# Oxidation of Ketones by Ferric Perchlorate in the Presence of Conjugated Dienes to Hexahydrofuro[2,3-*b*]furans and 1,6-Dioxaspiro[4,4]nonanes

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Iron(III) perchlorate nonahydrate (FEP) in acetonitrile in the presence of conjugated dienes oxidizes carbonyl compounds (aldehydes and ketones) to α,α-diaddition products hexahydrofuro[2,3-*b*]-furans **3**, in moderate yield (nine examples). α,α-Disubstituted ketones afford the α,α′-diaddition products 1,6-dioxaspiro[4,4]nonanes **4** or monoaddition products **6** and **7**. The isomer distribution and the influence of the reaction conditions are discussed based on selective oxidative deprotonation of the carbonyl compound by iron(III) and addition of α-carbonylalkyl radicals to conjugated olefins.

Oxidative deprotonation of carbonyl compounds by high valence metal salts is a general and versatile approach to the selective α-functionalization of such compounds with the formation of new C–C bonds.[1–4] The relevant data in this field refer to the use of $Mn^{III}$ acetate and only recently have comparative studies, using different high valent metal salts, recognized the widespread generality of these processes.[2] Consistent results in terms of yield, product distribution and selectivity can be obtained by an appropriate choice of metal, counter ion, solvent and added base.

Our recent studies[2–4] particularly emphasize close analogies between iron(III) salts possessing anions of low nucleophilicity [*i.e.* $Fe(ClO_4)_3 \cdot 9\ H_2O$ (FEP)] in acetonitrile and $Mn^{III}$ acetate in acetic acid. With these salts the ligated water plays a specific role, as, for example, in the lactonization process from malonic esters and olefins.[3]

We have recently extended these studies to ketones in the presence of styrene and other conjugated dienes and herein we report a new example of selective α,α- or α,α′-difunctionalization of carbonyl compounds to hexahydrofuro[2,3-*b*]furans (**3**, where $R^3$, $R^4$, $R^5$ and $R^6$ are the olefin substituents R and R′ numbered differently to evidence the stereochemical pattern) or 1,6-dioxaspiro[4,4]nonanes (**4**) (Schemes 1 and 2, respectively).

A similar reaction to give a mixture of all possible isomeric ketals **3** and **4** in low yield has been reported in which acetone was oxidized by the system $Mn^{III}/Cu^{II}$ acetates in the presence of butadiene,[5] but generally these processes afford dihydrofuran derivatives in moderate yield.[6]

## Results

We first examined the oxidation of cyclohexanone (**1a**) by FEP in acetonitrile in the presence of styrene (**2a**). At 20 °C the reaction is complete in 1.5 h, as deduced from the nearly quantitative conversion of iron(III) to iron(II) and the fading of the colour of the solution. A mixture of two diastereoisomeric furo[2,3-*b*]furans **3a** and **3a′** (1:1.3) is formed in yields increasing with the concentration of styrene (Table 1, entries 1–4) and decreasing with the conversion of ketone (Table 1, entries 7, 8). Raising the temperature to 50 °C improves slightly the yield of **3**. Basic additives, *i.e.* water in excess and pyridine (Table 1, entries 9–10), only marginally affect the yield, but increase the oxidation time (from 1.5 to 3 and 4 h, respectively). A significant improvement of the reaction can be obtained upon addition of stoichiometric amounts of 2,2′-bipyridine (Table 1, entries 11, 12), whereas the reaction is totally suppressed by the addition of acetic anhydride in stoichiometric amounts corresponding to the water of hydration of FEP (Table 1, entry 13). On the contrary, only oxidation to the α-hydroxy derivative of the ketone was observed in analogous reactions in the presence of oct-1-ene or allyl alcohols as trapping agents.

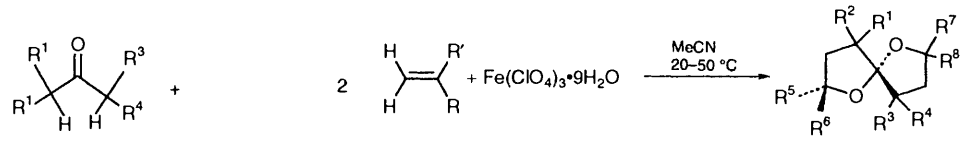
The following features of the reaction are observed in all experiments of Table 1: (i) only diaddition products of cyclohexanone to styrene are obtained; (ii) no α,α′-diaddition product contaminates the α,α-diaddition product **3**; (iii) of the three possible diastereoisomers of **3**, only isomers **3a** and **a′** are detected (except for **3f**); and (iv) the ratio **3a**/**3a′** is marginally affected by the reaction conditions.

The structure of **3a** and **a′** were assigned on the basis of Pt/C catalyzed hydrogenation of two independent samples to the same 2,2-bis(2-phenylethyl)cyclohexanone (**5**). The stereochemical assignment was made by $^1H$ NMR spectroscopy and $^1H$ NOE difference spectra on two different spectrometers at 300 and 500 MHz, taking into consideration the symmetric nature of compound **3a** and previous work on furo[2,3-*b*]furans.[7] In compound **3a**, selective saturation of the benzylic hydrogens at 5.36 ppm results in no enhancement of methylene signals belonging to the cyclohexane moiety, whereas irradiation of the aromatic hydrogens affords a 1.5% enhancement of the multiplet centred at 1.6 ppm of cyclohexane. The two equivalent phenyls, attached to C-2 and C-5, respectively, display therefore a *cis* relationship with respect to the cyclohexane bridge. With **3a′** an NOE enhancement is observed only between the benzylic hydrogens at 5.21 ppm and the methylene hydrogens of the cyclohexane (1.2%), whereas selective irradiation of the multiplet at 5.38 ppm did not afford any NOE enhancement of the same hydrogens. We conclude that, with respect to the cyclohexane bridge, the phenyls at C-2 and C-5 display a *cis* and *trans* relationship, respectively.

In order to obtain further insights on the chemo- and stereoselectivity observed with cyclohexanone, other carbonyl compounds (**1b–g**) were investigated. The results of the reactions carried out under standard conditions with a ratio [**1**]:[**2**]:FEP of 1:2:4 and without additive, unless expressly stated, are collected in Table 2. Compounds **3** were obtained from carbonyl compounds **1** carrying two hydrogens in the α position (both aldehydes and ketones) with all olefins tested. The presence of a basic nitrogen in the carbonyl starting material (*i.e.* **1g**) was found to lower the yield of **3**, but did not change the overall reaction features (Table 2, entry 7). In some cases, *i.e.* with pentan-2-one (Table 2, entry 4), a large excess of the ketone was needed to produce **3** in good yield. On the contrary, methyl ketones (*i.e.* acetone, acetophenone and methyl-*tert*-butyl ketone) were remarkably less reactive. Compounds **3** were never observed with these substrates, but FEP efficiently oxidized the

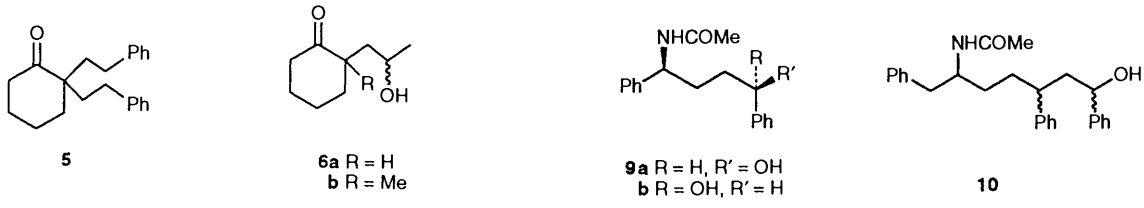
| 1 | | 2 | | 3 | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $R^1$ | $R^2$ | R | R′ | $R^1$ | $R^2$ | $R^3$ | $R^4$ | $R^5$ | $R^6$ |
| **1a** | $-[CH_2]_4-$ | **2a** | Ph H | **3a** | $-[CH_2]_4-$ | Ph | H | Ph | H |
| **b** | Et Me | **b** | $CH{=}CH_2$ H | **a′** | $-[CH_2]_4-$ | H | Ph | Ph | |
| **c** | Ph Me | | | **b** | Et Me | Ph | H | Ph | H |
| **d** | Me Et | | | **b′** | Et Me | H | Ph | Ph | H |
| **e** | H Et | | | **c** | Ph Me | Ph | H | Ph | H |
| **f** | H $PhCH_2$ | | | **c′** | Ph Me | H | Ph | Ph | H |
| **g** | $-[CH_2]_2NMe[CH_2]-$ | | | **d** | Me Et | Ph | H | Ph | H |
| | | | | **d′** | Me Et | H | Ph | Ph | H |
| | | | | **e** | H Et | Ph | H | Ph | H |
| | | | | **e′** | H Et | H | Ph | Ph | H |
| | | | | **f** | H $PhCH_2$ | Ph | H | Ph | H |
| | | | | **f′** | H $PhCH_2$ | H | Ph | Ph | H |
| | | | | **g** | $-[CH_2]_3NMe-$ | Ph | H | Ph | H |
| | | | | **g′** | $-[CH_2]_3NMe-$ | H | Ph | Ph | H |
| | | | | **h** | $-[CH_2]_4-$ | $CH{=}CH_2$ | $CH{=}CH_2$ | $CH{=}CH_2$ | H |
| | | | | **h′** | $-[CH_2]_4-$ | H | | $CH{=}CH_2$ | H |

