Intramolecular Homolytic Displacements. Part 18.[1] Stereochemical Effects of the Induced Decomposition of Unsaturated Peroxidic Compounds Leading to the Formation of Five-Membered Rings

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Free-radical additions of methylene dichloride and chloroform to various peroxidic compounds having unsaturation δ to the peroxidic bond and a substituent on the chain linking both functions gave five-membered heterocycles with some stereoselectivity. The influence of various structural factors such as the size of the substituent, the nature of the peroxidic function (peroxide, perester and percarbonate), *etc.* have been studied.

Over the last two decades, as applications of free-radical reactions in synthesis have grown, it appeared that some of them could be performed with good stereoselectivity. Thus, considerable effort has been devoted to attaining better knowledge of the various factors which influence different reactions:[2] intermolecular[3a] and intramolecular[3b] additions to unsaturated compounds, homolyses adjacent to a radical centre,[3c] hydrogen-atom abstractions,[3d] atom-group transfers,[3e] radical couplings,[3f] intermolecular[3g] and intramolecular[3h,4,5] homolytic substitutions. To our knowledge, very few examples mentioning the stereochemical effects of intramolecularly induced decomposition of peroxidic compounds have been reported in the literature[4,5] although they were essentially related to the efficiency of the S_Hi reaction according to the isomer involved in the reaction. Our interest in the definition of the synthetic potentialities of the induced decompositions of unsaturated peroxidic compounds[1] prompted us to investigate the stereochemical effects of substituents on the distribution of the heterocyclic diastereoisomers obtained in free-radical additions to *O*-allylic *O*,*O*-di-t-butyl percarbonates, γ-unsaturated t-butyl peresters and δ-unsaturated alkyl peroxides.

The general mechanism of induced decomposition of the various families of unsaturated peroxidic compounds studied here has been established[6,7] as that shown in equation (1).

$$\begin{aligned} &CH_2{=}CH\text{-}[\dot{C}]_n\text{-}X\text{-}OO\text{-}Bu^t + Z^{\bullet} \longrightarrow \\ &Z\text{-}CH_2\text{-}\dot{C}H\text{-}[C]_n\text{-}X\text{-}OO\text{-}Bu^t \longrightarrow \\ &ZCH_2\text{-}CH\text{-}[C]_n\text{-}X\text{-}O + Bu^tO^{\bullet} \quad (1) \end{aligned}$$

$X = CH_2, CO; n = 2$ or $X = OCO; n = 1$

Clearly the presence of a substituent on the chain linking both reacting functional groups introduces the possibility of the formation of heterocyclic *cis*- and *trans*-diastereoisomers. Our study has been divided into three main parts according to the relative positions of the substituents (2,3, 2,4 and 2,5).†

Fig. 1 summarizes the peroxidic compounds studied and the heterocycles obtained.

The substrate ZH used in this study (CH_2Cl_2) was chosen for the following reasons. It is a good reagent; in previous studies[1] we obtained acceptable yields of heterocycles. The excess is readily eliminated after the reaction. The dichloromethyl group is easily identified in ^{13}C and ^1H NMR spectra, allowing an easier identification of the different heterocyclic isomers to be made.

† The use of this terminology corresponds to a prohibited extension of IUPAC nomenclature rules for tetrahydrofurans to cyclic esters. However, although incorrect, we use it to simplify discussion of the results.

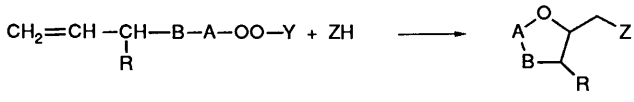


Fig. 1a

Peroxidic compound	A	B	R	Y	Hetero-cycle	Z
P1a	CH_2	CH_2	Me	Bu^t	**1**	$CHCl_2$
P1b	CH_2	CH_2	Me	Pe	**1α**	CCl_3
P2a	CO	CH_2	Me	Bu^t	**2**	$CHCl_2$
					2α	CCl_3
P3a	CO	O	Me	Bu^t	**3**	$CHCl_2$
					3α	CCl_3
P4a	CO	O	Et	Bu^t	**4**	$CHCl_2$
					4α	CCl_3
P5a	CO	O	Pr^i	Bu^t	**5**	$CHCl_2$
					5α	CCl_3
P6a	CO	O	Bu^t	Bu^t	**6**	$CHCl_2$
					6α	CCl_3

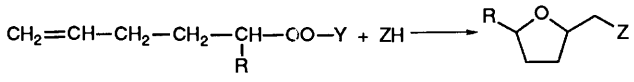


Fig. 1b

Peroxidic compound	R	Y	Hetero-cycle	Z
P7a	Me	Bu^t	**7**	$CHCl_2$
P7b	Me	Pe	**7α**	CCl_3
P7c	Me	Pe^s		
P7d	Me	CEt_3		
P8a	Pr^i	Bu^t	**8**	$CHCl_2$
P8b	Pr^i	Pe	**8α**	CCl_3

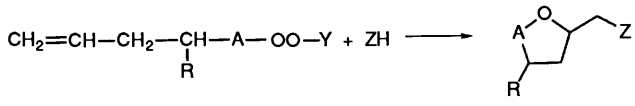


Fig. 1c

Peroxidic compound	A	R	Y	Hetero-cycle	Z
P9a	CH_2	Me	Bu^t	**9**	$CHCl_2$
P9b	CH_2	Me	Pe	**9α**	CCl_3
P10a	CH_2	Bu^t	Bu^t	**10**	$CHCl_2$
P10b	CH_2	Bu^t	Pe		
P11a	CO	Me	Bu^t	**11**	$CHCl_2$
				11α	CCl_3

Table 1 Free-radical additions to unsaturated peroxy compounds leading to 2,3-substituted heterocycles

Entry	Peroxidic compound	R	Y	ZH	Heterocycle	Yield (%)[a]	*cis*:*trans*[b]
1[c]	**P1a**	Me	Bu^t	CH_2Cl_2	**1**	43	20:80
2[c]	**P1b**	Me	Pe	CH_2Cl_2	**1**	49	19:81
3[d]	**P2a**	Me	Bu^t	CH_2Cl_2	**2**	43	25:75
4[d]	**P3a**	Me	Bu^t	CH_2Cl_2	**3**	64	25:75
5[c]	**P1a**	Me	Bu^t	$CHCl_3$	**1α**	54	16:84
6[d]	**P2a**	Me	Bu^t	$CHCl_3$	**2α**	44	25:75
7[d]	**P3a**	Me	Bu^t	$CHCl_3$	**3α**	35	20:80
8[d]	**P4a**	Et	Bu^t	CH_2Cl_2	**4**	64	23:77
9[d]	**P5a**	Pr^i	Bu^t	CH_2Cl_2	**5**	61	20:80
10[d]	**P6a**	Bu^t	Bu^t	CH_2Cl_2	**6**	60	7:93
11[e]	**P1a**	Me	Bu^t	CH_2Cl_2	**1**	37[b]	17:83
12[d]	**P1a**	Me	Bu^t	CH_2Cl_2	**1**	45[b]	19:81
13[e]	**P3a**	Me	Bu^t	CH_2Cl_2	**3**	50[b]	22:78
14[c]	**P3a**	Me	Bu^t	CH_2Cl_2	**3**	59[b]	26:74

[a] Isolated. [b] Determined by gas chromatography. [c] 110 °C. [d] 80 °C. [e] 40 °C.

conformer A conformer B

Fig. 2

Two different initiators have previously been used in free-radical additions to unsaturated peroxides[1] with different ratios according to the peroxide used. The reaction conditions used in this study were based on earlier studies: molar proportions CH_2Cl_2:unsaturated peroxide:t-butyl peracetate (50:1:0.5), 110 °C, 12 h; and molar proportions CH_2Cl_2:unsaturated perester:benzoyl peroxide (50:1:0.5), 80 °C, 24 h.

To determine the temperature effect, ethyl perdicarbonate was also used as an initiator with the same proportions of the reactants at 40 °C for a reaction time of 8 days.

Results and Discussion

Formation of 2,3-*Substituted Heterocycles.*—The reaction products (yields, relative ratios of isomers) obtained from the different peroxidic precursors are described in Table 1.

