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Chemoselective Oxidation of Organozinc Reagents with Oxygen

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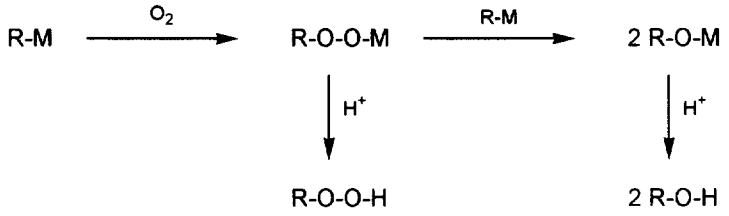
Abstract: Functionalized organozinc compounds prepared by hydrozincation, carbozincation or by boron-zinc exchange can be directly oxidized in a selective manner to the corresponding functionalized alcohols or hydroperoxides depending on the reaction conditions. © 1997 Elsevier Science Ltd.

Organometallic compounds react with molecular oxygen in a stepwise reaction, providing an alkylperoxy species first, which may then react with excess starting organometallic leading to an alcoholate (Scheme 1).[2] Usually, a mixture of alcohol and hydroperoxide is obtained from the oxidation of organometallics (Li, Mg, Al, Cd, Zn).[3] Among these, organozinc compounds are known to provide the best yield of alcohols.[4]

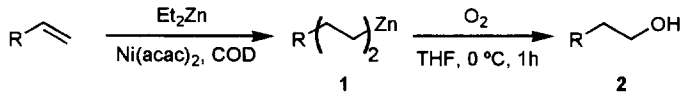


Scheme 1

However, this way of preparing alcohols has usually little synthetic value, as the organometallic species are often prepared from halides which in turn are prepared from the corresponding alcohols. On the other hand, if the organometallic reagent is prepared via another route, its oxidation may provide a convenient way to alcohols otherwise difficult to synthesize.[5]

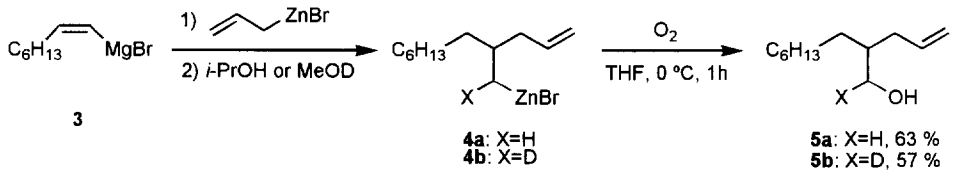
Organozinc compounds can be prepared by a number of methods.[6] One of these is the direct hydrozincation of olefins by diethylzinc in the presence of $Ni(acac)_2$ and cyclooctadiene (COD)[7] which avoids the intermediate use of borane.[6] Whereas conversions are modest in the case of simple unfunctionalized olefins, in the case of allylic and homoallylic amines and alcohols conversions lay over 90 %.

The dialkylzinc compounds thus prepared can be easily oxidized to the corresponding alcohols with oxygen in THF at 0 °C (Scheme 2 and Table 1).



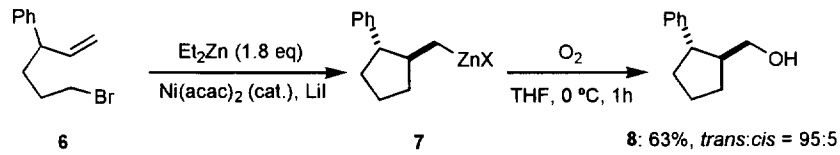
Scheme 2

Carbozincation is another attractive way for preparing organozincs that can be further converted into alcohols. Thus, the addition of allylzinc bromide[8] to the alkenylmagnesium bromide **3** provides an intermediate 1,1-bimetallic of zinc and magnesium. Its selective hydrolysis or deuterolysis furnishes the zinc reagents **4a-b** which can be oxidized giving the alcohols **5a** and **5b** (Scheme 3).[9]



Scheme 3

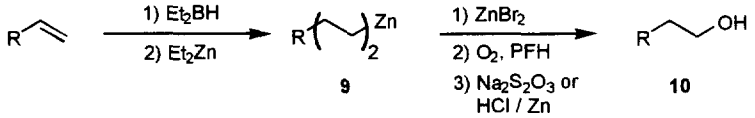
Also, the intramolecular carbozincation reaction of the unsaturated bromide **6** in the presence of diethylzinc, a catalytic amount of $Ni(acac)_2$ and LiI[10] furnishes the cyclopentylmethylzinc derivative **7**. Its oxidation gives the *trans*-alcohol **8** (Scheme 4).