**Scheme 1**



| 2 | | | | 4 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $R^1$ | $R^2$ | $R^3$ | $R^4$ | $R^1$ | $R^2$ | $R^3$ | $R^4$ | $R^5$ | $R^6$ | $R^7$ | $R^8$ |
| **1h** | H $-[CH_2]_3-$ | Me | **4a** | H | $-[CH_2]_3-$ | Me | Ph | H | Ph | H | |
| **i** | H Et Me | Me | **a′** | H | $-[CH_2]_3-$ | Me | H | Ph | Ph | H | |
| | | | **b** | H | Et | Me | Me | Ph | H | Ph | H |
| | | | **b** | H | Et | Me | Me | H | Ph | Ph | H |

**Scheme 2**

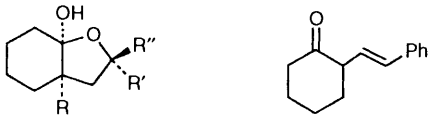


**5**

**6a** R = H
**b** R = Me

**9a** R = H, R′ = OH
**b** R = OH, R′ = H

**10**



**7a** R = H, R′ = Ph, R″ = H
**a** R = H, R′ = H, R″ = Ph
**b** R = Me, R′ = Ph, R″ = H
**c** R = Me, R′ = H, R″ = Ph

**8**

styrene, affording a complex mixture of telomerization products, from which 1,4-diphenylbutadiene, 1,4-diphenylbutane derivatives **9** and 1,4,6-triphenylhexane derivatives **10** were identified. It is noteworthy that styrene was inert to FEP at 20 °C in the absence of carbonyl compounds.

The stereochemical assignment of structures **3b–h′** was accomplished by $^1H$ NMR spectroscopy. The assignments are made with reference to Fig. 1, employing derivatives **3f** and **f′** as representative examples. Typically, symmetrical (2α,3aα,5α,6aα) derivatives show chemical equivalence of homologous hydrogens, the contrary being true for (2β,3aα,5α,6aα) compounds. An exception to this general rule are the benzyl derivatives **3f** formed in the reaction with 3-phenylpropanal, for which chemical non equivalence is observed for all hydrogens and minor amounts of the (2β,3aα,5β,6aα) isomer were detected by GLC-MS. The stereochemical assessment of **3f** and **f′** was accomplished with a set of NOE experiments on both compounds (see Experimental part).

α,α-Dialkyl substituted ketones, *i.e.* 2-methylcyclohexanone (**1h**) and 2-methylhexan-3-one (**1i**), are also easily oxidized in the presence of conjugated olefins but the products are the spiroketals **4** (Table 2, entries 8, 9). The reaction with **1h** was further investigated and the results are collected in Table 3. With these substrates the following features are observed: (i) α,α′-diaddition products are selectively obtained without traces of α,α-diaddition products; (ii) two diastereoisomers (**4a** and **a′**) are preferentially observed, even if traces of other isomers were

**Table 1** Oxidation of cyclohexanone (**1a**) by FEP in the presence of styrene (**2a**)[a]

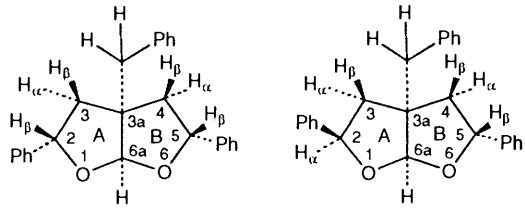
| Entry | [**2a**]/mol dm$^{-3}$ | [FEP]/mol dm$^{-3}$ | Additive (mol dm$^{-3}$) | $T$/°C | **3** (Yield %) | **3a**/**3a**′ |
|---|---|---|---|---|---|---|
| 1 | 0.12 | 0.4 | — | 20 | 48 | 0.71 |
| 2 | 0.2 | 0.4 | — | 20 | 41 | 0.73 |
| 3 | 0.3 | 0.4 | — | 20 | 67 | 0.77 |
| 4 | 0.4 | 0.4 | — | 20 | 77 | 0.80 |
| 5 | 0.4 | 0.4 | — | 3 | 45 | 0.79 |
| 6 | 0.4 | 0.4 | — | 56 | 91 | 0.68 |
| 7 | 0.1 | 0.2 | — | 20 | 80 | 0.69 |
| 8 | 0.4 | 0.2 | — | 20 | 95 | 0.83 |
| 9 | 0.4 | 0.2 | $H_2O$ (1.8)[b] | 20 | 68 | 0.61 |
| 10 | 0.4 | 0.2 | Py (0.4)[c] | 20 | 63 | 0.72 |
| 11 | 0.12 | 0.2 | Bipy (0.2)[c] | 20 | 100 | 0.61 |
| 12 | 0.3 | 0.4 | Bipy (0.4)[c] | 20 | 81[d] | 0.62 |
| 13 | 0.2 | 0.4 | $Ac_2O$ (3.2)[e] | 20 | — | — |

[a] MeCN, [**1a**] = 0.1 mol dm$^{-3}$, 1.5 h. [b] Reaction time 3 h. [c] Reaction time 4 h. [d] Traces of hemiketal **7a** were detected by GC. [e] Added at 0 °C to a solution of FEP in acetonitrile.

**Table 2** Reaction conditions and product distribution in the oxidation of ketones **1** by FEP in the presence of styrene[a]

| Entry | **1** | **2** | [FEP]/[**1**] | $T$ °C | Product (Yield %) 3[b] | **4**[c] |
|---|---|---|---|---|---|---|
| 1 | **1a** | **2a** | 4 | 20 | 55(1.3) | — |
| 2 | **1b** | **2a** | 4 | 20 | 51(1.2) | — |
| 3 | **1c** | **2a** | 4 | 20 | 51(0.7) | — |
| 4 | **1d** | **2a** | 0.33 | 20 | 96(1.2) | — |
| 5 | **1e** | **2a** | 2 | 20 | 80(1.1) | — |
| 6 | **1f** | **2a** | 4 | 50 | 63(1.2) | — |
| 7 | **1g** | **2a** | 4 | 20 | 33(0.9) | — |
| 8 | **1a** | **2b** | 4 | 20 | 38(1.1) | — |
| 9 | **1h** | **2a** | 4 | 20 | — | 35(1.4[d] |
| 10 | **1i** | **2a** | 0.33 | 20 | — | 68(1.3) |

[a] MeCN, [**1**] = 0.06 mol dm$^{-3}$. [b] Ratio **3**:**3**′. [c] Ratio **4**:**4**′. [d] Side products (8%) were the hemiketals **6** (isomer ratio 1.8:1).




**3f** **3f′**

**Fig. 1**

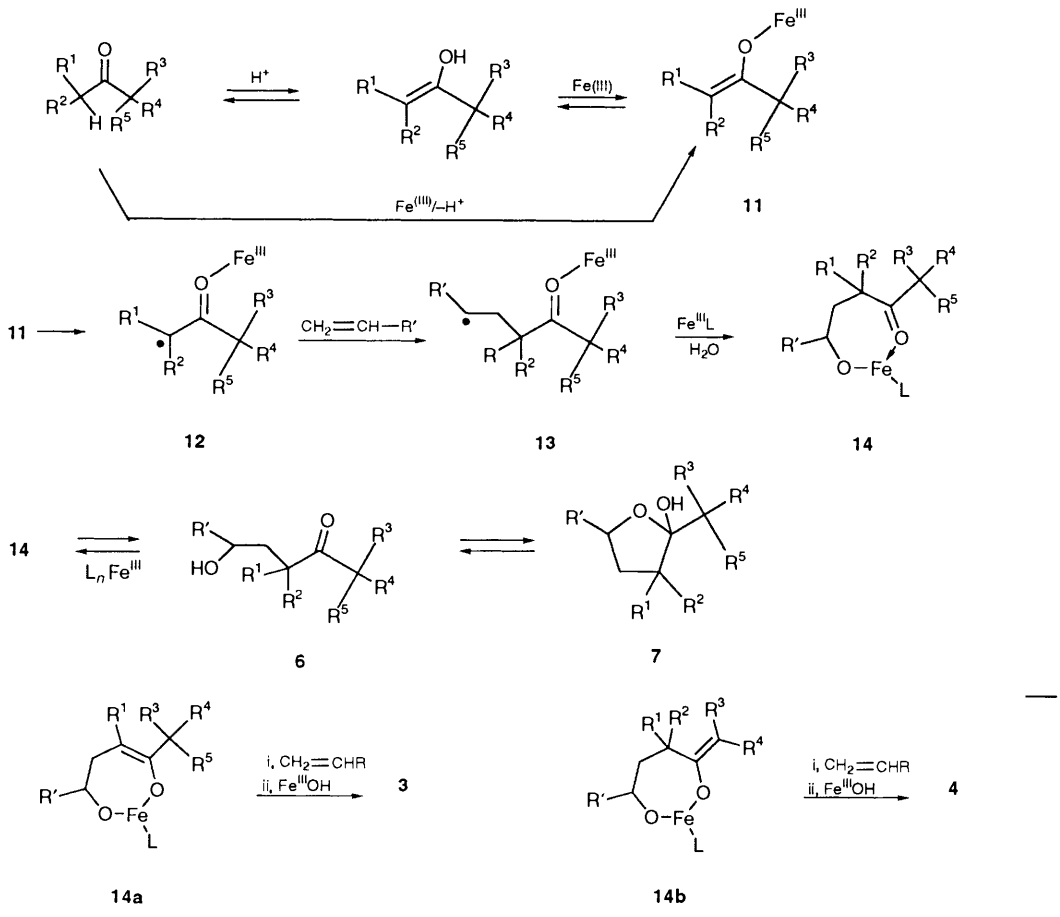
detected by GLC-MS; (iii) the presence of basic additives slows the reaction and significantly affects the isomer distribution of **4**; and (iv) δ-hydroxyketone hemiketal isomers **7b** and **b**′ are formed in the presence of excess water.

