 1H; CH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 11.63/12.01$, 14.35/18.24, 24.95/25.52, 49.76/51.73, 56.36/56.82, 59.23/67.89, 74.20/75.98, 77.67/81.94, 88.16/89.70, 165.73/165.82, 173.33/173.80; IR (neat): $\tilde{\nu} = 2974$ (m), 2935 (m), 2828 (w), 1710 (s), 1653 (s), 1465 (m), 1190 (s), 1125 (s), 1096 (s), 1047 cm^{-1} (s); MS (70 eV): m/z (%): 214 (22) $[M]^+$, 183 (100), 169 (80), 155 (88); the exact molecular mass $m/z = 214.1205 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_{11}H_{18}O_4$: C 61.66, H 8.47; found C 61.35, H 8.28.

2-(*E*)-(Ethoxycarbonylmethylidene)-3-butyl-4-methoxytetrahydrofuran (9i): Preparation from diene **4f** (158 mg, 0.48 mmol) gave compound **9b** in two steps. Yield: 36 mg, 32%; ^{1}H NMR ($CDCl_3$, 250 MHz, mixture of diastereomers, *trans*:*cis* = 10:1, $E:Z > 98:2$): $\delta = 0.82$ (m, 6H; CH_3), 1.20–1.40 (m, 6H; CH_2), 2.35 (t, $J = 8$ Hz, 1H; $CHCH_2$), 3.33 (s, 3H; OCH_3), 3.69 (dd, $J = 10, 5$ Hz, 1H; OCH_2), 3.80 (d, $J = 5$ Hz, 1H; $CHOCH_3$), 4.13 (m, 2H; OCH_2), 4.27 (m, 1H; OCH_2), 5.32 (s, 1H; CH); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 13.88$, 14.12, 22.63, 30.37, 47.56, 56.12, 59.23, 74.34, 82.66, 90.53, 167.88, 179.11; IR (neat): $\tilde{\nu} = 2958$ (s), 2932 (s), 2873 (m), 1704 (s), 1643 (s), 1466 (m), 1370 (m), 1170 (m), 1121 (s), 1048 cm^{-1} (m); MS (70 eV): m/z (%): 242 (10) $[M]^+$.

2-(*E*)-(Ethoxycarbonyl-1′-ethylidene)-4-methoxytetrahydrofuran (9j): Preparation from diene **4i** (168 mg, 0.58 mmol) gave compound **9j** in two steps. Yield: 67 mg, 58%; ^{1}H NMR ($CDCl_3$, 250 MHz, $E:Z > 98:2$): $\delta =$ 1.25 (t, $J = 7$ Hz, 3H; CH_3), 1.80 (s, 3H; CH_3), 2.95 (dd, $J = 14, 7$ Hz, 1H; CH_2), 3.33 (s, 3H; OCH_3), 3.45 (dd, $J = 14, 2$ Hz, 1H; CH_2), 4.08–4.20 (m, 4H; OCH_2CH_3, $CHOCH_3$, OCH_2), 4.35 (dd, $J = 10, 2$ Hz, 1H; OCH_2); ^{13}C NMR ($CDCl_3$, 62.5 MHz): $\delta = 11.12$ (+), 14.40, (+), 37.15 (−), 56.40 (+), 59.53 (−), 74.83 (−), 78.63 (+), 98.97 (−), 168.09 (−), 169.14 (−); IR (neat): $\tilde{\nu} = 2983$ (m), 2933 (m), 2827 (w), 1701 (s), 1646 (s), 1465 (m), 1305 (s), 1289 (s), 1105 cm^{-1} (s); MS (70 eV): m/z (%): 200 (24) $[M]^+$, 186 (8), 155 (100); the exact molecular mass $m/z = 200.1048 \pm 2$ mD $[M]^+$ was confirmed by HRMS (EI, 70 eV); elemental analysis calcd (%) for $C_{10}H_{16}O_4$: C 59.98, H 8.05; found C 59.66, H 8.18.

Acknowledgement

P.L. thanks Professor A. de Meijere for his support. Financial support from the *Fonds der Chemischen Industrie e. V.* (Liebig scholarship and funds for P.L.) is gratefully acknowledged.

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Received: June 27, 2000 [F2571]