Scheme 4

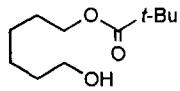
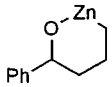
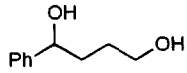
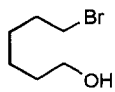
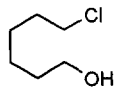
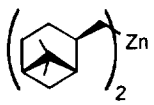
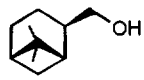
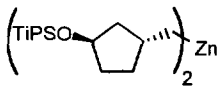
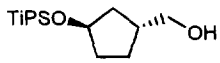
Furthermore, dialkylzinc compounds of type **9** may be prepared from olefins followed by a boron-zinc exchange.[11] These can be cleanly oxidized either directly or after conversion to the coresponding alkylzinc halides. When perfluorohexane (PFH) was used as solvent instead of THF, a mixture of alcohol and

hydroperoxide was obtained in excellent yield. This mixture could be converted to the corresponding alcohols of type **10** by reductive workup (Zn/HCl or $Na_2S_2O_3$, Scheme 5).[12]



Scheme 5

Table 1: Alcohols by oxidation of organozinc compounds

Entry	organozinc compound		product		yield (%)
1	$Zn(C_8H_{17})_2$	**1a**	$C_8H_{17}OH$	**2a**	82[a] (82[b])
2	$Zn((CH_2)_6OPiv)_2$	**1b**		**2b**	71[a] (71[b])
3	$Zn((CH_2)_6N(Bn)SO_2CF_3)_2$	**1c**		**2c**	87[a]
4		**1d**		**2d**	67[a]
5	$Zn((CH_2)_6Br)_2$	**9a**		**10a**	75[b]
6	$Zn((CH_2)_6Cl)_2$	**9b**		**10b**	69[b]
7		**9c**		**10c**	71[b]
8		**9c**		**10d**	64[b]

[a] reaction performed in THF; [b] reaction performed in PFH (perfluorohexane)

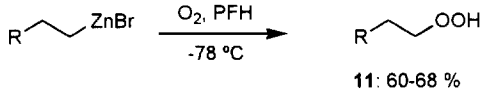
These findings prompted us to extend this procedure into a general method for the preparation of hydroperoxides.

Organic hydroperoxides are attractive synthetic targets. They are versatile synthetic intermediates, and despite their instability a surprisingly high number of natural products contain the hydroperoxide moiety.[13] Furthermore, chiral hydroperoxides are of interest as asymmetric oxidation reagents.[14]

A number of synthetic routes to hydroperoxides are known, including nucleophilic substitution by hydroperoxide anion,[15] anomeric oxidation,[16] autoxidation of alkanes,[17] oxidation of olefins[18] and enzymatic methods.[19] Another pathway to hydroperoxides is the reaction of organometallic compounds with oxygen. For obtaining a good hydroperoxide/alcohol ratio, it is necessary to slowly add the organometallic species to a large excess of oxygen at low temperatures. This avoids the side reaction of the zinc organometallic with already formed alkylperoxozinc species (ROOZnX) leading to the corresponding alcoholate (cf. Scheme 1). Due to the low solubility of oxygen in most organic solvents, large solvent volumes were needed even for small scale reactions.

We have found[20] that by using PFH instead of ether or THF, this problem can be overcome. PFH like most perfluorinated solvents dissolves large quantities of oxygen.[21] Hence, the volume of solvent required for these oxidations is considerably lower. For example, 3 mmol of dialkylzinc can be oxidized in 50 mL of PFH instead of 1000 mL of ether with similar yields. Another advantage that should not be neglected when exposing organometallics to oxygen is the non-inflammability of PFH and therefore the safer reaction conditions.

A further improvement was achieved by converting the dialkylzincs to the less reactive organozinc halides prior to addition, thus making the oxidation of the zinc reagent by the zinc hydroperoxide (ROOZnX) less likely. Under these conditions a number of primary and secondary organozincs were converted in good yields and excellent selectivities (usually <2 % alcohol) into the corresponding hydroperoxides (Scheme 6 and Table 2).



11: 60-68 %

Scheme 6

Since organozincs tolerate the presence of functional groups, a short and efficient preparation of functionalized hydroperoxides is possible. Also, starting from naturally occurring chiral olefins, chiral hydroperoxides **11a-c** are easily prepared (see entries 1-3 of Table 2).

Table 2. Hydroperoxides prepared by oxidation of zinc compounds with oxygen in PFH

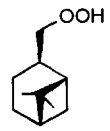
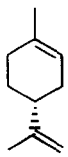
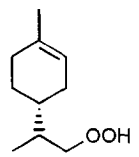
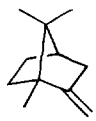
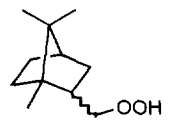
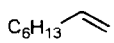
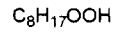
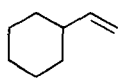
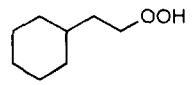
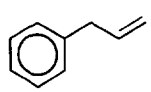
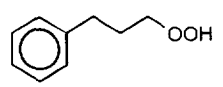
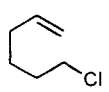
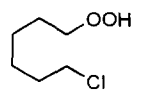
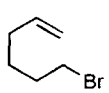
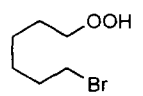
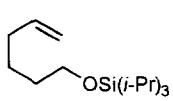
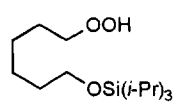
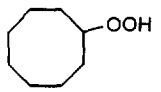
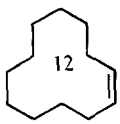
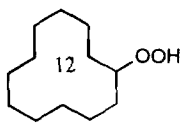
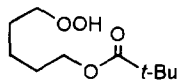
entry	olefin	hydroperoxide		yield
1			**11a**	64
2			**11b**	62
3			**11c**	67[a]
4			**11d**	85
5			**11e**	69
6			**11f**	69
7			**11g**	62
8			**11h**	68
9			**11i**	61