In order to assess the importance of δ-hydroxyketones **6** or hemiketals **7** as intermediates of these oxidations, the two diastereoisomers **6a** and **b** (in equilibrium with the cyclic hemiketals **7a** and **b** in several solvents) were synthesized. Compounds **6a** and **b** were synthesized *via* condensation between the lithium salt of cyclohexanone dimethylhydrazone and styrene oxide in dry THF at 0 °C; the diastereoisomers were isolated by flash chromatography on $SiO_2$ eluting with hexane–AcOEt (8:2) and identified by $^1$H NMR, MS and IR spectroscopy. The reported syntheses of **6**[8] were found irreproducible. Ketoolefin **8** was synthesized by dehydration of **6**. Full experimental details will be reported elsewhere. Compounds **6a**, **b**, either separately or as a mixture, were submitted to oxidation by FEP under standard conditions (MeCN, 20 °C, [**6**] = [**1a**] =0.5; [FEP] = 0.1 mol dm$^{-3}$) in the presence of styrene. The same mixture of compounds **3a** and **a**′ was obtained in high yield and the reaction time was lower than with substrates cyclohexanone and 2-methylcyclohexanone, respectively (15 min *vs.* 1.5 h). It was also verified that the

**Table 3** Oxidation of 2-methylcyclohexanone (**1h**) by FEP in the presence of styrene (**2a**) and some additives[a]

| Entry | [**2a**]/mol dm$^{-3}$ | [FEP]/mol dm$^{-3}$ | Additive (mol dm$^{-3}$) | Products (Yield %) **4** | **6** | $R$(**4**)[b] | **6a**/**6a**′ |
|---|---|---|---|---|---|---|---|
| 1 | 0.11 | 0.2 | — | 36 | 2 | 40:10:8:42 | 0.52 |
| 2 | 0.4 | 0.2 | — | 64 | — | 46:10:8:36 | — |
| 3 | 0.3 | 0.4 | — | 48 | 2 | 48:11:9:34 | 0.55 |
| 4 | 0.4 | 0.4 | — | 62 | — | 46:14:7:33 | — |
| 5 | 0.4 | 0.2 | $H_2O$ (1.8) | 11 | 65 | 32:03:4:61 | 2.9 |
| 6 | 1.1 | 0.2 | Py (0.2) | 41 | 4 | 35:10:7:48 | 1.0 |
| 7 | 0.4 | 0.2 | EtOH (1.8) | 12 | 17 | 32:06:4:58 | 1.12 |
| 8 | 0.3 | 0.4 | Bipy (0.4) | 47 | — | 38:14:5:43 | — |

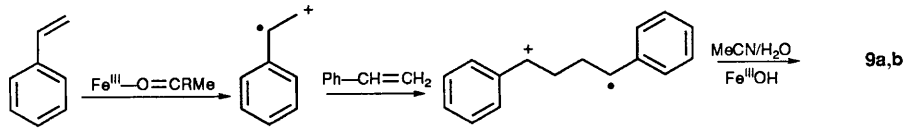
[a] MeCN, 20 °C, [**1h**] = 0.1 mol dm$^{-3}$. [b] Isomer distribution (%) by GLC.



alternative intermediate 2-styrylcyclohexanone (**8**) under similar conditions was oxidized in 3 h to **3a** and **a'** in moderate yield.

## Discussion

The results of this work indicate that the reactivity sequence CH > $CH_2$ > $CH_3$ is valid in the oxidative α-deprotonation of carbonyl compounds by iron(III) perchlorate in acetonitrile. Tertiary C–H bonds are in fact selectively oxidized in the presence of secondary ones (*i.e.* in substrates **1h**, **i**, **7a**, **b**) and secondary C–H bonds are selectively oxidized in the presence of primary ones (*i.e.* in substrates **1e** and **f**), whereas methyl ketones are so unreactive that the olefin is preferentially oxidized. This high selectivity is surprising taking into consideration the frequently observed competition between differently substituted α-carbon atoms in the oxidation of carbonyl compounds by metal oxidants. In particular, a prominent preference for the less substituted carbon atom was observed with $Mn^{III}$ [9] and $Pb^{IV}$ [10] acetates, whereas oxidations by CAN occur at the more substituted carbon atom.[11] As suggested in Scheme 3, the selectivity observed with iron(III) can be the result of a combination of two effects: (i) enolization of the carbonyl compound induced by the metal ion or protic acid; and (ii) a highly efficient trapping of the intermediate α-carbonylalkyl radical by the olefin,[4] which prevents any intermolecular hydrogen abstraction by the same radical. A similar high selectivity was previously observed in the $FeCl_3$ catalyzed oxidation of cycloalkanones to ω-oxoesters by molecular oxygen,[12] but in this system it was hard to differentiate between the contribution of the autoxidation and the metal oxidation. In the present system, the selectivity observed can be attributed exclusively to the metal, and, in analogy to known acid catalyzed halogenations, which generally involve the more substituted positions,[13] a Lewis or proton acid catalyzed enolization of the carbonyl compound is probably involved in the rate determining step. We suggest the iron(III) enolate **11** as the more reasonable intermediate in the formation of α-carbonylalkyl radicals. Our preference for an inner-sphere through the iron complexes intermediates **11** and **14** over an outer-sphere oxidation mechanism is supported by the following two facts: (i) bidentate γ-hydroxycarbonyl intermediates **6** (which are in equilibrium with the corresponding hemiketals **7**) are oxidized considerably faster than would be anticipated from the secondary to tertiary α-C–H reactivity difference of simple ketones, so α,α-disubstituted derivatives **3** are also obtained at high concentation of the monodentate carbonyl compound or in the presence of bases, *i.e.* water in excess or 2,2'-bipyridine (Table 1), whereas in the oxidation of 2-methylcyclohexanone (Table 3), the products of monoaddition to styrene (**6** and/or **7**) arising from the oxidation of a tertiary hydrogen, compete with products of diaddition (**4**) arising from the oxidation of a secondary hydrogen; and (ii) the strongly electron-rich styrene is not oxidized by FEP in the presence of secondary and tertiary carbonyl compounds despite the fact that the ionization and redox potential of this olefin is lower than that of di- or tri-substituted enols; however, styrene is oxidized to dimeric and telomeric products in the presence, but not in the absence, of methyl ketones, probably through an electron-transfer mechanism. Therefore, coordination of carbonyl compounds to iron(III) salts in acetonitrile is important even in cases where they are not oxidized. Iron(III) enolates can be formed by metal coordination to the carbonyl substrate followed by base induced deprotonation of the carbonyl complex, or from a proton/iron(III) exchange with the enol. The keto–enol equilibration is certainly a fast process in the strongly




**Scheme 4**

acidic medium which develops as a consequence of the oxidation and of the presence of the weakly nucleophilic anion $ClO_4^-$. The effect of basic additives (*i.e.* water in excess, pyridine or bipyridine) is also in accord with this interpretation. Their coordination to the metal induces a decrease of the overall oxidation rate of the carbonyl compounds,[2] but does not change the reaction pattern. Acetic anhydride, on the contrary, by eliminating any water ligated to the metal ion, makes the iron(III) a more efficient oxidant,[2] so that the carbonyl compound is oxidized to the corresponding acetoxy derivative and styrene is oxidatively telomerized, and neither compound **3** or **4** is obtained.

Electron-transfer from the bound ligand to the metal or bond homolysis of the enolate complex **11** represent alternative extreme routes to the α-carbonylalkyl radicals, which can exist in equilibrium with the metal complexed (**12**) and free form. Addition to the unsaturated substrate to give **13** or oxidation by the metal are alternative pathways for these paramagnetic species. The first process prevails in the presence of conjugated olefins owing to the electrophilic behaviour of α-carbonylalkyl radicals in their addition to unsaturated substrates, despite the remarkable oxidizing ability of Fe(III) salts toward carbon-centred radicals.[2] The relative rate constants for the addition of α-carbonylalkyl radicals of ketones to olefins are unknown, but they are expected to be very close to those reported for malonyl radicals[4] and *tert*-butoxycarbonylmethyl radicals,[13] for which styrene was 80 and 50 times more reactive than oct-1-ene, respectively. Oxidation of the radical adduct **13** by $Fe^{III}$ prevents polymerization of the olefin and affords, *via* an electron- or ligand-transfer mechanism, the hydroxy derivative **6** which is in equilibrium with the hemiketal **7**, or, after deprotonation, with the iron(III) complex **14**. The presence of hydrogens in the alpha position to the carbonyl group controls the fate of these intermediates. When $R^1$, $R^2$ and $R^3$ are hydrogens, compound **14a** is selectively oxidized to the endocyclic α-carbonylalkyl radical, whereas when $R^1$, $R^2$ and $R^5$ are hydrogens, the intermediate **14b** is oxidized to corresponding exocyclic radical. These radicals are trapped by the conjugated olefin to give the radical adducts, which are finally oxidized by FEP to the cyclic derivative **3** and **4**, respectively.