The *trans*-isomer was always the predominant product, irrespective of the unsaturated peroxidic compound used. The determination of the *cis*:*trans* ratios for the free-radical additions of methylene dichloride to peroxides **P1a**, **P2a** and **P3a** at different reaction times indicated no isomerization of the diastereoisomeric heterocycles during the reaction period. These results are in good agreement with a reaction under kinetic control.

Although all of these heterocycles are formed by addition of a dichloromethyl radical to a double bond followed by intramolecular homolytic substitution on the peroxidic bond, it is clear that the stereochemical reaction is the second step.

A comparative analysis of these results indicates a minor effect of (i) replacement of a t-butyl by a pentyl group a less hindering group (entries 1 and 2); (ii) presence of a sp^2-carbon, as a carbonyl group, between the double bond and the peroxidic group (entries 1 and 3), taking into consideration the low-temperature effect (see below); (iii) replacement of a carbon by an oxygen atom (entries 3 and 4).

Preferential formation of a *trans*-isomer is explicable when the reaction pathways leading to each isomer are investigated. Porter[5] elegantly demonstrated that, in intramolecular homolytic substitutions leading to three-membered rings, the attacking carbon and both oxygens have to be aligned. By extending this reasoning to other intramolecular homolytic substitutions on peroxidic bonds, it is clear that, for steric reasons, of the two possible conformations A and B of the initial radical adduct, the second one predominates (Fig. 2).

According to the relative position of the substituents and the leaving group in both conformers, it is not surprising that changing of the latter (pentoxy *versus* t-butoxy) (entries 1 and 2) involved no modification of the selectivity.

To check the influence of the size of the CH_2Z substituent on the relative ratios of both *cis*- and *trans*-diastereoisomers, free-radical additions of chloroform to peroxidic compounds **P1a** and **P3a** have been studied. These experiments have analysed the effect of the R substituent through a study of the free-radical addition of methylene dichloride to allylic percarbonates, chosen as probes because of their easier syntheses.

The size of the radical Z has a low influence on the relative ratios of both isomeric heterocycles produced from the peroxide **P1a** and the percarbonate **P3a** (entries 1 and 5, 4 and 7) and no effect in the case of the perester **P2a** (entries 3 and 6). This could be explained by the different distances between the methyl and group Z in the conformers A and B of the starting radical as well as in the heterocycle itself.

The bulk of the R group had a significant effect on the relative ratios of *cis*/*trans* isomers only for the hindering t-butyl group (entries 4, 8, 9 and 10). It was found, from models, that the interaction between the two substituents in conformer A changes drastically only when all the hydrogens of the methyl group are replaced by methyl groups, whereas in conformer B there is no real effect.

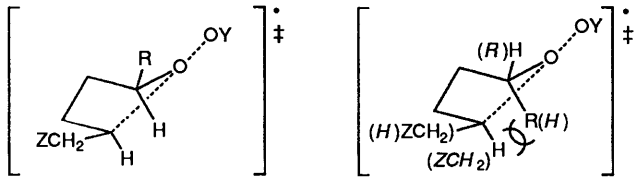
Free-radical additions of methylene dichloride to the peroxide **P1a** and the percarbonate **P3a** have been performed at various temperatures, using different initiators. The relative ratios of *cis*/*trans* isomers were found to have little dependence on temperature, both for the peroxide (entries 11, 12 and 1) and the percarbonate (entries 13, 4 and 14). However, we did note an underlying decrease of the selectivity with increasing temperature. Taking into account the similar feature for the unsaturated peresters and the corresponding percarbonates,[8] it seems reasonable to extend this conclusion to the perester **P2a**.

Formation of 2,5-*Substituted Heterocycles.*—Only peroxides can lead to the formation of 2,5-substituted heterocycles. The peroxides **P7** and **P8** have been synthesized as models for this

Table 2 Free-radical additions to 2-alkyl-γ-unsaturated peroxides leading to 2,5-substituted heterocycles

	Peroxidic compound				Heterocycle		
Entry		R	Y	ZH		Yield (%)[a]	*cis*:*trans*[b]
15[c]	**P7a**	Me	Bu^t	CH_2Cl_2	**7**	54	65:35
16[c]	**P7b**	Me	Pe	CH_2Cl_2	**7**	47	48:52
17[c]	**P7c**	Me	Pe^s	CH_2Cl_2	**7**	53	56:44
18[c]	**P7d**	Me	CEt_3	CH_2Cl_2	**7**	51	68:32
19[c]	**P7a**	Me	Bu^t	$CHCl_3$	**7α**	52	65:35
20[c]	**P7b**	Me	Pe	$CHCl_3$	**7α**	40	51:49
21[c]	**P7c**	Me	Pe^s	$CHCl_3$	**7α**	48	55:45
22[c]	**P7d**	Me	CEt_3	$CHCl_3$	**7α**	45	68:32
23[c]	**P8a**	Pr^i	Bu^t	CH_2Cl_2	**8**	43	73:27
24[c]	**P8b**	Pr^i	Pe	CH_2Cl_2	**8**	20	53:47
25[e]	**P7d**	Me	CEt_3	CH_2Cl_2	**7**	40[b]	70:30
26[d]	**P7d**	Me	CEt_3	CH_2Cl_2	**7**	43[b]	71:29

[a–e] See Table 1.



Transition state C — Transition state D $D^1(D^2)$

Fig. 3

study and the effect of the parameters checked in the formation of 2,5-substituted heterocycles have been determined here. Table 2 describes the various results obtained from the different peroxides, giving the following analysis. The *cis*-isomer was generally predominant (entries 15–24). The bulk of the leaving group appeared to be an important factor on the relative ratios of the isomers (entries 15–18 and 19–22). The size of the R substituent had a low effect on the distribution of isomers (entries 15 and 23, 16 and 24) in opposition to that of Z (entries 15–18 and 19–22), which had none. The temperature of the reaction did not significantly influence the repartition of isomers (entries 25, 26 and 18).

The analysis of the diastereoisomeric transition states (C, D^1 and D^2 in Fig. 3) may help us to understand why the major isomer was generally the *cis*-compound. Indeed, taking into account their conformations, one can see weaker 1,4-*syn*-axial interactions in transition state C than in state D (D^1 or D^2), favouring more the formation of *cis*-isomer *via* state C than the *trans*-isomer *via* state D. Different interactions between R and OY in transition states C and D may explain the observed distribution of *cis*/*trans* isomers. Nevertheless, the significant effect of the size of OY on the stereochemistry of the S_Hi reaction is difficult to understand only on the basis of both of the last hypotheses. Comparison of entries 15 and 19, 16 and 20, 17 and 21, 18 and 22 seems to indicate the existence of a significant interaction between the Z and OY groups in the D transition state only when Y is pentyl. Indeed, if we consider that the replacement of a hydrogen in group Z by a chlorine will not affect the interaction between ZCH_2 and R in transition state C (in the case of 2,3 relationships of both substituents, a minor effect was observed), one could find an explanation for this result in the existence of a possible interaction between groups CH_2Z and OY in state D^2. Then, the relative interactions between the three groups CH_2Z, R and OY would be responsible for the stereochemistry of the intramolecular homolytic substitution. Nevertheless, this explanation is not fully convincing but no better one is currently available.

Such an effect by the leaving group has been observed by Bartlett[9] in the synthesis of *cis*-2,5-disubstituted tetrahydrofurans by electrophilic cyclization of γ-unsaturated alcohols and ethers. No direct comparison can be made between electrophilic and free-radical reactions since the transition states have very different geometries.

Highly stereochemical effects have been observed in the preparation of 2,5-disubstituted tetrahydrofurans in which an S_Hi reaction occurred,[10] but in this method the stereoselectivity did not come from the homolytic substitution.