Table 2 (continued)

10			11j	60
11			11k	58
12			11l	68[b]

[a] obtained in *exo*:*endo* ratio of 88:12; [b] the organozinc reagent was prepared by iodine-zinc exchange

Experimental

General remarks. All manipulations involving air or moisture sensitive compounds were conducted under an atmosphere of argon using standard techniques. Dry oxygen-free solvents were used where appropriate. **Warning:** All operations involving pyrophoric diethylzinc should be performed wearing leather gloves and a face shield for additional protection. ^{1}H-NMR and ^{13}C-NMR spectra were recorded on Bruker ARX-200 and AC-300 spectrometers and were indirectly referenced to TMS using residual solvent signals. IR spectra were recorded on a Perkin-Elmer 281 spectrophotometer. Mass spectra were obtained on a Varian MAT CH-7A at 70 eV. Elemental analyses were performed in our Institute. Optical rotations were measured on a Perkin-Elmer 141 polarimeter at room temperature. Flash chromatography was conducted according to the procedure of Still[22], using mixtures of petroleum ether (PE) and methyl *tert*-butyl ether (MTBE) as eluant.

Preparation of 1-octanol (2a) by hydrozincation and oxidation (typical procedure). To 1-octene (1.12 g, 10 mmol), nickel(II) acetylacetonate (26 mg, 0.1 mmol) and 1,5-cyclooctadiene (22 mg) was added diethylzinc (0.6 mL, 6 mmol) at -78 °C, affording a yellow solution. The reaction mixture was warmed to 50 °C for 2 h (it turned black during this time). Iodolysis showed 36 % conversion. All volatiles were removed *in vacuo* and the dialkylzinc compound was dissolved in THF (20 mL). Oxygen was bubbled slowly through this solution at 0 °C for 1 h. After workup, flash chromatography (eluant PE-MTBE 10:1) afforded the alcohol **2a** (378 mg, 2.95 g, 82 % based on the dialkylzinc). ^{1}H-NMR ($CDCl_3$, 300 MHz): 3.51 (t, J=6.7, 2H), 2.46 (s, 1H), 1.49-1.42 (m, 2H), 1.21-1.19 (m, 10H), 0.79 (t, J=6.7, 3H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 62.7, 32.7, 31.8, 29.3, 29.2, 25.7, 22.6, 14.0; IR (film): 3332 (s), 2956 (s), 2926 (s), 1467 (m), 1058 (m); MS (EI): 84 (39), 83 (30), 70 (52), 69 (40), 56 (100), 54 (56), 43 (60); analysis calculated for $C_8H_{18}O$: C: 73.78, H: 13.93; found: C: 73.66, H: 13.91.

Preparation of 6-hydroxyhexyl pivalate (2b). As described above, 5-hexenyl pivalate (1.50 g, 8 mmol) was converted into the corresponding dialkylzinc compound in 35 % conversion. After oxidation as described above, workup and flash chromatography (eluant PE-MTBE 10:1) afforded the alcohol **2b** (400 mg, 1.98 mmol, 71 % based on dialkylzinc). ^{1}H-NMR ($CDCl_3$, 300 MHz): 3.98 (t, 2H, J=6.6), 3.94 (t, 2H, J=6.5), 2.25 (br s, 1H), 1.62-1.51 (m, 4H), 1.37-1.29 (m, 4H), 1.10 (s, 9H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 179.1, 76.7, 64.4, 38.8, 28.5, 27.5, 27.2, 25.7, 25.5; IR (film): 3500 (br, s), 2940 (s), 1720 (s), 1295 (m), 1165 (s); MS (EI): 157 (1), 103 (22), 85 (14), 57 (100), 41 (26); analysis calculated for $C_{11}H_{22}O_3$: C: 65.31, H: 10.96; found: C: 65.39, H: 10.92.

Preparation of N-benzyl-N-(6-hydroxyhexyl)trifluormethanesulfonamide (2c). As described above, N-benzyl-N-(5-hexenyl)trifluormethanesulfonamide (1.61 g, 5 mmol) was converted into the corresponding dialkylzinc compound in 35 % conversion. After oxidation as described above, workup and flash chromatography (eluant PE-MTBE 2:1) afforded the alcohol **2c** (610 mg, 1.8 mmol, 87 % based on dialkylzinc). ^{1}H-NMR ($CDCl_3$, 200 MHz): 7.33-7.23 (m, 5H), 4.43 (br,

2H), 3.56 (t, 2H, J=6.6), 3.17 (t, 2H, J=7.6), 2.03 (br s, 1H), 1.41-1.10 (m, 8H); ^{13}C-NMR ($CDCl_3$, 50 MHz): 135.0, 129.6, 129.2, 129.0, 120.8 (q, J=161), 63.0, 52.6, 48.7, 32.9, 28.3, 26.7, 25.7; IR (film): 3330 (br, s), 2930 (s), 1455 (m), 1385 (s), 1185 (s), 735 (m); MS (EI): 206 (20), 160 (5), 133 (8), 91 (100), 41 (4); analysis calculated for $C_{14}H_{20}F_3NO_3S$: N: 4.13, C: 49.55, H: 5.94; found: N: 4.29, C: 49.82, H: 5.88.