The stereochemical preference observed in compounds **3** (and the nearly constant value of the ratio **3a**/**3a′** observed in reactions with different additives), and in oxidations of diastereoisomers **7a** and **a′** in the presence of styrene, along with the isomer distribution in **4**, suggest an acid induced thermodynamic equilibration between isomers. Benzylic carbocations are in fact expected to be easily formed in such a strongly acidic medium, leading to epimerization at these centres, and steric hindrance between the phenyl (or vinyl) groups in compounds **3** differs remarkably between the isomers owing to the preferential *cis* stereochemistry and conformation of the hexahydrofuro[2,3-*b*]furan ring system. In any case, no evidence for the previously reported[14] preferential regioselectivity in the oxidations of carbon centred free-radicals by iron(III) salts through interaction with alcoholic groups can be deduced from this study.

The oxidation of 20 °C of styrene to **9** and **10** in the presence of methyl ketones deserves some additional comments, because these compounds cannot be formed in the absence of the carbonyl substrates. This suggests that $Fe^{III}$–carbonyl complexes or $Fe^{III}$–enolate complexes are in any case formed by coordination of the metal to the carbonyl derivative, but that they do not evolve at low temperature to α-carbonylalkyl radicals. However, they are substantially strong oxidants to attack the conjugated olefin. An electron-transfer mechanism with formation of conjugated radical cations can be suggested to explain the product distribution observed (Scheme 4). The different fate of the cationic and radical centre in the radical cation dimer, formed by addition of monomer radical cation to the neutral olefin, can explain the exclusive formation of hydroxyamide derivatives **9a** and **b**. The former adds to the solvent in a Ritter reaction to produce the acetamide moiety, whereas the latter can be oxidized by a $Fe^{III}OH$ complex to the corresponding benzyl alcohol.

In conclusion, the results from this and other laboratories demonstrate the successful exploitation of different metals salts to selectively oxidize carbonyl compounds and elucidate polar effects that influence the rate of addition of carbon-centred radicals to unsaturated olefins which ultimately could lead to the development of useful procedures for the formation of new C–C bonds and heterocyclic ring systems. The wide range of ligands and solvents compatible with monoelectronic metal salts open the possibility to control the chemo-, diastereo-, and enantio-selectivity of metal induced radical reactions. In this context, iron(III) salts deserve particular attention as valuable candidates for model studies owing to the low cost, the low pollution problems, and their redox and ligand versatility.

## Experimental

M.p.s were measured with a Büchi capillary melting point apparatus and are uncorrected. $^1H$ and $^{13}C$ NMR spectra were obtained in $CDCl_3$ with a Bruker AC 250 or 300 spectrometer and chemical shift data are reported (ppm) downfield from $Me_4Si$, internal standard (*J*-values in Hz). NOE experiments were carried out on Bruker 300 and 500 MHz instruments. Mass spectra were obtained on a GLC-MS Finnigan TSQ 70 instrument, using a Varian 3700 gas chromatograph, equipped with a SBP-1 fused silica column (30 m × 0.2 mm i.d., 0.2 μm film thickness) and helium as carrier gas. GLC analyses were performed on a DANI 6500 capillary gas chromatograph, equipped with a 25 m × 0.25 mm i.d. SBP-5 fused silica column (1 μm film thickness) at a hydrogen flow rate of 8 $cm^3$ $min^{-1}$, PTV injector, flame ionization detector, and a temperature program from 50 to 220 °C at 15 ° $min^{-1}$, 5 min at 220 °C and from 220 to 270 °C at 10 °C $min^{-1}$. HPLC analyses were performed on a Bruker LC 2151 liquid chromatograph with UV detection at 254 nm. Both instruments use Bruker software (Chromstar) for quantitative determinations. Elemental analyses were performed by Redox laboratory (Milano, I).

Acetonitrile, all carbonyl compounds, styrene and 2,3-dimethylbutadiene were distilled before use or stored over molecular sieves. Butadiene was purified by using columns of $CaSO_4$ and $MnO_2$ on vermiculite, condensation at −70 °C and distillation directly into the reaction flask. $Fe(ClO_4)_3 \cdot 9H_2O$ (FEP) was purchased from Carlo Erba or Aldrich and stored under $P_2O_5$ for 12 h before use. Silica gel (0.020–0.032 mm, Merck) was used for flash chromatographic separations. The water added in some experiments was doubly distilled. All reactions were carried out under a positive pressure of nitrogen with magnetic stirring.

*FEP Oxidation of Cyclohexanone in the Presence of Styrene.—General procedure.* FEP (21.4 g, 40.8 mmol) was weighed as rapidly as possible in a flask containing a magnetic stirring bar, and acetonitrile (85 $cm^3$) was added at 0–5 °C. The refrigerating bath was removed and a solution of cyclohexanone (1 g, 10.2 mmol) and styrene (3.18 g, 30.6 mmol) in acetonitrile (15 $cm^3$) added. After stirring for 1.5–4 h at 20 °C, the solution was evaporated under reduced pressure without heating to about one third of its volume, diluted with water (50 $cm^3$) and extracted with diethyl ether (3 × 30 $cm^3$). The combined extracts were washed with NaCl saturated solution, dried ($Na_2SO_4$), evaporated and flash chromatographed on $SiO_2$ with hexane–diethyl ether (9:1) as eluent to give 2.13 g (65% yield) of isomeric ketals **3a** and **a'** in 1:1.3 ratio.[6] The two isomers were separated by further chromatography on $SiO_2$ with cyclohexane as eluent. No monoaddition or polyaddition product was isolated by using cyclohexanone in excess or by addition of water (18 mol) or pyridine, as reported in Table 1. The reaction times reported in Table 1 were determined at 90% conversion of FEP by titration of $Fe^{III}$ in the reaction mixture with standardized $TiCl_3$ 0.1 mol $dm^{-3}$.

(2α,3aα,5α,6aα)-2,5-*Diphenyl*-2,3,3a,4,5,6a-*hexahydro*-(3a,6a)-*butanofuro*[2,3-b]*furan* (**3a**).—M.p. 95–6 °C (cyclohexane); GLC $t_r$ = 23.6 min; $\nu_{max}/cm^{-1}$ 1690m, 1465s, 1450s, 1384m, 990m, 756m and 700m; *m/z* 320 ($M^+$, 2%), 319 (5, 242 (25), 216 (96), 129 (35), 122 (35), 111 (40), 104 (100), 91 (50) and 77 (30); $\delta_H$ 7.2–7.5 (10 H, m), 5.35 (2 H, dd, $H_{2\beta}$, $J_{2\beta-3\beta}$ 7.0, $J_{2\beta-3\alpha}$ 9.5), 2.47 (2 H, dd, $H_{3\beta}$, $J_{2\beta-3\beta}$ 7.0, $J_{3\alpha-3\beta}$ 12.6), 2.01 (2 H, dd, $H_{3\alpha}$, $J_{2\beta-3\alpha}$ 9.5, $J_{3\alpha-3\beta}$ 12.6) and 1.3–1.9 (8 H, m); NOE, irradiation at δ 5.35 did not increase $CH_2$s of cyclohexane, whereas irradiation of aromatic protons increased (1.5%) the multiplet ($CH_2$s of cyclohexane) centred at δ 1.6 (Found: C, 82.6; H, 7.7. $C_{22}H_{24}O_2$ requires: C, 82.46; H 7.55%).

(2β,3aα,5α,6aα)-*Stereoisomer* (**3a'**).—Oil; GLC $t_r$ = 24.9 min; $\nu_{max}/cm^{-1}$ 1690m, 1465s, 1450s, 1374m, 1035, 1015m, 755s, 702m and 695s; *m/z* 320 ($M^+$, 25%), 242 (14), 216 (30), 214 (45), 200 (15), 129 (20), 104 (100), 91 (45) and 77 (25); $\delta_H$ 7.2–7.5 (10 H, m), 5.38 (1 H, dd, $H_{5\beta}$, $J_{5\beta-4\beta}$ 6.0, $J_{5\beta-4\alpha}$ 10.2), 5.20 (1 H, dd, $H_{2\alpha}$, $J_{2\alpha-3\alpha}$ 7.1, $J_{2\alpha-3\beta}$ 9.1), 2.28 (1 H, dd, $H_{3\alpha}$, $J_{2\alpha-3\alpha}$ 7.1, $J_{3\alpha-3\beta}$ 12.6), 2.21 (1 H, dd, $H_{3\beta}$, $J_{2\alpha-3\alpha}$ 9.1, $J_{3\alpha-3\beta}$ 12.6), 2.18 (1 H, dd, $H_{4\beta}$, $J_{5\beta-4\beta}$ 6.0, $J_{4\alpha-\beta}$ 12.6), 1.99 (1 H, dd, $H_{4\alpha}$, $J_{5\beta-4\alpha}$ 9.6, $J_{4\alpha-4\beta}$ 12.4) and 1.3–1.9 (8 H, m); NOE, irradiation at δ 5.38 ($H_{5\beta}$) does not increase the $CH_2$s of cyclohexane, whereas irradiation at δ 5.20 ($H_{2\alpha}$) increases (1.2%) the multiplet centred at δ 1.65 (Found: C, 82.7; H, 7.5%).