Similar heterocycles have also been obtained through free-radical reactions but the creation of the cycle corresponded to an ionic process after, or in place of, a free-radical one. Mihailovic *et al.*[11] compared the stereochemical features in the acid cyclization of hex-5-en-2-ol and in the reaction of hexan-2-ol with lead tetraacetate or cerium(IV) ammonium nitrate. They concluded that a similar cyclization mechanism occurred, *via* ring closure of a δ-hydroxy carbonium ion to form a tetrahydrofuran. The lower stereoselectivity in this case when compared with the present work is not surprising if we consider the importance of the leaving group, assuming similar geometries of the transition states in the free-radical and ionic reactions (hybridization of the reactive carbons is sp^2; substitution corresponds to a linear relationship of the attacking moiety, the attacked oxygen and the leaving group).

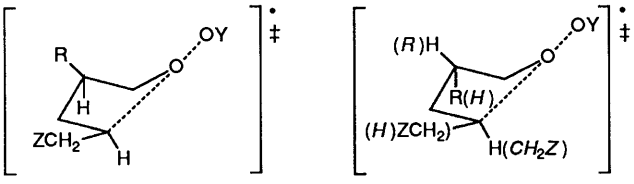
Mihailovic *et al.* also studied the formation of the same tetrahydrofurans from the decomposition of hypohalides. The identification in several cases of the halogenohydrin prompted them to propose a different mechanism to explain the formation of the same heterocycles in the decomposition of the 1-methylpentyl hypohalides. This led them to propose an intramolecular hydrogen transfer to alkoxyl radical followed by attack of the alkyl radical on a molecule of hypohalide. Then, the formation of the heterocycle would correspond to an intramolecular nucleophilic attack on the carbon linked to the halide by the oxygen of the hydroxy group, such reaction occurring rapidly for iodides and bromides (for chlorides, a basic medium is necessary). They supposed that the free-radical steps would occur stereochemically. Then, although the diastereomeric excesses are similar in the hypohalides reaction and the addition–S_Hi process, there is no correlation, transition-state geometries of the cyclizations being very different.

Formation of 2,4-*Substituted Heterocycles.*—Table 3 describes the various results obtained from the different peroxides and perester. The *cis*-isomer is always the major product of the reaction. Slight or no effects were observed for: (i) the introduction of an sp^2-carbon in the chain (entries 27 and 32, 29 and

Table 3 Free-radical additions to unsaturated peroxy compounds leading to 2,4-substituted heterocycles

	Peroxidic compound				Heterocycle		
Entry		R	Y	ZH		Yield (%)[a]	*cis*:*trans*[b]
27[c]	**P9a**	Me	Bu^t	CH_2Cl_2	**9**	58[a]	53:47[b]
28[c]	**P9b**	Me	Pe	CH_2Cl_2	**9**	51[b]	59:41[b]
29[c]	**P9a**	Me	Bu^t	$CHCl_3$	**9α**	63[a]	54:46[b]
30[c]	**P10a**	Bu^t	Bu^t	CH_2Cl_2	**10**	60[a]	58:42[b]
31[c]	**P10b**	Bu^t	Pe	CH_2Cl_2	**10**	44[b]	64:36[b]
32[d]	**P11a**	Me	Bu^t	CH_2Cl_2	**11**	71[a]	58:42[f]
33[d]	**P11a**	Me	Bu^t	$CHCl_3$	**11α**	50[a]	65:35[f]
34[e]	**P9a**	Me	Bu^t	CH_2Cl_2	**9**	39[b]	53:47
35[d]	**P9a**	Me	Bu^t	CH_2Cl_2	**9**	46[b]	56:44
36[e]	**P11a**	Me	Bu^t	CH_2Cl_2	**11**	60[b]	58:42
37[c]	**P11a**	Me	Bu^t	CH_2Cl_2	**11**	65[b]	58:42

[a–e] See Table 1. [f] Determined by ^{1}H NMR (250 MHz) spectroscopy.



Transition state E Transition state F

Fig. 4

33); (ii) the bulk of the leaving group (entries 27 and 28, 30 and 31); (iii) the size of the R substituent (entries 27 and 30, 28 and 31); (iv) the size of the Z group (entries 27 and 29, 32 and 33); (v) the temperature (entries 34, 35 and 27; 36, 32 and 37).

Analysis of the two diastereoisomeric transition states suggests that, for the same reasons as in the 2,5-substituted tetrahydrofurans, the E-form, precursor of the *cis*-compound, is lower in energy than the F form (F^1 and F^2) either to reach the lactone or the oxolane (Fig. 4). Increasing the volume of the R group would favour the equatorial position for this substituent.

No explanation for the effect of the leaving group on the isomer distribution could be found.

Conclusions.—The induced decomposition of an unsaturated peroxidic compound leading to a five-membered ring is a reaction presenting some stereochemical features in which the intramolecular homolytic substitution, responsible for this property, is under kinetic control. The main parameters governing the stereochemistry of the reaction are: the relative relationship of the substituents and the size of the R group present in the chain linking the double bond and the peroxidic function (the major isomer is the *trans* one for 2,3-substituted heterocycles, and the *cis* one for 2,4- and 2,5-oxolanes); the leaving group OY is only efficient in the creation of the 2,4- and 2,5-substituted oxacyclanes.

The size of the radical Z added to the double bond, the temperature of the reaction, and the nature of the peroxidic function (peroxide, perester or percarbonate) are inactive or only slightly effective factors.

Experimental

General Details.—Two gas chromatography apparatus were used, connected with an integrator Intersmat ICR-1 B: an Intersmat IGC 112F (flame ionization, N_2) fitted with stainless steel columns (diameter 2 mm) of FFAP (10% on Chromosorb WAW, 80–100 mesh, length 1.5 m), OV-17 (10% on Chromosorb WHP, 80–100 mesh, length 2 m), Carbowax 20 M (5% on Chromosorb W, 80–100 mesh treated with DMCS, length 3 m); a Delsi DI 200 (flame ionization, N_2) fitted with silica capillary columns of CP Sil 5 CB (length 25 m, diameter 0.32 mm), BP 20 (length 25 m, diameter 0.22 mm).

^{1}H NMR spectra were recorded on Perkin-Elmer R 24B (60 MHz) and Bruker AC 250 (250 MHz) spectrometers (CCl_4 solvent). *J*-Values are given in Hz.

^{13}C NMR spectra were recorded on Bruker WP 90 (23.6 MHz) and Bruker AC 250 (62.9 MHz) spectrometers ($CDCl_3$ solvent).

Mass spectra were recorded on a VG Micromass 16 F spectrometer fitted with a Pye-Unicam 204 gas chromatograph.

General Procedures.—(a) *Analytical studies.* A sealed ampoule containing reactant solution (2 cm^3) was heated in an oil-bath for various periods of time and temperature. Yields of the expected compounds were obtained by gas chromatography analyses of the reaction mixtures, using an internal standard.

(b) *Preparative-scale experiments.* A solution of the reactants was introduced into: (i) a steel bomb placed in a thermostatted oven set at the required temperature (110 or 80 °C) or (ii) in a round-bottom glass flask fitted with a condenser placed in a thermostatted oil-bath at 40 °C. After the reaction, the excess of substrate was removed under reduced pressure and the products were distilled.

In the experiments carried out in chloroform, sodium sulphate (0.1 mol) and sodium carbonate (0.2 mol) per mol of peroxidic compound were added to the reaction mixtures in order to trap water and HCl present in the solvent or produced in the reaction.

Starting Materials.—(a) *Substrates.* Methylene dichloride and chloroform were commercial products purified by distillation before use.

(b) *Free-radical initiators.* Commercial benzoyl peroxide stored in water was extracted with chloroform; the extract was dried (Na_2SO_4), then evaporated, and the recovered benzoyl peroxide was used without further purification. t-Butyl peracetate and ethyl perdicarbonate were prepared according to the methods of Bartlett and Hiatt,[12] and Strain *et al.*[13]

(c) *Starting materials for preparation of peroxidic reactants.* The syntheses of hydroperoxides, alcohols and acids is given below. The physical and spectroscopic characteristics of these compounds are summarized in Table 4.