Preparation of 1-phenyl-1,4-butanediol (2d). As described above, 1-phenylbut-3-enol (741 mg, 5 mmol) was converted into the corresponding dialkylzinc compound in >90 % conversion. After oxidation as described above, workup and flash chromatography (eluant MTBE) afforded the alcohol **2d** as a solid (mp 60 °C, 560 mg, 3.37 mmol, 67 %). ^{1}H-NMR ($CDCl_3$, 300 MHz): 7.40-7.24 (m, 5H), 4.69 (t, 1H, J=6.3), 3.70-3.57 (m, 2H), 3.31 (br s, 1H), 2.86 (br s, 1H), 1.87-1.81 (m, 2H), 1.75-1.55 (m, 2H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 144.7, 128.4, 127.4, 125.8, 74.3, 62.7, 36.2, 29.2; IR (KBr): 3360 (br, s), 2940 (w), 1325 (m), 1260 (m), 1015 (m), 770 (s), 705 (s); MS (EI): 166 (16), 120 (6), 107 (100), 79 (44); analysis calculated for $C_{10}H_{14}O_2$: C: 72.26, H: 8.49; found: C: 72.09, H: 8.10.

Preparation of 2-allyloctanol (5a). 1-Octenyl bromide (1.34 g, 7 mmol) and magnesium turnings (168 mg, 7 mmol) in THF (8 mL) were heated to reflux for 1 h. The solution was cooled to rt and a solution of allylzinc bromide (9.5 mmol) in THF (9 mL) was added. An exothermic reaction took place. The yellow solution was cooled to -70 °C and i-propanol (300 mg, 5 mmol) was added. The solution was slowly warmed to 0 °C and oxidized as described above. Workup and flash chromatography (eluant PE-MTBE 4:1) afforded the alcohol **5a** (750 mg, 4.41 mmol, 63 %). ^{1}H-NMR ($CDCl_3$, 200 MHz): 5.81-5.67 (m, 1H), 5.03-4.91 (m, 2H), 3.46 (d, 2H, J=4.6), 2.42 (br s, 1H), 2.04 (t, 2H, J=6.6), 1.51-1.48 (m, 1H), 1.21-1.12 (m, 10H), 0.81 (t, 3H, J=6.8); ^{13}C-NMR ($CDCl_3$, 50 MHz): 137.1, 116.1, 65.4, 40.4, 35.7, 31.8, 30.6, 29.6, 26.9, 22.7, 14.1; IR (film): 3360 (br, s), 3080 (w), 2930 (s), 1640 (m), 1470 (m), 1030 (m), 910 (m); MS (EI): 139 (2), 110 (12), 95 (27), 82 (43), 69 (92), 55 (100), 41 (58); analysis calculated for $C_{11}H_{22}O$: C: 77.58, H: 13.02; found: C: 77.40, H: 13.00.

Preparation of 1-deutero-2-allyloctanol (5b). 1-Octenyl bromide (1.91 g, 10 mmol) and magnesium turnings (240 mg, 10 mmol) in THF (10 mL) were heated to reflux for 1 h. The solution was cooled to rt and a solution of allylzinc bromide (15 mmol) in THF (14 mL) was added. An exothermic reaction took place. The yellow solution was cooled to -70 °C and deuteromethanol (330 mg, 10 mmol) was added. The solution was slowly warmed to 0 °C and oxidized as described above. Workup and flash chromatography (eluant PE-MTBE 4:1) afforded the alcohol **5b** (976 mg, 5.7 mmol, 57 %). ^{1}H-NMR ($CDCl_3$, 300 MHz): 5.83-5.67 (m, 1H), 5.04-4.94 (m, 2H), 3.46 (dd, 1H, J=6.6, J=5.5), 2.29 (br s, 1H), 2.06 (t, 2H, J=7.1), 1.56-1.52 (m, 1H), 1.32-1.20 (m, 10H), 0.83 (t, 3H, J=6.8); ^{13}C-NMR ($CDCl_3$, 75 MHz): 137.2, 116.8, 65.1 (t, J=10.2), 40.3, 35.7, 31.9, 30.6, 29.6, 26.9, 22.7, 14.1; IR (film): 3360 (br, s), 3080 (w), 2930 (s), 1640 (m), 1470 (m), 1030 (m), 910 (m); MS (EI): 125 (s), 111 (8), 96 (23), 83 (51), 70 (55), 69 (74), 55 (100), 41 (46); analysis calculated for $C_{11}H_{21}DO$: C: 77.13, H: 13.53; found: C: 77.17, H: 13.66.