The α,α-disubstitution of both isomers was further confirmed by hydrogenation (8 bar $H_2$, 5% Pt/C, AcOH, 8 h, 60 °C, 85%) of samples of **3a** and **a'**. The same compound (**5**) was obtained in both cases.

2,2-*Bis*(2-*phenylethyl*)*cyclohexanone* (**5**).—Oil; $\nu_{max}/cm^{-1}$ 1710s; *m/z* 306 ($M^+$, 0.2%), 202 (36), 111 (100), 105 (5), 91 (36) and 77 (6); $\delta_H$ 7.2–7.4 (10 H, m), 2.6 (2 H, m), 2.4 (2 H, m), 1.99 (4 H, m) and 1.3–2.0 (6 H, m); $\delta_C$ 221.8 (s), 143.1 (s), 129.1 (d), 128.9 (d), 126.5 (d), 52.37 (s), 39.8 (d), 37.6 (d), 37.1 (d), 30.7 (d), 27.7 (d) and 21.4 (d).

*Compounds* **3b–h**.—By using the general procedure described for cyclohexanone with the amounts of reagents, additives and conditions reported in Table 2, the following compounds were isolated by column chromatography from the reaction mixture after workup.

(2β,3aα,5a,6aα)-6a-*Ethyl*-3a-*methyl*-2,5-*diphenyl*-2,3,3a,4,5,-6a-*hexahydrofuro*[2,3-b]*furan* (**3b**). M.p. 123–124 °C; GLC $t_r$ = 20.7 min; *m/z* 308 ($M^+$, 2%), 234 (40), 219 (25), 204 (100), 187 (22), 173 (57), 145 (56), 143 (52), 131 (25), 105 (30), 91 (38) and 77 (18); $\delta_H$ 7.2–7.5 (10 H, m), 5.28 (1 H, dd, $H_{2\beta}$, $J_{2\beta-3\beta(\alpha)}$ 6.6, $J_{2\beta-3\alpha(\beta)}$ 10.3), 2.50 (1 H, dd, $H_{3\beta(\alpha)}$, $J_{2\beta-3\beta(\alpha)}$ 6.6, $J_{3\alpha-3\beta}$ 12.3), 1.86 (1 H, dd, $H_{3\alpha(\beta)}$, $J_{2\beta-3\alpha(\beta)}$ 10.3, $J_{3\alpha-3\beta}$ 12.3), 1.81 (2 H, q, *J* 7), 1.31 (3 H, s) and 1.21 (3 H, t); $\delta_C$ 143.2 (s), 129.08 (d), 129.02 (d), 126.35 (d), 116.76 (s), 79.72 (d), 52.61 (s), 50.79 (d), 29.68 (t), 25.01 (q) and 9.00 (q) (Found: C, 82.6; H, 7.7. $C_{21}H_{24}O_2$ requires: C, 81.78; H 7.84%).

(2α,3aα,5α,6aα)-*Stereoisomer* (**3b'**). M.p. 75–76 °C; GLC $t_r$ = 19.7 min; *m/z* 308 ($M^+$, 0.7%), 204 (100), 173 (12), 143 (16), 105 (13), 100 (13), 91 (10), 77 (10) and 57 (15); $\delta_H$ 7.2–7.5 (10 H, m), 5.23 (1 H, dd, $H_{2\alpha}$, $J_{2\alpha-3\alpha(\beta)}$ 4.8, $J_{2\alpha-3\beta(\alpha)}$ 10.9), 4.96 (1 H, dd, $H_{5\beta}$, $J_{5\beta-4\alpha(\beta)}$ 9.9, $J_{5\beta-4\beta(\alpha)}$ 6.3), 2.25 (1 H, dd, $H_{3\alpha(\beta)}$, $J_{2\alpha-3\alpha(\beta)}$ 4.8, $J_{3\alpha-3\beta}$ 12.3), 2.24 (1 H, dd, $H_{4\beta(\alpha)}$, $J_{5\beta-4\beta(\alpha)}$ 6.3, $J_{4\alpha-4\beta}$ 12.3), 2.16 (1 H, dd, $H_{4\alpha(\beta)}$, $J_{5\beta-4\alpha(\beta)}$ 9.9, $J_{4\alpha-4\beta}$ 12.3), 1.67 (1 H, dd, $H_{3\beta(\alpha)}$, $J_{2\alpha-3\beta(\alpha)}$ 10.9, $J_{3\alpha-3\beta}$ 12.3), 1.67 (2 H, q, *J* 7.4), 1.26 (3 H, s) and 1.21 (3 H, t); $\delta_C$ 143.21 (s), 142.60 (s), 129.03 (d), 129.93 (d), 129.02 (d), 126.39 (d), 116.73 (s), 78.93 (t), 53.02 (s), 50.01 (dd), 49.38 (dd), 29.45 (t), 22.57 (q) and 8.90 (q) (Found: 82.9; H, 8.0%).

(2α,3aα,5α,6aα)-3α-*Methyl*-2,5,6a-*triphenyl*-2,3,3a,4,5,6a-*hexahydrofuro*[2,3-b]*furan* (**3c**). M.p. 140 °C; GLC $t_r$ = 27.68 min; *m/z* 356 ($M^+$, 2.7%), 234 (43), 219 (15), 156 (17.5), 143 (33.8), 105 (100), 91 (14.8) and 71 (31.8); $\delta_H$ 7.3–7.7 (15 H, m), 5.57 (1 H, dd, $H_{2\beta}$, $J_{2\beta-3\beta}$ 5.7, $J_{2\beta-3\alpha}$ 11), 2.65 (1 H, dd, $H_{3\beta}$, $J_{2\beta-3\beta}$ 5.7, $J_{3\alpha-3\beta}$ 12.5), 2.07 (1 H, dd, $H_{3\alpha}$, $J_{2\beta-3\alpha}$ 11, $J_{3\alpha-3\beta}$ 12.5) and 0.86 (3 H, s) (Found: C, 84.1; H 7.0. $C_{25}H_{24}O_2$ requires: C 84.24; H, 6.79%).

(2β,3aα,5α,6aα)-*Stereoisomer* (**3c'**). Oil: GLC $t_r$ = 27.06 min; *m/z* 356 ($M^+$, 1%), 338 (2), 252 (19), 234 (26), 219 (12), 194 (10), 158 (10), 156 (12), 143 (22), 105 (100), 91 (17) and 77 (41); $\delta_H$ 7.2–7.6 (15 H, m), 5.44 (1 H, dd, $H_{2\alpha}$, $J_{2\alpha-3\beta(\alpha)}$ 4, $J_{2\alpha-3\alpha(\beta)}$ 10.2), 5.20 (1 H, dd, $H_{5\beta}$, $J_{5\beta-4\beta(\alpha)}$ 6.5, $J_{5\beta-4\alpha(\beta)}$ 10), 2.41 (1 H, dd, $H_{4\beta}$, $J_{5\beta-4\beta}$ 6.5, $J_{4\alpha-4\beta}$ 12.5), 2.34 (1 H, dd, $H_{3\beta(\alpha)}$, $J_{2\alpha-3\beta(\alpha)}$ 4, $J_{3\alpha-3\beta}$ 11.0), 2.33 (1 H, dd, $H_{4\alpha}$, $J_{5\beta-4\alpha(\beta)}$ 10, $J_{4\alpha-4\beta}$ 12.5), 1.90 (1 H, dd, $H_{3\alpha(\beta)}$, $J_{2\alpha-3\alpha(\beta)}$ 10.2, $J_{3\alpha-3\beta}$ 11.0) and 0.88 (3 H, s) (Found: C, 84.2; H, 6.9%).

(2α,3aα,5α,6aα)-3a-*Ethyl*-6a-*methyl*-2,5-*diphenyl*-2,3,3a,4,5,-6a-*furo*[2,3-b]*furan* (**3d**). M.p. 126–127 °C; GLC $t_r$ = 20.9 min.; *m/z* 308 ($M^+$, 2%), 219 (26), 205 (16), 204 (100), 173 (10), 145 (14), 129 (12), 117 (11), 111 (13), 110 (27), 107 (13), 105 (32), 104 (21), 99 (30), 91 (32) and 77 (16); $\delta_H$ 7.2–7.5 (10 H, m, Ar), 5.28 (2 H, dd, $H_{2\beta}$, $J_{2\beta-3\beta}$ 6.1, $J_{2\beta-3\alpha}$ 10.5), 2.50 (2 H, dd, $H_{3\beta}$, $J_{2\beta-3\beta}$ 6.1, $J_{3\alpha-3\beta}$ 12.5), 1.85 (2 H, dd, $H_{3\alpha}$, $J_{2\beta-3\alpha}$ 10.5, $J_{3\alpha-3\beta}$ 12.5), 1.61 (2 H, m, $CH_2Me$), 1.60 (3 H, s) and 0.95 (3 H, t) (Found: C, 81.6; H, 7.9. $C_{21}H_{24}O_2$ requires: C, 81.78; H, 7.84%).