Hydroperoxides. t-Butyl hydroperoxide was distilled off from the commercially available solution containing water, t-butyl alcohol and di-t-butyl peroxide. Primary and secondary hydroperoxides were prepared according to general procedures for nucleophilic substitution on mesates;[23] 1,1-diethylpropyl hydroperoxide was prepared from the corresponding and available alcohol in acid medium.[24]

Table 4 Physical and spectroscopic characteristics of precursors of peroxy compounds

Hydroperoxides	Yield (%)	n_D^{20}	B.p. (°C/mmHg)	^{1}H NMR (δ_H)
PeOOH	56	1.4127	54/10 41–42/4[14]	8.4 (1 H, s, OH), 3.9 (2 H, t, *J* 7, CH_2O), 1.8–0.9 (9 H, m, other H)
Pe^{s}OOH	30	1.4186	51/10 46–47/7[14]	8.6 (1 H, s, OH), 4.0–3.7 (1 H, m, CHO), 2.2–1.3 (10 H, m, d, *J* 7, other H)
Et_3COOH	51	1.4275	43/1 71–73/7[15]	9.2 (1 H, s, OH), 1.5 (6 H, q, *J* 8, CH_2), 0.9 (9 H, t, *J* 7, Me)
Alcohol precursor of				
P1	41		78–80/60 63–66/25[16]	6.1–4.8 (3 H, m, CH_2=CH), 3.7 (2 H, t, *J* 8, CH_2O), 3.0 (1 H, s, OH), 2.7–1.3 (3 H, m, CH_2CH), 1.0 (3 H, d, *J* 8, Me)
P4	25		111/760 113.5/760[17]	6.2–4.8 (3 H, m, CH_2=CH), 3.8 (1 H, t, *J* 7, CHO), 3.2 (1 H, s, OH), 2.0–1.2 (2 H, m, CH_2), 0.9 (3 H, t, *J* 7, Me)
P5	40		121/760 124/760[18]	6.1–4.9 (3 H, m, CH_2=CH), 3.7 (1 H, t, *J* 7, CHO), 2.6 (1 H, s, OH), 2.0–1.3 (1 H, m, Me_2CH), 0.9 (6 H, d, *J* 7, Me_2CH)
P6	32		68/100 51/25[18]	6.2–4.9 (3 H, m, CH_2=CH), 3.6 (1 H, d, *J* 7, CHO), 3.1 (1 H, s, OH), 0.9 (9 H, s, Bu^t)
P7	55		73/80 138–139/760[19]	6.2–4.7 (3 H, m, CH_2=CH), 3.9–3.5 (2 H, m, CHOH), 2.4–1.2 (4 H, m, other CH_2), 1.1 (3 H, d, *J* 8, Me)
P8	24		chromatographed on SiO_2	6.2–4.7 (3 H, m, CH_2=CH), 3.5–3.1 (2 H, m, CHO, OH), 2.4–1.1 (5 H, m, CH_2CH_2, Me_2CH), 0.9 (6 H, d, *J* 8, Me_2CH)
P9	89		88/69 145/760[20]	6.0–4.8 (3 H, m, CH_2=CH), 3.6 (1 H, s, OH), 3.3 (2 H, d, *J* 8, CH_2OH), 2.3–1.4 (3 H, m, CH_2CH), 0.8 (3 H, d, *J* 8, Me)
P10	85		93/25	6.2–4.7 (3 H, m, CH_2=CH), 3.8–3.4 (2 H, m, CH_2O), 2.5–1.1 (4 H, m, CH_2CH, OH), 0.9 (9 H, s, Bu^t)
Acid precursor of				
P2a	83		107/25 75–76/4[21]	11.9 (1 H, s, CO_2H), 6.2–4.7 (3 H, m, CH_2=CH), 3.0–2.1 (3 H, m, $CHCH_2$), 1.1 (3 H, d, *J* 7, Me)
P11a	79		105/30 101/23[22]	12.3 (1 H, s, CO_2H), 6.2–4.8 (3 H, m, CH_2=CH), 2.8–1.8 (3 H, m, $CHCH_2$), 1.1 (3 H, d, *J* 8, Me)

Table 5 Physical and spectroscopic characteristics of peroxy compounds

Peroxy compound	Yield (%)	n_D^{20}	^{1}H NMR (δ_H)
P1a	72	1.4246	6.2–4.8 (3 H, m, CH_2=CH), 4.0 (2 H, t, *J* 8, CH_2O), 2.5–1.3 (3 H, m, $CHCH_2$), 1.2 (9 H, s, Bu^t), 0.9 (3 H, d, *J* 8, Me)
P1b	49	1.4302	6.2–4.8 (3 H, m, CH_2=CH), 3.8 (4 H, m, CH_2OOCH_2), 2.5–1.9 (1 H, m, CH), 1.85–1.0 (14 H, m, other H)
P2a	82	1.4304	6.1–4.7 (3 H, m, CH_2=CH), 3.0–2.0 (3 H, m, $CHCH_2$), 1.2 (9 H, s, Bu^t), 1.2 (3 H, d, *J* 7, Me)
P3a	62	1.4204	6.2–4.9 (4 H, m, CH_2=CHCH), 1.4 (12 H, m, Bu^t, Me)
P4a	80	1.4239	6.1–4.8 (4 H, m, CH_2=CHCH), 1.9–1.4 (2 H, m, CH_2), 1.3 (9 H, s, Bu^t), 0.9 (3 H, t, *J* 7, Me)
P5a	70	1.4263	6.1–4.6 (4 H, m, CH_2=CHCH); 2.3–1.6 (1 H, m, $CHMe_2$), 1.3 (9 H, s, Bu^t), 1.0 (6 H, d, *J* 7, Me_2CH)
P6a	58	1.4280	6.2–4.9 (3 H, m, CH_2=CH), 4.8 (1 H, d, *J* 7, CH), 1.3 (9 H, s, Bu^{t}O), 1.0 (9 H, s, *Bu*^{t}CH)
P7a	49	1.4247	6.2–4.8 (3 H, m, CH_2=CH), 4.2–3.9 (1 H, m, CHO), 2.5–1.5 (4 H, m, other CH_2), 1.2 (12 H, s, Bu^t, *Me*CH)
P7b	48	1.4301	6.2–4.8 (3 H, m, CH_2=CH), 4.2–3.7 (3 H, m, $CHOOCH_2$), 2.5–0.9 (16 H, m, other H)
P7c	49	1.4330	6.2–4.7 (3 H, m, CH_2=CH), 4.3–3.7 (2 H, m, CHOOCH), 2.0–0.8 (17 H, m, other H)
P7d	45	1.4372	6.2–4.6 (3 H, m, CH_2=CH), 4.2–3.6 (1 H, m, CHO), 2.3–1.2 [13 H, m, CH_2CH_2, CH*Me*, ($MeCH_2$)$_3$], 0.83 [9 H, t, *J* 8, (*Me*CH_2)$_3$]
P8a	16	1.4260	6.2–4.7 (3 H, m, CH_2=CH), 3.6 (1 H, m, CHO), 2.4–1.3 (5 H, m, CH_2CH_2, $CHMe_2$), 1.2 (9 H, s, Bu^t), 0.9 (6 H, d, *J* 7, Me_2)
P8b	12	1.4279	6.2–4.9 (3 H, m, CH_2=CH), 4.0–3.6 (3 H, m, CH_2OOCH), 2.5–0.8 (20 H, m, other H)
P9a	54	1.4232	6.2–4.8 (3 H, m, CH_2=CH), 4.0–3.8 (2 H, m, CH_2O), 2.3–1.6 (3 H, m, CH_2CH), 1.2 (9 H, s, Bu^t), 0.8 (3 H, d, *J* 8, *Me*CH)
P9b	40	1.4312	6.2–4.7 (3 H, m, CH_2=CH), 4.1–3.6 (4 H, m, CH_2OOCH_2), 2.4–0.9 (15 H, m, other H)
P10a	60	1.4311	6.2–4.7 (3 H, m, CH_2=CH), 3.9 (2 H, d, *J* 7, CH_2O), 2.4–1.4 (3 H, m, CH_2CH), 1.3 (9 H, s, Me_3CO), 0.9 (9 H, s, Bu^t)
P10b	15	1.4310	6.1–4.7 (3 H, m, CH_2=CH), 4.1–3.6 (4 H, m, CH_2OOCH_2), 2.3–1.0 (12 H, m, other H), 0.9 (9 H, s, Bu^t)
P11a	92	1.4294	6.2–4.8 (3 H, m, CH_2=CH), 2.8–1.9 (3 H, m, $CHCH_2$), 1.3 (9 H, s, Bu^t), 1.2 (3 H, d, *J* 7, Me)

Alcohols. Alcohols were synthesized by classical organic reactions (Grignard reaction or malonic synthesis). 2-t-Butylpent-4-en-1-ol was prepared by lithium aluminium hydride reduction of the alkylation product of ethyl 3,3-dimethylbutanoate with allyl bromide, according to the classical procedure described by Macphee and Dubois.[25]

Acids. 3-Methylpent-4-enoic acid was provided by the hydrolysis of the corresponding ester, prepared by the Claisen rearrangement[26] of the compound formed by the reaction of but-2-enoic acid and triethyl orthoacetate. 2-Methylpent-4-enoic acid was obtained from diethyl allylmalonate.