Preparation of *trans*-(1*R*,2*R*)-(2-phenylcyclopentyl)methanol (8). To a solution of LiI (0.2 g, 1.5 mmol), nickel(II) acetylacetonate (38 mg, 0.15 mmol) and 6-bromo-3-phenyl-1-hexene **6** (0.71 g, 3.0 mmol) in THF (8 mL) was added diethylzinc (0.45 mL, 4.5 mmol) at -78 °C. The mixture was warmed to rt and stirred for 3 h. All volatiles were removed *in vacuo*. The organozinc compound was dissolved in THF (7 mL) and oxidized as described above. Workup and flash chromatography (eluant PE-MTBE 8:1) afforded the alcohol **8** (330 mg, 1.9 mmol, 63 %) as a 95:5 mixture of *trans-cis* isomers. ^{1}H-NMR ($CDCl_3$, 300 MHz): 7.27 (m, 5H), 3.56-3.36 (m, 2H), 2.62 (q, J=8.8, 1H), 2.03-0.80 (m, 8H). ^{13}C-NMR ($CDCl_3$, 75 MHz): 146.0, 129.2, 128.3, 126.8, 66.6, 51.0, 49.8, 36.6, 30.2, 25.3; MS (EI): 176 (22), 158 (75), 143 (65), 130 (65), 129 (45), 117 (60); IR (film): 3353 (m), 2951 (s), 2870 (s), 1493 (m), 1452 (m), 1057 (m), 1021 (m), 734 (s); analysis calculated for $C_{12}H_{16}O$: C: 81.77, H: 9.15; found: C: 81.98, H: 9.24.

Preparation of 6-bromohexanol (10a) by boron-zinc exchange and oxidation in perfluorohexane (typical procedure). To 6-bromohexene (3.26 g, 20 mmol) was added a solution of diethylborane (4.47 g, 20 mmol) in ether at -10 °C and the resulting solution stirred at 0 °C for 2 h and an additional 8 h at rt. All volatiles were removed *in vacuo*. The residue was taken up in hexane (5 mL) and cooled to 0 °C. Diethylzinc (4.0 mL, 40 mmol) was added and the solution stirred with exclusion of light for 30 min at rt. Again, all volatiles were removed *in vacuo*. The resulting dialkylzinc compound was dissolved in THF and added at 0°C to a solution of zinc bromide (2.00 g, 9 mmol) in THF. The resulting solution containing the alkylzinc bromide was added in one portion to perfluorohexane (150 mL) previously saturated with oxygen for 2 h at -78 °C. The emulsion was stirred for 2 h and then worked up with 2 M HCl. The PFH layer was separated and the aqueous phase extracted with ether. The combined organic phases were shaken with a saturated aqueous NaS_2O_3 solution (30 mL) for 1 h. Workup and flash chromatography (eluant PE-MTBE 9:1) afforded the alcohol **10a** (2.44 g, 13.8 mmol, 75 %). ^{1}H-NMR ($CDCl_3$, 300 MHz): 3.56 (t, J=6.5, 2H), 3.34 (t, J=6.7, 2H), 3.05 (s, 1H), 1.80 (quin, J=7.0, 2H), 1.51 (quin, J=6.9, 2H), 1.45-1.29 (m, 4H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 62.5, 33.7, 32.6, 32.2, 27.9, 24.9; IR (film): 3343 (m), 2935 (s), 2860 (m), 1053 (m), 417 (m); MS (EI): 136 (11), 134 (14), 83 (66), 82 (17), 69 (21), 67 (15), 56 (17), 55 (100); analysis calculated for $C_6H_{13}BrO$: C: 39.80, H: 7.24; found: C: 39.74, H: 7.26.

Preparation of 1-octanol (2a). As described above, starting from 1-octene (0.56 g, 5 mmol) was obtained after hydroboration, boron-zinc exchange, oxidation in PFH and reductive workup the alcohol **2a** (0.53 g, 4.1 mmol, 82 %) as a clear oil. See above for the spectral data.

Preparation of 6-hydroxyhexyl-1-pivalate (2b). As described above, starting from 5-hexenyl pivalate (0.92 g, 5 mmol) was obtained after hydroboration, boron-zinc exchange, oxidation in PFH and reductive workup the alcohol **2b** (0.71 g, 3.6 mmol, 71 %) as a clear oil. See above for the spectral data.

Preparation of 6-chlorohexan-1-ol (10b). As described above, starting from 6-chlorohexene (0.78 g, 6.5 mmol) was obtained after hydroboration, boron-zinc exchange, oxidation in PFH and reductive workup the alcohol **10b** (0.61 g, 4.4 mmol, 69 %) as a clear oil. ^{1}H-NMR ($CDCl_3$, 300 MHz): 3.57 (t, J=6.5, 2H), 3.47 (t, J=6.6, 2H), 1.75-1.67 (m, 3H), 1.51 (quin, J=6.9, 2H), 1.45-1.26 (m, 4H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 62.7, 45.1, 32.6, 32.6, 26.7, 25.1; IR (film): 3344 (m), 2937 (s), 2861 (m), 1462 (m), 1074 (m), 1056 (m), 730 (m), 651 (m); MS (EI): 90 (32), 83 (13), 82 (33), 69 (64), 67 (29), 56 (41), 55 (100); analysis calculated for $C_6H_{13}ClO$: C: 52.75, H: 9.59; found: C: 52.83, H: 9.79.