(2β,3aα,5α,6aα)-*Stereoisomer* (**3d'**). M.p. 72 °C; GLC $t_r$ = 21.6 min; *m/z* 308 ($M^+$, 5%), 219 (12), 205 (32), 204 (100), 145 (19), 129 (14), 110 (34), 107 (19), 105 (24), 104 (17), 99 (19), 91 (43) and 77 (20); $\delta_H$ 7.2–7.6 (10 H, m), 5.22 (1 H, dd, $H_{2\alpha}$, $J_{2\alpha-3\alpha(\beta)}$ 4.6, $J_{2\alpha-3\beta(\alpha)}$ 11.0), 4.95 (1 H, dd, $H_{5\beta}$, $J_{5\beta-4\alpha(\beta)}$ 6.5, $J_{5\beta-4\beta(\alpha)}$ 10.0), 2.25 (1 H, dd, $H_{3\alpha(\beta)}$, $J_{2\alpha-3\alpha(\beta)}$ 4.6, $J_{3\alpha-3\beta}$ 12.5), 2.24 (1 H, dd, $H_{4\beta(\alpha)}$, $J_{5\beta-4\beta(\alpha)}$ 10.0, $J_{4\alpha-4\beta}$ 12.2), 2.16 (1 H, dd, $H_{4\alpha(\beta)}$, $J_{5\beta-4\alpha(\beta)}$ 6.5, $J_{4\alpha-4\beta}$ 12.2), 1.67 (1 H, ddd, $H_{3\beta(\alpha)}$, $J_{2\alpha-3\beta(\alpha)}$ 11.0, $J_{3\alpha-3\beta}$ 12.5, *J* 1.3), 1.61 (2 H, m), 1.58 (3 H, s) and 1.07 (3 H, t) (Found: C, 81.9, H, 7.6%).

(2α,3aα,5α,6aα)-3a-*Ethyl*-2,5-*diphenyl*-2,3,3a,4,5,6a-*hexahydrofuro*[2,3-b]*furan* (**3e**). Oil; GLC $t_r$ = 14.69 min; *m/z* 294 ($M^+$, 1%), 219 (7), 190 (65), 145 (12), 129 (21), 105 (76), 91 (38), 80 (50), 79 (55) and 77 (100); $\delta_H$ 7.27–7.38 (10 H, m, Ar), 5.70 (1 H, s), 5.39 (2 H, dd, $H_{2\beta-3\beta}$ 6.0, $J_{2\beta-3\alpha}$ 10), 2.42 (2 H, dd, $H_{3\beta}$, $J_{2\beta-3\beta}$ 6.0, $J_{3\alpha-3\beta}$ 13), 1.91 (2 H, dd, $H_{3\alpha}$, $J_{2\beta-3\alpha}$ 10.0, $J_{3\alpha-3\beta}$ 13), 1.73 (2 H, q, *J* 7) and 0.97 (3 H, t, *J* 7) (Found: C, 81.5; H, 7.4. $C_{20}H_{22}O_2$ requires: C, 81.60; H, 7.53%).

(2β,3aα,5α,6aα)-*Stereoisomer* (**3e'**). Oil; GLC $t_r$ = 14.99 min; *m/z* 294 ($M^+$, 0.8%), 265 (1), 219 (24), 190 (21), 159 (17), 145 (12), 128 (19), 115 (21), 105 (63), 91 (45), 80 (60), 78 (32) and 77 (100); $\delta_H$ 7.2–7.5 (10 H, m), 5.58 (1 H, s), 5.23 (1 H, dd, $H_{2\alpha}$, $J_{2\alpha-3\alpha(\beta)}$ 4.9, $J_{2\alpha-3\beta(\alpha)}$ 11.5), 4.96 (1 H, dd, $H_{5\beta}$, $J_{5\beta-4\alpha(\beta)}$ 5.8, $J_{5\beta-4\beta(\alpha)}$

10), 2.43 (1 H, dd, $H_{3\alpha(\beta)}$, $J_{2\alpha-3\alpha(\beta)}$ 5.8, $J_{3\alpha-3\beta}$ 12.5), 2.40 (1 H, dd, $H_{4\beta(\alpha)}$, $J_{5\beta-4\beta(\alpha)}$ 6.0, $J_{4\alpha-4\beta}$ 12.8), 2.14 (1 H, dd, $H_{4\alpha(\beta)}$, $J_{5\beta-4\alpha(\beta)}$ 5.0, $J_{4\alpha-4\beta}$ 12.5), 1.91 (1 H, dd, $H_{3\beta(\alpha)}$, $J_{2\alpha-3\beta(\alpha)}$ 11.5, $J_{3\alpha-3\beta}$ 12.5) and 1.04 (3 H, t, $J$ 7.5) (Found: C, 81.7; H, 7.4%).

(2α,3aα,5α,6aα)-*3a-Benzyl-2,5-diphenyl-2,3,3a,4,5,6a-hexahydrofuro*[2,3-b]*furan* (**3f**). M.p. 122–123 °C; GLC $t_r$ = 29.9 min; *m/z* 356 ($M^+$, 1%), 265 (95), 252 (42), 236 (21), 219 (22), 187 (17), 159 (18), 145 (16), 131 (23), 117 (28), 115 (32), 105 (100), 91 (90) and 77 (26); $\delta_H$ 7.0–7.5 (15 H, m, Ar), 5.17 (1 H, dd, $H_{2\beta}$, $J_{2\beta-3\beta}$ 5.5, $J_{2\beta-3\alpha}$ 10.0), 4.79 (1 H, s, O–CH–O, $H_{6a}$), 4.11 (1 H, t, $H_{5\beta}$, $J_{5\beta-4\beta} = J_{5\beta-4\alpha}$ 3.0), 3.21 (1 H, d, $PhCH_2$, $J_{gem}$ 17.5), 2.90 (1 H, dd, $PhCH_2$, $J_{gem}$ 17.2 $^4J$ 2.5), 2.40 (1 H, dd, $H_{3\beta}$, $J_{2\beta-3\beta}$ 5.5, $J_{3\alpha-3\beta}$ 12.5), 2.31 (1 H, ddd, $H_{4\beta}$, $J_{4\alpha-4\beta}$ 12.5, $^4J$ 2.5, $J_{5\beta-4\beta}$ 3.0), 2.24 (1 H, dd, $H_{3\alpha}$, $J_{2\beta-3\alpha}$ 10.0, $J_{3\alpha-3\beta}$ 12.5) and 2.10 (1 H, dd, $H_{4\alpha}$, $J_{4\alpha-4\beta}$ 12.5, $J_{5\beta-4\alpha}$ 3.0).

DNOE irradiation at 4.79 ppm (acetalic $H_{6a}$) produced a 1.4% and 5.5% enhancement for the signal at 2.24 ppm ($H_{3\alpha}$) and 2.40 ppm ($H_{3\beta}$), respectively, as a consequence of saturation of the signal at 5.17 ppm ($H_{2\beta}$). Phenyl at C-2 exhibits therefore a *cis* relationship to the benzyl group. The *cis* stereochemistry of furo-furan ring fusion was assigned based on NOE experiments: irradiation at 2.90 ppm (benzylic hydrogen) produced a 7% enhancement for the signal at 4.79 ($H_{6a}$). Interestingly, the same benzylic hydrogen exhibits $^4J$ 2.5 with $H_{4\beta}$ (2.31 ppm), suggesting a W relationship; moreover $H_{4\beta}$ shows a cross peak with $H_{2\beta}$ (5.17 ppm) in 2D-NOESY spectrum. These data unambiguously assign hydrogens $H_4$. Both $H_{4\beta}$ and $H_{4\alpha}$ show a 3.7% NOE due to a saturation of $H_5$ (4.10 ppm). The combined use of these data and those of the vicinal coupling constants ($J_{4\alpha-5\beta} = J_{4\beta-5\alpha}$ 3.0) indicate that both the dihedral angles $H_{4\alpha}$–$C_4$–$C_5$–$H_5$ and $H_{4\beta}$–$C_4$–$C_5$–$H_5$ must be less than 90°, indicating a *cis* relationship between $H_5$ and $H_{4\beta}$. The A ring of Fig. 1 lays in a $^2V$ conformation ($J_{2\beta-3\alpha}$ 10.0, $J_{2\beta-3\beta}$ 5.5), while ring B may be thought in a $^oT_5$ conformation.[16] (Found: C, 84.4; H, 6.6. $C_{25}H_{24}O_2$ requires: C, 84.24; H, 6.79%).