(d) *Unsaturated peroxidic reactants.* All these products were

Table 6 ^{13}C Chemical shifts (δ_C) of tetrahydrofurans[a]

	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9, -10		
R1	87.3	38.6	34.9	66.7	27.1	10.6	17.5		*trans*	
	83.4	35.1	34.0	66.0	23.4	11.1	14.1		*cis*	
1	81.9	39.2	34.5	67.1	48.9	71.5	16.5		A	*trans*
	78.1	35.9	33.7	66.6	45.4	72.0	14.4		B	*cis*
1α	82.4	39.8	33.6	67.3	59.2	97.9	16.3		A	*trans*
	78.4	36.1	33.4	65.9	55.3	98.0	14.5		B	*cis*
R7	80.2	32.0	34.1	74.6	29.1	10.7	21.5		*trans*	
	81.0	30.9	33.0	75.2	29.0	10.4	21.5		*cis*	
7	75.3 or 74.7	31.8 or 33.4		74.7 or 75.3	50.1	71.2	20.9		A	*trans*
	75.7 or 75.3	31.0 or 32.5		75.3 or 75.7	50.5	71.2	21.4		B	*cis*
7α	75.6 or 74.8	33.5 or 33.7		74.8 or 75.6	60.5	97.3	21.2		A	*trans*
	76.3 or 75.3	32.6 or 32.5		75.3 or 76.3	60.9	97.4	21.4		B	*cis*
8	75.2	29.5 or 32.2		84.5	50.2	71.6	33.3	18.5, 19.4	A	*trans*
	75.3	28.4 or 31.2		85.4	50.6	71.5	33.4	18.6, 19.5	B	*cis*
R9	80.2	39.4	33.4	74.9	29.1	18.0	10.4		*trans*	
	81.6	40.6	34.5	74.5	29.1	18.1	10.5		*cis*	
9	75.0	39.3	33.2	75.0	50.2	71.3	17.8		A	*trans*
	76.1	40.4	34.3	74.5	50.2	71.3	17.5		B	*cis*
9α	75.6	40.6	33.0	74.8	60.5	97.4	17.9		A	*trans*
	76.8	41.7	34.1	74.4	60.5	97.5	17.4		B	*cis*
10	75.5	32.5	49.0	69.3	49.9	70.9	31.1	27.5	A	*trans*
	76.0	33.5	50.3	68.7	49.6	71.0	31.0	27.4	B	*cis*

[a] C-2, -3, -4 and -5 correspond to the carbons of the heterocycle; C-6 and -7 represent, respectively, α- and β-carbons of the substituent ethyl and C-8, -9 and -10 those of the substituent R.

Table 7 ^{13}C Chemical shifts (δ_C) of γ-lactones[a]

	C-2	C-3	C-4	C-5	C-6	C-7	C-8		
R11	180.3	34.6	35.7	79.0	34.5		16.1	*trans*	
	179.6	36.1	37.5	79.1	34.2		15.3	*cis*	
11	179.4	33.9	35.1	74.6	49.4	69.7	15.9	A	*trans*
	178.8	35.6	36.8	74.6	49.6	69.7	15.1	B	*cis*
11α	179.0	33.7	36.4	74.7	59.3	95.9	15.8	A	*trans*
	178.5	35.3	38.0	74.7	59.4	95.8	14.8	B	*cis*
R2	176.2	37.1	38.2	83.3	19.0		16.6	*trans*	
	176.7	36.9	33.5	79.6	13.8 or 15.3		15.3 or 13.8	*cis*	
2	175.7	36.7	36.0	82.9	48.1	69.8	16.8	A	*trans*
	175.8	36.9	32.7	79.3	44.6	70.4	14.3	B	*cis*
2α	175.4	36.1	36.6	82.8	58.4	96.5	16.2	A	*trans*
	175.4	37.4	33.8	79.3	54.7	96.5	14.3	B	*cis*

[a] See Table 6.

Table 8 ^{13}C Chemical shifts (δ_C) of cyclic carbonates[a]

	C-2	C-4	C-5	C-6	C-7	C-8	C-9, -10		
R3	154.8	80.1	80.1	18.3		18.3		*trans*	
	154.8	76.2	76.2	14.3		14.3		*cis*	
3	153.9	79.7	78.0	47.0	68.6	19.0		A	*trans*
	153.9	76.1	75.6	43.2	69.2	14.9		B	*cis*
3α	154.2	80.3	78.8	57.9	95.5	19.1		A	*trans*
	154.2	78.8	76.2	53.9	96.1	15.8		B	*cis*
4	154.4	82.9	78.3	47.9	69.1	27.0	9.1	A	*trans*
	154.4	81.2	76.4	43.4	69.7	22.9	10.5	B	*cis*
5	154.3	86.1	76.6	48.8	69.1	32.1	17.6 and 17.4	A	*trans*
	154.3	84.9	76.6	43.2	69.7	28.0	19.6 and 18.6	B	*cis*
6	153.7	88.0	74.2	49.2	68.6	33.9	24.3	A	*trans*
	153.7	86.3	74.5	44.1	69.3	33.4	26.1	B	*cis*

[a] See Table 6.

prepared according to known procedures (see below) and were purified by chromatography on silica gel, with pentane–diethyl ether mixture as eluents. The physical and spectroscopic characteristics of the compounds are given in Table 5.

Peroxides. The unsaturated peroxides were synthesized from the alkenyl mesates[27] by a method previously published by our group.[28]

Peralkenoates. Peresters were prepared from the corresponding acid, *N,N'*-carbonyldiimidazole and t-butyl hydroperoxide using the procedure previously described by Rüchardt.[29]

Percarbonates. Unsaturated percarbonates were synthesized from the corresponding unsaturated alcohol, the t-butyl hydroperoxide, and *N,N'*-carbonyldiimidazole.[30]

Reaction Products.—This part describes physical and spec-

troscopic characteristics of each heterocycle, except the ^{13}C NMR data, which are summarized in Tables 6–8.

2,3-*Substituted Heterocycles*.—2-(2,2-*Dichloroethyl*)-3-*methyltetrahydrofuran* **1**: n_D^{20} 1.4686; b.p. 98 °C/7 mmHg; δ_H 6.1–5.9 (1 H, m, 7-H), 4.1–3.5 (3 H, m, 2-H, 5-H_2), 2.8–1.3 (5 H, m, 3-H, 4-H_2, 6-H_2) and 1.1 (3 H, d, *J* 8, Me); *m/z* 29 (13), 41 (35), 43 (17), 55 (12), 56 (88), 57 (10) and 58 (100) (Found: C, 45.8; H, 6.6; Cl, 38.6. $C_7H_{12}Cl_2O$ requires C, 45.9; H, 6.55; Cl, 38.8%).

3-*Methyl*-2-(2,2,2-*trichloroethyl*)*tetrahydrofuran* **1α**: n_D^{20} 1.4838; b.p. 50 °C/0.01 mmHg; δ_H 4.2–3.5 (3 H, m, 2-H, 5-H_2), 2.85 (2 H, d, *J* 6, 6-H_2), 2.5–1.3 (3 H, m, 3-H, 4-H_2) and 1.15 (3 H, d, *J* 6, Me); *m/z* 29 (16), 41 (41), 55 (15), 56 (100) and 85 (73) (Found: C, 38.75; H, 5.1; Cl, 48.8. $C_7H_{11}Cl_3O$ requires C, 38.6; H, 5.05; Cl, 49.0%).