Preparation of (-)-*cis*-myrtanol (10c). As described above, starting from (-)-β-pinene (0.68 g, 5 mmol) was obtained after hydroboration, boron-zinc exchange, oxidation in PFH and reductive workup the alcohol **10c** (0.54 g, 3.5 mmol, 71 %) as a clear oil. ^{1}H-NMR ($CDCl_3$, 300 MHz): 3.55-3.43 (m, 2H), 2.34-2.27 (m, 1H), 2.22-2.11 (m, 1H), 1.97-1.88 (m, 1H), 1.88-1.79 (m, 5H), 1.44-1.35 (m, 1H), 1.12 (s, 3H), 0.90-0.84 (m, 4H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 67.6, 44.3, 42.8, 41.4, 38.5, 33.0, 27.8, 25.8, 23.2, 18.6; IR (film): 3329 (m), 2910 (s), 2869 (m), 1468 (m), 1044 (m); MS (EI): 136 (10), 123 (65), 121 (25), 95 (25), 93 (79), 82 (52), 81 (52), 69 (100); analysis calculated for $C_{10}H_{18}O$: C: 77.87, H: 11.76; found: C: 77.93, H: 11.65; $[\alpha]_D$: -21.1 (c = 2.4, $CHCl_3$).

Preparation of *trans*-3-triisopropylsilyloxy-1-cyclopentanol (10d). As described above, starting from 3-triisopropylsilyloxy-1-cyclopentene (2.40 g, 10 mmol) was obtained after hydroboration, boron-zinc exchange, oxidation in PFH and reductive workup the alcohol **10d** (1.65 g, 6.4 mmol, 64 %) as a clear oil. ^{1}H-NMR ($CDCl_3$, 300 MHz): 4.46-4.35 (m, 2H), 2.05-1.93 (m, 2H), 1.82-1.75 (m, 2H), 1.66 (s, 1H), 1.54-1.43 (m, 2H), 0.97 (s, 21H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 72.9, 72.5, 45.9, 34.0, 33.4, 17.9, 11.9; IR (film): 3388 (m), 2959 (s), 2943 (s), 1464 (m), 1091 (m), 883 (m), 682 (m); MS (EI): 197 (14), 149 (14), 131 (51), 103 (40), 75 (41), 67 (100); analysis calculated for $C_{14}H_{30}SiO_2$: C: 65.05, H: 11.96; found: C: 65.21, H: 12.13.

CAUTION: While no incidents occurred during the performance of this work, hydroperoxides should be handeld with care due to their potential explosive decomposition.

Preparation of (-)-*cis*-myrtanylhydroperoxide (11a) by oxidation of the organozinc bromide (typical procedure). As described above, dimyrtanylzinc (1.68 g, 5 mmol) was dissolved in THF (6 mL) and added to a solution of zinc bromide (1.12 g, 5 mmol) in THF (5 mL). The resulting solution of *cis*-myrtanylzinc bromide was slowly added at -78 °C into perfluorohexane (PFH) previously saturated with oxygen for 2 h. After 4 h, 2 M HCl (6 mL) was added, the PFH layer separated and the aqueous layer extracted with ether. Flash chromatography (eluant PE-MTBE 9:1) afforded the hydroperoxide **11a** (1.08 g, 6.4 mmol, 64 %) as a clear oil. ^{1}H-NMR ($CDCl_3$, 300 MHz): 8.38 (s, 1H), 3.97-3.87 (m, 2H), 2.41-2.32 (m, 1H), 2.30-2.25 (m, 1H), 1.92-1.78 (m, 5H), 1.49-1.39 (m, 1H), 1.11 (s, 3H), 0.90-0.86 (m, 4H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 82.2, 43.3, 41.2, 38.9, 38.4, 33.2, 27.7, 26.5, 23.1, 18.3; IR (film): 3329 (m), 2910 (s), 2867 (m), 1467 (m), 1042 (m); MS (EI): 123 (46), 83 (41), 82 (69), 81 (75), 79 (51), 69 (100), 67 (93); analysis calculated for $C_{10}H_{18}O_2$: C: 70.54, H: 10.56; found: C: 70.85, H: 10.49.

Preparation of (R)-(+)-limonylhydroperoxide (11b). As described above, starting from (*R*)-(+)-limonene (0.68 g, 5 mmol) was obtained after hydroboration, boron-zinc exchange, conversion to the alkylzinc bromide and oxidation the hydroperoxide **11b** (0.49 g, 2.9 mmol, 58 %). ^{1}H-NMR ($CDCl_3$, 300 MHz): 9.05 (s, 1H), 5.28 (s, 1H), 4.00-3.74 (m, 2H), 1.88-0.81 (m, 14H). ^{13}C-NMR ($CDCl_3$, 75 MHz): 134.2, 120.8, 80.9, 36.1, 30.9, 29.7, 27.8, 23.6, 14.1, 13.7; IR (film): 3400 (m), 2935 (s), 2865 (m), 1039 (m); MS (EI): 149 (100), 94 (38), 85 (24), 71 (61), 69 (31), 57 (82), 55 (40), 43 (46), 41 (37); analysis calculated for $C_{10}H_{18}O_2$: C: 70.54, H: 10.65; found: C: 70.70, H: 10.45.