(2β,3aα,5α,6aα)-Stereoisomer (**3f′**). M.p. 137–138 °C; GLC $t_r$ = 30.3 min; *m/z* 356 ($M^+$, 1%), 278 (4), 265 (23), 252 (55), 236 (10), 219 (62), 159 (36), 131 (38), 119 (41), 117 (40), 115 (28), 105 (32), 91 (100) and 77 (21); $\delta_H$ 7.2–7.5 (15 H, m, Ar), 5.78 (1 H, s, O–CH–O, $H_{6a}$), 5.24 (1 H, dd, $H_{5\beta}$, $J_{5\beta-4\beta}$ 4.7, $J_{5\beta-4\alpha}$ 10.7), 4.88 (1 H, dd, $H_{2\alpha}$, $J_{2\alpha-3\alpha}$ 6.0, $J_{2\alpha-3\beta}$ 10.7), 3.07 and 2.98 (2 H, d, $CH_2Ph$, $J_{gem}$ 13.7), 2.53 (1 H, dd, $H_{3\alpha}$), $J_{2\alpha-3\alpha}$ 6.0, $J_{3\alpha-3\beta}$ 13.2), 2.13 (1 H, dd, $H_{4\beta}$, $J_{5\beta-4\beta}$ 4.7, $J_{4\alpha-4\beta}$ 12.5), 1.92 (1 H, dd, $H_{4\alpha}$, $J_{5\beta-4\alpha}$ 10.7, $J_{4\alpha-4\beta}$ 12.5) and 1.86 (1 H, dd, $H_{3\beta}$, $J_{2\alpha-3\beta}$ 10.7, $J_{3\alpha-3\beta}$ 13.2); NOE experiments: (i) selective saturation of the acetalic hydrogen at 5.78 ppm enhanced (2%) the $H_{2\alpha}$ (4.88 ppm), indicating a *cis* relationship with both $H_{6a}$ and benzylic hydrogens; (ii) $H_{3\alpha}$ is assigned from the NOE (5.8%) of the signal at 2.53 ppm and 0% NOE of the signal at 1.86 ppm ($H_{3\beta}$) on irradiation at 4.88 ppm ($H_{2\alpha}$); (iii) no significant NOE was detected for the signals of hydrogens belonging to ring B by saturation of exocyclic benzylic hydrogens (3.07 and 2.98 ppm), while 2.3%, 2.3% and 4.4% enhancements are observed for $H_{2\alpha}$ (4.88 ppm), $H_{3\alpha}$ (2.53 ppm) and $H_{3\beta}$ (1.86 ppm), respectively—this indicates a preferential orientation of the benzylic methylene towards ring A; (iv) the values of vicinal coupling constants $J_{4\alpha-5\beta}$ 10.5 and $J_{4\alpha-5\beta}$ 4.7 Hz, are within the typical range observed for the (2β,5α)-isomers, and the recorded NOE [5.0% and 5.4% of $H_{4\beta}$ (2.13 ppm) and $H_{4\alpha}$ (1.92 ppm) on irradiation at 5.24 ($H_{5\beta}$)] suggests a *trans* relationship between H-5 and the acetalic and benzylic hydrogens (Found: C, 84.2; H 6.7%).

(2β,3aα,5β,6aα)-*Stereoisomer* (**3f″**). Detected by GLC-MS ($t_r$ = 29.1 min), but not isolated; *m/z* 356 ($M^+$, 8%), 265 (20), 252 (29), 237 (18), 159 (26), 130 (33), 117 (40), 116 (32), 105 (95), 91 (100) and 77 (18).

(2*a*,3aα,5a,6aα)-2,5-*Diphenyl*-2,3,3*a*,4,5,6*a*-*hexahydro*-3*a*,-6*a*N-*methyliminopropanofuro*[2,3-b]*furan* (**3g**). Oil; GLC $t_r$ = 21.5 min; *m/z* 335 ($M^+$, 4%), 232 (2), 231 (18), 215 (18), 214 (6), 125 (14), 124 (100) and 105 (8); $\delta_H$ 7.2–7.5 (10 H, m), 5.39 (2 H, dd, $H_{2\beta}$, $J_{2\beta-3\beta}$ 7.5, $J_{2\beta-3\alpha}$ 9.5), 2.43 (2 H, dd, $H_{3\beta}$, $J_{2\beta-3\beta}$ 7.5, $J_{3\alpha-3\beta}$ 13.8), 2.31 (2 H, m), 2.27 (3 H, s), 2.16 (2 H, dd, $H_{3\alpha}$, $J_{2\beta-3\alpha}$ 9.5, $J_{3\alpha-3\beta}$ 13.8) and 2.49 (4 H, m) (Found: C, 78.5; H, 7.7; N 4.1. $C_{22}H_{25}NO_2$ requires: C, 78.77; H, 7.51; N, 4.18%).

(2β,3aα,5α,5α,6aα)-*Stereoisomer* (**3g′**). Oil; GLC $t_r$ = 19.6 min; *m/z* 335 ($M^+$, 3%), 232 (7), 231 (50), 216 (12), 214 (6), 173 (39), 126 (100), 124 (16), 11 (9) and 105 (6); $\delta_H$ 7.49 (2 H, dd, *J* 7, 2) 7.2–7.4 (8 H, m), 5.31 (1 H, dd, $H_{5\beta}$, *J* 7.5, 9.0), 4.53 (1 H, dd, $H_{2\alpha}$, *J* 7.4, 9.0), 2.80 (1 H, dd, *J* 12, 1.5), 2.66 (1 H, m), 2.3 (2 H, m) and 2.14–2.39 (8 H, m) (Found: C, 78.6; H, 7.4; N, 4.0%).

(2α,3aα,5α,6aα)-2,5-*Divinyl*-2,3,3*a*,4,5,6*a*-*hexahydro*-3*a*,6*a*-*butanofuro*[2,3-b]*furan* (**3h**). Oil; GLC $t_r$ = 18.1 min; *m/z*: 220 ($M^+$, 0.1%), 166 (16), 164 (28), 150 (33), 149 (65), 148 (100), 134 (18), 121 (24), 107 (21), 93 (23), 91 (26), 79 (33), 67 (28) and 54 (22); $\delta_H$ 5.84 (1 H, ddd, C*H*=$CH_2$, *J* 17.2, 10, 6.5), 5.27 (1 H, ddd, CH=C$H_2$, *J* 17.2, 1.3, 1.5), 5.10 (1 H, ddd, CH=C$H_2$, *J* = 10.1, 1.3, 1.5), 4.66 (1 H, m, $H_{2\beta}$, $J_{2\beta-3\beta}$ 6.9, $J_{2\beta-3\alpha}$ 9.1, *J* 6.5, 1.1), 2.13 (1 H, dd, $H_{3\beta}$, *J* 12.7, 7.0), 1.77 (1 H, dd, $H_{3\alpha}$, $J_{2\beta-3\alpha}$ 12.7, $J_{3\alpha-3\beta}$ 9.1) and 1.4–1.9 (8 H, m, $CH_2$) (Found: C, 76.2; H, 9.0. $C_{14}H_{20}O_2$ requires: C, 76.33; H 9.15%).

(2β,3aα,5α,6aα)-*Stereoisomer* (**3h′**). Oil; GLC $t_r$ = 17.7 min; *m/z* 220 ($M^+$, 0.5%), 192 (3), 177 (4), 164 (26), 151 (62), 149 (100), 148 (95), 135 (58), 121 (37), 107 (35), 93 (36), 91 (41), 79 (50) and 67 (34); $\delta_H$ 5.96 (1 H, ddd, C*H*=$CH_2$, *J* 17, 10, 6.5), 5.86 (1 H, ddd, C*H*=$CH_2$, *J* 16.8, 10.2, 6.6), 5.27 (1 H, ddd, CH=C$H_2$, *J* 16.8, 1.3, 1.5), 5.29 (1 H, ddd, CH=C$H_2$, *J* 16.8, 1.5, 1.4), 5.11 (1 H, ddd, CH=C$H_2$, *J* 10.2, 1.3, 1.5), 5.08 (1 H, ddd, CH=C$H_2$, *J* 10.3, 1.4, 1.5), 4.69 (1 H, m, *J* 9.2, 6.5, 6.5, 1.4, 1.5), 4.56 (1 H, m, *J* 8.8, 7.0, 6.6, 1.0, 1.2), 2.14 (1 H, dd, *J* 7, 12.7), 1.97 (1 H, dd, *J* 6.5, 12.5), 1.79 (1 H, dd, *J* 9, 12.5), 1.76 (1 H, dd, *J* 7.0, 12.7) and 1.2–2.0 (8 H, m, $CH_2$) (Found: C, 76.1; H, 9.2%).

*Compounds* **4a,a′**.—(2α.3aβ.9α)3a-*Methyl*-2,8-*diphenylperhydrofuro*[3,2-h]*benzofuran* (**4a**). Oil; GLC $t_r$ = 26 min; *m/z* 334 ($M^+$, 100%), 289 (10), 222 (21), 214 (22), 171 (49), 157 (62), 156 (50), 143 (84), 127 (57), 104 (77) and 91 (75); $\delta_H$ 7.2–7.5 (10 H, m), 5.25–5.35 (2 H, m), 2.83 (1 H, ddd, *J* 8.0, 12.4, 12.5), 2.35 (1 H, dddd, *J* 3.1, 6.1, 8.2, 9.0), 2.13 (1 H, dd, *J* 6.1, 12.4), 2.06 (1 H, dd, *J* 8.2, 12.4), 1.1–1.8 (8 H, m) and 1.40 (3 H, s) (Found: C, 86.7; H, 7.6. $C_{23}H_{26}O_2$ requires: C, 86.60; H, 7.84%).