5-(2,2-*Dichloroethyl*)-4-*methyl*-2-*oxotetrahydrofuran* **2**: n_D^{20} 1.4850; b.p. 95 °C/0.01 mmHg; δ_H 6.05–5.85 (1 H, m, 7-H), 4.7–4.5 (1 H, m, 5-H *cis*), 4.5–4.1 (1 H, m, 5-H *trans*), 3.1–2.0 (5 H, m, 3-H_2, 4-H, 6-H_2), 1.1 (3 H, d, *J* 7, Me *cis*), 1.2 (3 H, d, *J* 7, Me *trans*); *m/z trans*: 41 (25), 42 (80), 43 (27), 70 (18), 71 (26) and 99 (100); *cis*: 41 (26), 42 (100), 43 (23), 70 (28), 71 (27) and 99 (68) (Found: C, 42.7; H, 5.1; Cl, 35.9. $C_7H_{10}Cl_2O_2$ requires C, 42.6; H, 5.1; Cl, 36.0%).

4-*Methyl*-2-*oxo*-5-(2,2,2-*trichloroethyl*)*tetrahydrofuran* **2α**: n_D^{20} 1.4971; b.p. 120 °C/0.05 mmHg; δ_H 5.0–4.5 (1 H, m, 5-H *cis*), 4.4–4.1 (1 H, m, 5-H *trans*), 3.2–2.9 (2 H, m, 6-H_2), 2.9–1.8 (3 H, m, 3-H_2, 4-H), 1.1 (3 H, d, *J* 7, Me *cis*), 1.2 (3 H, d, *J* 7, Me *trans*) (Found: C, 36.3; H, 3.9; Cl, 45.9. $C_7H_9Cl_3O_2$ requires C, 36.3; H, 3.9; Cl, 46.0%).

5-(2,2-*Dichloroethyl*)-4-*methyl*-2-*oxo*-1,3-*dioxolane* **3**: n_D^{20} 1.4774; b.p. 95 °C/0.01 mmHg; δ_H 6.1–5.8 (1 H, m, 7-H), 5.2–4.3 (2 H, m, 5- and 4-H), 3.0–2.3 (2 H, m, 6-H_2) and 1.5 (3 H, d, *J* 6, Me); *m/z trans*: 56 (60), 57(100), 62 (88), 71 (34), 75 (79) and 101 (60); *cis*: 56 (100), 57 (93), 71 (69), 75 (60) and 101 (39) (Found: C, 36.4; H, 3.9; Cl, 36.0. $C_6H_8Cl_2O_3$ requires C, 36.2; H, 4.0; Cl, 35.7%).

4-*Methyl*-2-*oxo*-5-(2,2,2-*trichloroethyl*)-1,3-*dioxolane* **3α**: n_D^{20} 1.4911; b.p. 100 °C/0.01 mmHg; δ_H 5.2–4.3 (2 H, m, 5-and 4-H), 3.6–2.8 (2 H, m, 6-H_2), 1.6 (3 H, d, *J* 6, Me *trans*), 1.5 (3 H, d, *J* 6, Me *cis*); *cis*- and *trans*-signals could be differentiated but not interpreted *m/z trans*: 29 (100), 56 (43), 62 (47) and 75 (49); *cis*: 29 (100), 56 (85), 57 (65), 62 (43) and 75 (58) (Found: C, 30.6; H, 2.9; Cl, 45.55. $C_6H_7Cl_3O_3$ requires C, 30.8; H, 3.0; Cl, 45.6%).

5-(2,2-*Dichloroethyl*)-4-*ethyl*-2-*oxo*-1,3-*dioxolane* **4**: n_D^{20} 1.4784; b.p. 110 °C/0.01 mmHg; δ_H 6.0–5.7 (1 H, m, 7-H), 5.0–4.0 (2 H, m, 5- and 4-H), 2.8–2.7 (2 H, m, 6-H_2), 2.1–1.4 (2 H, q, *J* 7, CH_2Me), 1.1 (3 H, t, *J* 7, CH_2*Me* trans), 1.0 (3 H, t, *J* 7, CH_2*Me cis*); *cis*- and *trans*-signals could be differentiated but not interpreted *m/z trans*: 27 (56), 41 (55), 42 (75), 43 (71), 57 (33), 71 (34) and 75 (100); *cis* 27 (65), 28 (69), 41 (62), 42 (86), 43 (65), 57 (36), 71 (25) and 75 (100) (Found: C, 39.4; H, 4.7; Cl, 33.2. $C_7H_{10}Cl_2O_3$ requires C, 39.4; H, 4.7; Cl, 33.3%).

5-(2,2-*Dichloroethyl*)-4-*isopropyl*-2-*oxo*-1,3-*dioxolane* **5**: n_D^{20} 1.4709; b.p. 115 °C/0.01 mmHg; δ_H 6.1–5.7 (1 H, m, 7-H), 5.0–4.2 (1 H, m, 5-H), 4 (1 H, t, *J* 6, 4-H), 2.9–1.4 (3 H, m, C*H*Me_2, 6-H_2), 1.1 (6 H, d, *J* 6, CHMe_2); *m/z trans*: 28 (89), 41 (46), 43 (79), 57 (100) and 75 (33); *cis*: 28 (98), 41 (36), 43 (63), 57 (100) and 75 (19) (Found: C, 42.4; H, 5.25; Cl, 31.4. $C_8H_{12}Cl_2O_3$ requires C, 42.3; H, 5.3; Cl, 31.3%).

4-*t*-*Butyl*-5-(2,2-*dichloroethyl*)-2-*oxo*-1,3-*dioxolane* **6**: n_D^{20} 1.4766; b.p. 120 °C/0.01 mmHg; δ_H 6.0–5.7 (1 H, m, 7-H), 4.8–4.3 (1 H, m, 5-H), 3.9 (1 H, d, *J* 6, 4-H), 3.1–2.0 (2 H, m, 6-H_2) and 1.0 (9 H, s, Bu^t); *m/z* 29 (19), 41 (14) and 57 (100) (Found: C, 45.1; H, 5.8; Cl, 29.4. $C_9H_{14}Cl_2O_3$ requires C, 44.8; H, 5.8; Cl, 29.45%).

2,5-*Substituted Heterocycles*.—2-(2,2-*Dichloroethyl*)-5-*methyltetrahydrofuran* **7**: n_D^{20} 1.4683; b.p. 52 °C/0.15 mmHg; δ_H 5.9 (1 H, t, *J* 8, 7-H), 4.3–3.9 (2 H, m, 2- and 5-H), 2.7–1.3 (6 H, m, 3-, 4- and 6-H_2) and 1.1 (3 H, d, *J* 8, Me); *m/z* 28 (11), 29 (11), 41 (26), 43 (19), 55 (14), 56 (21) and 85 (100) (Found: C, 45.85; H, 6.5; Cl, 38.0. $C_7H_{12}Cl_2O$ requires C, 45.9; H, 6.55; Cl, 38.8%).

5-*Methyl*-2-(2,2,2-*trichloroethyl*)*tetrahydrofuran* **7α**: n_D^{20} 1.4790; b.p. 55 °C/0.05 mmHg; δ_H 4.5–3.8 (2 H, m, 2- and 5-H), 3.1–2.8 (2 H, m, 6-H_2), 2.5–1.3 (4 H, m, 3- and 4-H_2) and 1.2 (3 H, d, *J* 6, Me); *m/z* 29 (19), 41 (40), 43 (68), 55 (18), 56 (36) and 85 (100) (Found: C, 38.5; H, 5.05; Cl, 48.8. $C_7H_{11}Cl_3O$ requires C, 38.6; H, 5.05; Cl, 49.0%).