Preparation of 2-bornylmethylhydroperoxide (11c). As described above, starting from 2-methylenebornane (0.75 g, 5 mmol) was obtained after hydroboration, boron-zinc exchange, conversion to the alkylzinc bromide and oxidation the hydroperoxide **11c** (0.61 g, 3.3 mmol, 67 %) as a 88:12 mixture of *exo*:*endo* isomers. ^{1}H-NMR ($CDCl_3$, 300 MHz): 8.35 (s, 1H), 4.13-4.07 (m, 1H), 3.83-3.78 (m, 1H), 1.74-1.56 (m, 2H), 1.55-1.40 (m, 3H), 1.16-1.03 (m, 2H), 0.83-0.75 (m, 10H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 81.4, 45.0, 44.9, 39.4, 34.7, 34.6, 27.2, 20.3, 20.2, 12.7, 12.6; IR (film): 3382 (s), 2948 (s), 1479 (s), 1459 (s), 1389 (s), 1336 (m), 999 (m); MS (EI): 137 (21), 107 (29), 95 (100), 81 (65), 79 (21), 71 (21), 69 (36), 67 (35), 55 (33), 41 (44); analysis calculated for $C_{11}H_{20}O_2$: C: 71.70, H: 10.94; found: C: 71.56, H: 11.08.

Preparation of octylhydroperoxide (11d). As described above, starting from 1-octene (0.67 g, 6 mmol) was obtained after hydroboration, boron-zinc exchange, conversion to the alkylzinc bromide and oxidation the hydroperoxide **11d** (0.74 g, 5.1 mmol, 85 %). ^{1}H-NMR ($CDCl_3$, 300 MHz): 8.86 (s, 1H), 3.93 (t, J=6.6, 2H), 1.57-1.50 (m, 2H), 1.31-1.15 (s, 11H), 0.87-0.78 (m, 3H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 77.4, 31.8, 30.3, 29.5, 27.7, 25.8, 22.9, 13.9, 67 (55); IR (film): 3332

(m), 2956 (s), (2925 (s), 1465 (m), 1058 (m); MS (EI): 111 (10), 110 (13), 98 (17), 95 (13), 84 (21), 82 (50), 81 (35), 69 (40), analysis calculated for $C_8H_{18}O_2$: C: 65.71, H: 12.40; found: C: 65.90, H: 12.71.

Preparation of 2-cyclohexylethylhydroperoxide (11e). As described above, starting from vinylcyclohexane (1.32 g, 12 mmol) was obtained after hydroboration, boron-zinc exchange, conversion to the alkylzinc bromide and oxidation the hydroperoxide **11e** (1.18 g, 8.2 mmol, 69 %). ^{1}H-NMR ($CDCl_3$, 200 MHz): 8.90 (s, 1H), 3.98 (t, J=6.6, 2H), 1.65-0.77 (m, 13H); ^{13}C-NMR ($CDCl_3$, 50 MHz): 76.1, 35.7, 35.5, 34.5, 27.3, 27.2; IR (film): 3386 (s), 2925 (s), 2853 (s), 1449 (s), 1377 (m), 1041 (m), 1007 (m); MS (EI): 62 (33), 57 (25); analysis calculated for $C_8H_{16}O_2$: C: 66.63, H: 11.18; found: C: 66.51, H: 11.25

Preparation of 3-phenylpropylhydroperoxide (11f). As described above, starting from allylbenzene (1.41 g, 12 mmol) was obtained after hydroboration, boron-zinc exchange, conversion to the alkylzinc bromide and oxidation the hydroperoxide **11f** (1.26 g, 8.2 mmol, 69 %). ^{1}H-NMR ($CDCl_3$, 300 MHz): 8.48 (s, 1H), 7.36-7.20 (m, 5H), 4.07 (t, J=6.4, 2H), 2.73 (t, J=7.7, 2H), 2.01 (quin, J=6.4, 2H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 141.6, 128.6, 128.5, 126.1, 76.3, 32.1, 29.0; IR (film): 3397 (m), 3029 (m), 2948 (m), 1497 (m), 1454 (s), 748 (s), 700 (s); MS (EI): 134 (15), 118 (42), 117 (44), 105 (24), 92 (62), 91 (100), 78 (17), 77 (19), 65 (12), 51 (15); analysis calculated for $C_9H_{12}O_2$: C: 71.02, H: 7.94; found: C: 70.98, H: 8.00.

Preparation of 6-chlorhexylhydroperoxide (11g). As described above, starting from 6-chlorohexene (0.71 g, 6 mmol) was obtained after hydroboration, boron-zinc exchange, conversion to the alkylzinc bromide and oxidation the hydroperoxide **11g** (0.56 g, 3.7 mmol, 62 %). ^{1}H-NMR ($CDCl_3$, 300 MHz): 8.49 (s, 1H), 3.95 (t, J=6.5, 2H), 3.47 (t, J=6.6, 2H), 1.71 (quin, J=6.9, 2H), 1.59 (quin, J=6.9, 2H), 1.45-1.26 (m, 4H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 76.6, 44.9, 32.4, 27.5, 26.6, 25.1; IR (film): 3433 (m), 2939 (s), 2863 (m), 1462 (m), 1309 (m), 1075 (m), 730 (m), 651 (m); MS (EI): 90 (13), 69 (36), 67 (16), 57 (17), 56 (23), 55 (63), 54 (23); analysis calculated for $C_6H_{13}ClO_2$: C: 47.22, H: 8.59; found: C: 46.99, H: 8.72.