(2β,3aβ,9α)-*Stereoisomer* (**4a′**). M.p. 120–121 °C; GLC $t_r$ = 25.2 min; *m/z*: 334 ($M^+$, 88%), 289 (13), 228 (71), 176 (36), 171 (43), 157 (68), 156 (57), 143 (73), 128 (60), 104 (100), 91 (89) and 77 (25); $\delta_H$ 7.1–7.6 (10 H, m, Ar), 5.36 (1 H, dd, CHO, *J* 7.5, 9.5), 5.11 (1 H, dd, CHO, *J* 6.5, 9.5), 1.2–2.4 (13 H, m, aliph.) and 1.31 (3 H, s, Me) (Found: C, 86.6; H, 7.9%).

*Compounds* **7b,b′**.—(2α,3aα,7aα)-*7a-Hydroxy-3a-methyl*-2-*phenylperhydrobenzofuran* (**7b**). M.p. 124–125 °C; GLC $t_r$ = 23.8 min; *m/z* 232 ($M^+$, 1%), 214 (100), 199 (26), 181 (20), 157 (22), 131 (25), 130 (25), 110 (35), 104 (27), 91 (40) and 77 (13); $\delta_H$ 7.3–7.4 (5 H, m), 5.32 (1 H, dd, *J* 4.3, 10.0), 2.58 (1 H, dd, *J* 10, 12), 2.14 (1 H, s, OH, $D_2O$ exch.), 1.77 (1 H, dd, *J* 4.3, 12), 1.25–1.7 (7 H, m) and 1.15 (3 H, s); $\delta_C$ 76.52 (d, C-2), 38.4 (t, C-3), 44.75 (s, C-3a), 106.5 (s, C-7a), 47.7 (t, C-7), 20.3, 22.9, 24.3 (t, C-4, 5, 6), 34.4 (q, Me), 145.5 (s, Arc), 128.9 (d, Arc), 125.9 (d, Arc) and 127.1 (d, Arc) (Found: C, 77.4; H, 8.8. $C_{15}H_{20}O_2$ requires: C, 77.55; H, 8.68%).

(2β,3aα,7aα)-*Stereoisomer* (**7b′**). M.p. 125–126 °C; GLC $t_r$ = 24.8 min; *m/z* 232 ($M^+$, 2%), 214 (3), 172 (2.5), 145 (6), 141 (7), 131 (100), 112 (20), 104 (20) and 91 (18); $\delta$ 7.15–7.5 (5 H, m, Ar), 5.17 (1 H, dd, *J* 7.0, 9.8), 2.16 (1 H, dd, *J* 9.8, 12), 2.15 (1 H, s, OH, $D_2O$ exch.), 2.05 (1 H, dd, H, *J* 7, 12), 1.96 (1 H, m, $J_{gem}$ 14), 1.4–1.7 (7 H, m, $CH_2$) and 1.16 (3 H, s, Me); $\delta_C$ 79.68 (d, C-2), 34.25 (t, C-3), 46.11 (s, C-3a), 106.6 (s, C-7a), 48.2 (t, C-7),

24.2, 22.4, 20.1 (t, C-4,5,6), 36.1 (q, Me), 144.6 (s, Arc), 129 (d, Arc), 127.9 (d, Arc), 127.1 (d, Arc) (Found: C, 77.3; H, 8.9%).

Two other minor isomers of **4** were detected by GLC and GLC-MS, but we were unable to isolate them as pure compounds.

*Compounds* **4b,b'**.—(2α,7α,9β)-9-*Ethyl*-4,4-*dimethyl*-2,7-*diphenyl*-1,6-*dioxaspiro*[4,4]*nonane* (**4b**). GLC $t_r$ = 19.5 min; *m/z* 336 ($M^+$, 100%), 321 (8), 232 (61), 217 (21), 171 (19), 157 (28), 128 (14), 104 (43) and 91 (30); $\delta_H$ 7.2–7.5 (10 H, m, Ar), 5.2–5.4 (2 H, m, CHO), 2.79 (1 H, ddd, *J* 7.4, 11.2, 12.5), 2.35 (1 H, ddt, *J* 3.1, 11.2, 7.6), 2.21 (1 H, ddd, *J* 3.1, 6.2, 12.5), 2.10 (1 H, dd, *J* 5.6, 12.4), 2.06 (1 H, dd, *J* 8.2, 12.4), 1.6 (2 H, dq, $CH_2Me$), 1.40 (3 H, s), 1.18 (3 H, s) and 0.96 (3 H, t) (Found: C, 81.9; H, 8.5. $C_{23}H_{28}O_2$ requires: C, 82.10; H, 8.39%).

(2α,7β,9β)-*Stereoisomer* (**4b'**). GLC $t_r$ = 20.1 min; *m/z* 336 ($M^+$, 31%), 321 (11), 232 (100), 217 (12), 171 (31), 157 (26), 128 (27), 104 (57) and 91 (18); δ 7.1–7.6 (10 H, m, Ar), 5.25 (1 H, dd, CHO, *J* 7.5, 9.5), 5.04 (1 H, dd, CHO, *J* 6.5, 9.5), 1.2–2.6 (7 H, m, aliph.), 1.31 (3 H, s), 1.23 (3 H, s) and 0.92 (3 H, s) (Found: C, 82.2; H, 8.4%).

*Oxidation of Styrene by FEP in the Presence of Less Reactive Ketones*.—Following the general procedure reported for cyclohexanone, but using acetone, 3,3-dimethylbutan-2-one, or acetophenone, the oxidation by FEP afforded a mixture of oxidation products of styrene without involvement of the carbonyl compound. A typical product distribution for the reaction in the presence of 3,3-dimethylbutan-2-one was: 1,4-diphenylbutadiene, compound **9** (isomers **9a** and **b** in ratio 1.3: 1 by GLC) and compound **10** (three isomers in ratio 1:0.35:0.43 by GLC) in 15, 26 and 20% yield, respectively.

*Compounds* **9a,b**.—(R*,R*)-1,4-*Diphenyl*-4-*acetamidobutanol* (**9a**). M.p. 191–192 °C, GLC $t_r$ = 14.5 min; $\nu_{max}/cm^{-1}$ 3500–3300m (br, OH), 3220m (NH) and 1630s (C=O); *m/z* 283 ($M^+$, absent), 265 (11), 206 (100), 191 (18), 178 (21), 165 (12), 128 (24), 119 (14), 115 (11), 91 (56) and 43 (25); $\delta_H$ 7.1–7.4 (10 H, m, Ar), 6.88 (1 H, d, OH, *J* 8), 5.80 (1 H, d, br, NH), 5.23 (1 H, ddd, CH-OH, *J* 8.5, 5, 5.2), 4.1 (1 H, m, br, CH-NH), 2.06 (3 H, s, Me) and 1.8–2.2 (3 H, m) (Found: C, 76.2; H, 7.7; N, 5.0. $C_{18}H_{21}NO_2$ requires: C, 76.30; H, 7.47; N. 4.94%).

(R*S*)-*Stereoisomer* (**9b**). M.p. 188–189 °C, GLC $t_r$ = 15.2 min; $\nu_{max}/cm^{-1}$ 3500–3300m (br, OH), 3220m, (NH) and 1640s (C=O); *m/z* 283 ($M^+$, absent), 265 (11), 206 (100), 191 (26), 178 (21), 165 (12), 128 (27), 119 (10), 115 (11), 91 (56) and 43 (28); δ 7.0–7.4 (10 H, m, Ar), 6.86 (1 H, d, OH, *J* 8.5), 5.70 (1 H, d br, NH), 5.34 (1 H, ddd, CH-OH, *J* 8.5, 6), 4.15 (1 H, dd, CH-NH, *J* 7, 8.5), 2.07 (3 H, s) and 1.7–2.3 (4 H, m) (Found: C, 76.1; H, 7.5; N, 4.7%).

Trimers **10** show similar MS spectra indicative of the structure proposed: first peak in GLC $t_r$ = 30.1 min); *m/z* 387 ($M^+$, absent), 369 (10), 310 (12), 206 (89), 149 (100), 129 (18), 128 (16), 120 (19), 106 (77), 91 (70), 79 (17) and 43 (31); second peak in GLC ($t_r$ = 30.4 min); *m/z* 387 ($M^+$, absent), 369 (10), 310 (9), 206 (100), 149 (71), 129 (15), 128 (14), 120 (14), 106 (70), 91 (68), 79 (14) and 43 (33); third peak in GLC ($t_r$ = 30.6 min); *m/z* 387 ($M^+$, absent), 369 (10), 310 (9), 206 (100), 149 (82), 129 (13), 128 (14), 120 (12), 106 (63), 91 (62), 79 (15) and 43 (28).

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