2-(2,2-*Dichloroethyl*)-5-*isopropyltetrahydrofuran* **8**: n_D^{20} 1.4631; b.p. 60 °C/0.01 mmHg; δ_H 5.9–5.6 (1 H, m, 7-H), 4.2–3.1 (2 H, m, 2- and 5-H), 2.5–1.1 (7 H, m, 3-, 4- and 6-H_2, C*H*Me_2 and 0.9–0.85 (6 H, dd, *J* 7, CHMe_2); *m/z* 27 (19), 41 (57), 43 (44), 55 (24), 56 (24), 57 (14), 67 (73), 95 (29), 103 (21), 105 (28) and 167 (100) (Found: C, 51.2; H, 7.6; Cl, 33.25. $C_9H_{16}Cl_2O$ requires C, 51.2; H, 7.6; Cl, 33.65%).

2,4-*Substituted Heterocycles*.—2-(2,2-*Dichloroethyl*)-4-*methyltetrahydrofuran* **9**: n_D^{20} 1.4695; b.p. 55 °C/0.5 mmHg; δ_H 6.0 (1 H, t, *J* 8, 7-H), 4.4–3.8 (1 H, m, 2-H), 3.6–3.2 (2 H, m, 5-H_2), 2.6–1.4 (5 H, m, 3- and 6-H_2, 4-H) and 1.1 (3 H, d, *J* 8, Me); *m/z* 29 (12), 41 (27), 43 (68), 55 (11), 56 (19), 57 (15) and 85 (100) (Found: C, 45.8; H, 6.5; Cl, 38.6. $C_7H_{12}Cl_2O$ requires C, 45.9; H, 6.55; Cl, 38.8%).

4-*Methyl*-2-(2,2,2-*trichloroethyl*)*tetrahydrofuran* **9α**: 1.4789; b.p. 55 °C/0.005 mmHg; δ_H 4.5–3.6 (3 H, m, 2-H and 5-H_2), 3.5–1.8 (5 H, m, 4-H and 3- and 6-H_2) and 1.1 (3 H, d, *J* 7, Me); *m/z* 29 (14), 41 (32), 43 (13), 55 (15), 56 (27), 57 (18) and 85 (100) (Found: C, 38.9; H, 5.1; Cl, 48.5. $C_7H_{11}Cl_3O$ requires C, 38.6; H, 5.05; Cl, 49.0%).

4-t-*Butyl*-2-(2,2-*dichloroethyl*)*tetrahydrofuran* **10**: n_D^{20} 1.4668; b.p. 80 °C/0.01 mmHg; δ_H 5.9–5.7 (1 H, m, 7-H), 4.3–3.2 (3 H, m, 2-H and 5-H_2), 2.5–1.5 (5 H, m, 4-H and 3- and 6-H_2), 0.9 (9 H, s, Bu^t); *m/z* 41 (32), 55 (17), 70 (16), 83 (25) and 127 (100) (Found: C, 53.2; H, 8.0; Cl, 31.85. $C_{10}H_{18}Cl_2O$ requires C, 53.3; H, 8.0; Cl, 31.55%).

5-(2,2-*Dichloroethyl*)-3-*methyl*-2-*oxotetrahydrofuran* **11**: m.p. 37 °C; b.p. 95 °C/0.02 mmHg; δ_H 5.9 (1 H, t, *J* 6, 7-H), 4.9–4.2 (1 H, m, 5-H), 3.3–1.3 (5 H, m, 3-H and 4- and 6-H_2) and 1.2 (3 H, d, *J* 6, Me); *m/z* 41 (57), 42 (34), 43 (39), 55 (42), 69 (74), 81 (41) and 99 (100) (Found: C, 42.7; H, 5.1; Cl, 35.9. $C_7H_{10}Cl_2O_2$ requires C, 42.6; H, 5.1; Cl, 36.0%).

3-*Methyl*-2-*oxo*-5-(2,2,2-*trichloroethyl*)*tetrahydrofuran* **11α**: m.p. 53 °C; b.p. 130 °C/0.05 mmHg; δ_H 5.1–4.4 (1 H, m, 5-H), 3.4–1.3 (5 H, m, 3-H and 4- and 6-H_2) and 1.2 (3 H, d, *J* 7, Me); *m/z* 41 (51), 42 (44), 43 (40), 55 (85), 69 (52) and 99 (100) (Found: C, 36.4; H, 3.8; Cl, 46.1. $C_7H_9Cl_3O_2$ requires C, 36.3; H, 3.9; Cl, 46.0%).

Reduction of Tetrahydrofurans **7** *and* **9**.—Compounds **7** and **9** were transformed respectively into **R7** and **R9** by heating them at 80 °C with 2 mol equiv. of tributyltin hydride in the presence of AIBN (1%). Products **R7** and **R9** isolated by distillation had physical and spectral properties in agreement with those established by Eliel *et al.*[31]

Stereochemical Attribution to the Heterocyclic Diastereoisomers.—The structure of *cis*- and *trans*-isomers was determined by NMR comparison of the chemical-shift differences of various carbons and protons of the heterocycle with those of the corresponding reference compounds described in the literature:

2-ethyl-3-(or 5- or 4-)-methyltetrahydrofurans, **R1**, **R7**, **R9**[31]
5-alkyl-4-(or 3-)-methyl-2-oxotetrahydrofurans, **R2**, **R11**,[32–34]
4,5-dimethyl-2-oxo-1,3-dioxolanes **R3**[35]

Table 9 ^{1}H Chemical shifts of 'lactonic hydrogen' 5-H

Lactone	Isomer	δ	Attribution
2	A	4.20–4.12	*trans*
	B	4.65–4.61	*cis*
2α	A	4.39–4.32	*trans*
	B	4.87–4.80	*cis*
11	A	4.80–4.64	*trans*
	B	4.61–4.46	*cis*
11α	A	4.96–4.86	*trans*
	B	4.80–4.70	*cis*

Confirmation of the assignment for heterocycles **7** and **9** was obtained by a ^{13}C NMR study of the corresponding methyl-(ethyl-)substituted tetrahydrofurans produced by their reaction with tributyltin hydride in excess.

Tables 6–8 show ^{13}C NMR spectral data of the various heterocycles produced and used as reference; the assignment of structures to the various isomers were allowed by comparison of the differences in the chemical shifts. Table 9 shows the chemical shifts of the 'lactonic hydrogen,' confirming these assignments.

References

1 E. Montaudon, M. Campagnole, F. Flies and B. Maillard, *J. Heterocycl. Chem.*, in the press, and earlier papers.

2 Many examples are described in the following reviews: A. L. J. Beckwith, *Tetrahedron*, 1981, **37**, 3073; C. Easton, *Sci. Prog. Oxf.*, **68**, 503; B. Giese, in *Stereochemistry of Organic and Bioorganic Transformations*, Workshop Conferences Hoechst, and W. Bartmann and K. B. Sharpless, 1987, vol. 17, 261; M. Ramaiah, *Tetraheron*, 1987, **43**, 3541; D. P. Curran, *Synthesis*, 1988, 417, 489.