Preparation of 6-bromhexylhydroperoxide (11h). As described above, starting from 6-bromohexene (0.97 g, 6 mmol) was obtained after hydroboration, boron-zinc exchange, conversion to the alkylzinc bromide and oxidation the hydroperoxide **11h** (0.80 g, 4.1 mmol, 68 %). ^{1}H-NMR ($CDCl_3$, 300 MHz): 8.81 (s, 1H), 3.95 (t, J=6.5, 2H), 3.35 (t, J=6.7, 2H), 1.80 (quin, J=6.8, 2H), 1.59 (quin, J=6.8, 2H), 1.45-1.26 (m, 4H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 76.8, 33.9, 32.6, 27.8, 27.4, 25.1; IR (film): 3395 (m), 2938 (s), 2860 (m), 1094 (s), 627 (m); MS (EI): 83 (33), 81 (40), 69 (22), 57 (30), 55 (91) 54 (32); analysis calculated for $C_6H_{13}BrO_2$: C: 36.57, H: 6.65; found: C: 36.61, H: 6.65.

Preparation of 6-triisopropylsiloxyhexylhydroperoxide (11i). As described above, starting from 6-triisopropylsilyloxy-1-hexene (0.69 g, 2.7 mmol) was obtained after hydroboration, boron-zinc exchange, conversion to the alkylzinc bromide and oxidation the hydroperoxide **11i** (0.48 g, 1.6 mmol, 62 %). ^{1}H-NMR ($CDCl_3$, 300 MHz): 8.91 (s, 1H), 3.92 (t, J=6.6, 2H), 3.60 (t, J=6.6, 2H), 1.58-1.46 (m, 4H), 1.30 (s, 4H), 0.99 (s, 21H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 77.3, 63.7, 32.9, 27.8, 25.9, 25.9, 18.2, 12.2; IR (film): 3370 (m), 2942 (s), 2893 (s), 1463 (m), 1103 (m), 883 (m), 681 (m); MS (EI): 229 (37), 187 (64), 131 (100), 103 (66), 83 (44), 75 (67); analysis calculated for $C_{15}H_{34}SiO_3$: C: 62.01, H: 11.79; found: C: 62.15, H: 12.13.

Preparation of cyclooctylhydroperoxide (11j). As described above, starting from cyclooctene (0.88 g, 8 mmol) was obtained after hydroboration, boron-zinc exchange, conversion to the alkylzinc bromide and oxidation the hydroperoxide **11j** (0.69 g, 4.8 mmol, 60 %). ^{1}H-NMR ($CDCl_3$, 200 MHz): 8.44 (s, 1H), 3.92-3.81 (m, 1H), 1.72-0.62 (m, 14H); ^{13}C-NMR ($CDCl_3$, 50 MHz): 86.9, 30.6, 27.8, 26.7, 24.2; IR (film): 3400 (m), 2935 (s), 1585 (m), 1265 (m); MS (EI): 111 (12), 55 (8); analysis calculated for $C_8H_{16}O_2$: C: 66.63, H: 11.18; found: C: 66.78, H: 11.31.

Preparation of cyclododecylhydroperoxide (11k). As described above, starting from cyclododecene (0.83 g, 5 mmol) was obtained after hydroboration, boron-zinc exchange, conversion to the alkylzinc bromide and oxidation the hydroperoxide **11k** (0.58 g, 2.9 mmol, 58 %). ^{1}H-NMR ($CDCl_3$, 300 MHz): 7.78 (s, 1H), 4.10-4.02 (m, 1H), 1.62-0.79 (m, 22H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 83.4, 27.4, 24.5, 23.9, 23.4, 23.3, 21.1; IR (film): 3400 (m), 2937 (s), 1591 (m), 1514 (s), 1261 (s); MS (EI): 167 (8), 111 (30), 109 (11), 97 (58), 95 (22), 83 (57), 82 (37); analysis calculated for $C_{12}H_{24}O_2$: C: 71.95, H: 12.07; found: C: 71.66, H: 12.34.

Preparation of 5-hydroperoxypentyl-1-pivalate (11l). To 5-iodopentyl pivalate (1.78 g, 6 mmol) and copper iodide (30 mg) was added diethylzinc (1.2 mL, 12 mmol) and the resulting black mixture stirred at 55 °C for 12 h. All volatiles were removed *in vacuo*, the dialkylzinc compound was dissolved in THF and converted to the alkylzinc halide by reaction with zinc bromide (1.35 g, 6 mmol). After oxidation and workup as described above was obtained the hydroperoxide **11l** (0.83 g, 4.1 mmol, 68 %) as an oil. ^{1}H-NMR ($CDCl_3$, 300 MHz): 9.52 (s, 1H), 3.99 (t, J=6.4, 2H), 3.93 (t, J=6.4, 2H), 1.63-1.52 (m, 4H), 1.40-1.35 (m, 2H), 1.12 (s, 9H); ^{13}C-NMR ($CDCl_3$, 75 MHz): 179.4, 76.6, 64.5, 38.9, 28.5, 27.3, 26.9, 22.6; IR (film): 3400 (m), 2935 (s), 1729 (s), 1480 (s), 1160 (m); MS (EI): 103 (19), 85 (29), 84 (13), 69 (17), 68 (16), 57 (100), 56 (17), 55 (10), 41 (35); analysis calculated for $C_{10}H_{20}O_4$: C: 58.80, H: 9.86; found: C: 59.07, H: 9.65.

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References and Notes

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