3 Some references to specific kinds of reactions are given as examples below: (*a*) B. Giese, *Angew. Chem., Int. Ed. Engl.*, 1984, **23**, 753, and cited references; B. Giese and T. Witzel, *Angew. Chem., Int. Ed. Engl.*, 1986, **25**, 450 and earlier papers; D. Crich and J. W. Davies, *Tetrahedron Lett.*, 1987, **28**, 4205; D. H. R. Barton, R. Gateau-Olesker, S. D. Gero, B. Lacher, C. Tachdjian and S. Z. Zard, *J. Chem. Soc., Chem. Commun.*, 1987, 1970; D. H. R. Barton, S. D. Gero, B. Quiclet-Sire and M. Samadi, *J. Chem. Soc., Chem. Commun.*, 1988, 1372; (*b*) M. Julia, C. Descoins, M. Baillarge, B. Jacquet, D. Uguen and F. A. Groeger, *Tetrahedron*, 1975, **31**, 1737; D. J. Hart and Y. M. Tsai, *J. Am. Chem. Soc.*, 1984, **106**, 8209 and earlier papers; A. L. J. Beckwith and D. H. Roberts, *J. Am. Chem. Soc.*, 1986, **108**, 5893 and earlier papers; R. Tsang and B. Fraser-Reid, *J. Am. Chem. Soc.*, 1986, **108**, 2116; M. Pezechk, A. P. Brunetière and J. Y. Lallemand, *Tetrahedron Lett.*, 1986, **27**, 3715; M. D. Bachi, A. de Mesmaeker and N. Stevenart-de Mesmaeker, *Tetrahedron Lett.*, 1987, **28**, 2887; D. L. J. Clive, T. L. B. Boivin and A. G. Angoh, *J. Org. Chem.*, 1987, **52**, 4923 and earlier papers; D. P. Curran and S. C. Kuo, *Tetrahedron*, 1987, **43**, 5653 and earlier papers; Y. Watanabe and T. Endo, *Tetrahedron Lett.*, 1988, **29**, 321 and earlier papers; T. Kametani, S. D. Chu, A. Itoh, S. Maeda and T. Honda, *J. Org. Chem.*, 1988, **53**, 2683; G. Stork, *Bull. Chem. Soc. Jpn.*, 1988, **61**, 149 and cited references, and earlier papers; (*c*) M. Castaing, M. Pereyre, M. Ratier, P. M. Blum and A. G. Davies, *J. Chem. Soc., Perkin Trans. 2*, 1979, 287; A. L. J. Beckwith and G. Moad, *J. Chem. Soc., Perkin Trans. 2*, 1980, 1083 and earlier papers; A. L. J. Beckwith and G. Moad, *J. Chem. Soc., Perkin Trans. 2*, 1980, 1473 and earlier papers; P. S. Mariano and E. Bay, *J. Org. Chem.*, 1980, **45**, 1763 and earlier papers; T. E. Boothe, J. L. Greene and P. B. Shevlin, *J. Org. Chem.*, 1980, **45**, 794 and earlier papers; Y. Ueno, H. Sano, S. Aoki and M. Okawara, *Tetrahedron Lett.*, 1981, **22**, 2675; N. Bensadoun, P. Brun, J. Casanova and B. Waegell, *J. Chem. Res.*, 1981, (*S*), 236; (*M*), 2601; A. Johns, J. A. Murphy, C. W. Patterson and N. F. Wooster, *J. Chem. Soc., Chem. Commun.*, 1987, 1238; F. Harris and L. Weiler, *Tetrahedron Lett.*, 1987, **28**, 2941; J. D. Hardling and W. B. Motherwell, *J. Chem. Soc., Chem. Commun.*, 1988, 1381; (*d*) L. A. Singer and N. P. Kong, *J. Am. Chem. Soc.*, 1966, **88**, 5213; A. L. J. Beckwith and C. J. Easton, *J. Am. Chem. Soc.*, 1981, **103**, 615; V. Malatesta and K. U. Ingold, *J. Am. Chem. Soc.*, 1981, **103**, 609; B. Giese and T. Witzel, *Tetrahedron Lett.*, 1987, **28**, 2571 and earlier papers; (*e*) G. Stork and P. M. Sher, *J. Am. Chem. Soc.*, 1986, **108**, 303 and earlier papers; P. Kocovsky, I. Stary and F. Turecek, *Tetrahedron Lett.*, 1986, **27**, 1513; B. Giese, K. S. Groninger, T. Witzel, H. G. Korth and R. Sustmann, *Angew. Chem., Int. Ed. Engl.*, 1987, **26**, 233; (*f*) P. Gouverneur, *Ind. Chim. Belg.*, 1974, **39**, 467; A. de Mesmaeker, L. Vertommen, R. Merenyi and H. G. Viehe, *Tetrahedron Lett.*, 1982, **23**, 69; R. Merenyi, A. de Mesmaeker and H. G. Viehe, *Tetrahedron Lett.*, 1983, **24**, 2765; (*g*) J. Fossey, D. Lefort and J. Sorba, *J. Org. Chem.*, 1986, **51**, 3584 and earlier papers; (*h*) A. L. J. Beckwith and D. R. Boate, *J. Chem. Soc., Chem. Commun.*, 1986, 189.

4 H. Hart and F. F. Chloupeck, *J. Am. Chem. Soc.*, 1963, **85**, 1155.

5 N. A. Porter and J. R. Nixon, *J. Am. Chem. Soc.*, 1978, **100**, 7116; N. A. Porter, M. A. Cudd, R. W. Miller and A. T. McPail, *J. Am. Chem. Soc.*, 1980, **102**, 414.

6 B. Maillard, A. Kharrat and C. Gardrat, *New J. Chem.*, 1987, **11**, 7.

7 M. J. Bourgeois, B. Maillard and E. Montaudon, *Tetrahedron*, 1986, **42**, 5309.

8 A. Kharrat, C. Gardrat and B. Maillard, *Bull. Soc. Chim. Belg.*, 1986, **95**, 535.

9 S. D. Rychnovsky and P. A. Bartlett, *J. Am. Chem. Soc.*, 1984, **106**, 3963.

10 N. A. Porter and P. J. Zuraw, *J. Org. Chem.*, 1984, **49**, 1335.

11 M. L. Mihailovic, S. Gojkovic and S. Konstantinovic, *Tetrahedron*, 1973, **29**, 3675.

12 P. D. Bartlett and R. R. Hiatt, *J. Am. Chem. Soc.*, 1958, **80**, 1398.

13 F. Strain, W. E. Bassinger, W. R. Dial, H. Rudoff, B. J. Dewitt, H. C. Stevens and J. H. Langston, *J. Am. Chem. Soc.*, 1950, **72**, 1254.

14 H. R. Williams and H. S. Mosher, *J. Am. Chem. Soc.*, 1954, **76**, 2984.

15 R. Criegee and N. Dietrich, *Justus Liebigs Ann. Chem.*, 1948, **560**, 135.

16 T. A. Pkheidze and O. S. Madaeva, *Zh. Obshch. Khim.*, 1960, **30**, 2067.

17 R. Delaby and J. Lecomte, *Bull. Soc. Chim. Fr.*, 1937, **4**, 738.

18 M. B. Green and W. J. Hickinbottom, *J. Chem. Soc. C*, 1957, 3263.

19 H. B. Jr. Wood and E. C. Horning, *J. Am. Chem. Soc.*, 1953, **75**, 5511.

20 G. I. Fray and N. Polgar, *J. Chem. Soc.*, 1956, 2036.

21 R. E. Ireland, R. H. Mueller and R. K. Willard, *J. Am. Chem. Soc.*, 1976, **98**, 2868.

22 R. Rossi and G. Ingrosso, *Gazz. Chim. Ital.*, 1968, **98**, 866.

23 H. R. Williams and H. S. Mosher, *J. Am. Chem. Soc.*, 1957, **79**, 3474.

24 J. K. Kochi, *J. Am. Chem. Soc.*, 1962, **84**, 1193.

25 J. A. Macphee and J. E. Dubois, *J. Chem. Soc., Perkin Trans. 1*, 1977, 694.

26 R. G. Parker and J. D. Roberts, *J. Am. Chem. Soc.*, 1970, **92**, 741.

27 A. Sekera and C. S. Marvel, *J. Am. Chem. Soc.*, 1933, **55**, 345.

28 M. J. Bourgeois, E. Montaudon and B. Maillard, *Synthesis*, 1989, 700.

29 R. Hecht and C. Rüchardt, *Chem. Ber.*, 1963, **96**, 1281.

30 M. J. Bourgeois, C. Filliatre, R. Lalande, B. Maillard and J. J. Villenave, *Tetrahedron Lett.*, 1978, 3355; M. J. Bourgeois, M. Campagnole, C. Filliatre, B. Maillard and J. J. Villenave, *Bull. Soc. Chim. Fr.*, 1982, 111.

31 E. L. Eliel, V. S. Rao and K. M. Pietrusiewicz, *Org. Magn. Reson.*, 1979, **12**, 461.

32 H. Frauenrath and T. Philipps, *Liebigs Ann. Chem.*, 1985, 1951.

33 Y. Nishida, M. Konno, Y. Fukushima, H. Ohrui and H. Meguro, *Agric. Biol. Chem.*, 1986, **50**, 191.

34 S. A. M. T. Hussain, W. D. Ollis, C. Smith and J. F. Stoddart, *J. Chem. Soc., Perkin Trans. 1*, 1975, 1480.

35 K. Pihlaja and K. Rossi, *Acta Chem. Scand., Ser. B*, 1977, **31**, 899.

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