Reactions of Hydroxyl Radicals with Polymerizable Olefins

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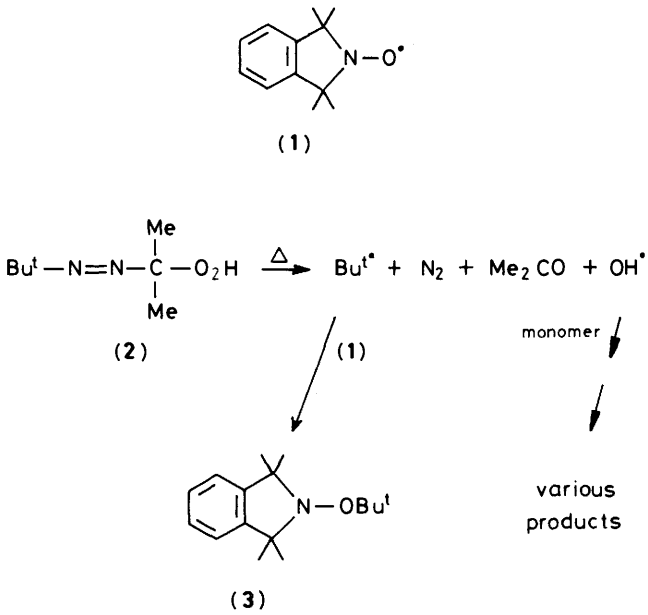
The reactions of hydroxyl radicals with methyl acrylate, methyl methacrylate, styrene, and α-methylstyrene have been investigated by a trapping technique which uses 1,1,3,3-tetramethylisoindolin-2-yloxyl (**1**) as a radical scavenger. The major reaction pathway in each case was addition to the unsubstituted (tail) end of the monomer, although addition to the substituted (head) end and reaction with the double-bond substituents were also observed. Absolute rates of reaction were estimated by means of competition experiments using cyclohexane as reference substrate. The implications of the results for the structure of polymers initiated by hydroxyl radicals are discussed.

We have recently been involved in an investigation of the reactions of free radicals with a variety of polymerizable olefins.[1–12] This work has been aimed at determining the nature and proportions of various chemical structures introduced into a polymer during the initiation stage of its formation.

Hydroxyl radicals are frequently used to initiate free radical polymerization. Examples include a wide range of redox initiators (such as Fenton's reagent) commonly used in emulsion polymerization,[13a] thermolysis or photolysis of hydroperoxide initiators or of hydrogen peroxide,[14] and radiolysis of water.[13b,15] Also, trace amounts of oxygen present in a free radical polymerization can produce hydroperoxides,[16] which then generate hydroxyl radicals on homolysis. Several previous studies[15,17–20] have been made of the reactions of polymerizable alkenes with hydroxyl radicals, and rate constants for these reactions have been determined for a few monomers.[15,19,20] The authors however generally dealt with aqueous systems, generating hydroxyl radicals by pulse radiolysis or redox reactions and identifying the product radicals by u.v. or e.s.r. spectroscopy.

In the present work, we have examined the reactions of hydroxyl radicals with monomers in a homogeneous organic solution, using a radical trapping technique which is capable of detecting and accurately quantifying even very minor reaction pathways.



Scheme 1.

Method.—An efficient method for studying free-radical reactions has been developed in these laboratories. This involves performing the reaction under investigation in the presence of a stable nitroxide, such as (**1**). The details of this technique have been described in previous publications,[2–12] and it is sufficient to mention here that, whereas heteroatom-centred radicals, such as hydroxyl, are essentially inert to (**1**), carbon-centred radicals produced in reactions with monomer couple rapidly with (**1**) to give isolable products. Thus the identity and relative rates of formation of the various carbon-centred radicals produced in a reaction can be readily deduced from the relative yields of the isolated adducts.

The source of hydroxyl radicals used in the present work was 2-(t-butylazo)prop-2-yl hydroperoxide (**2**). This material is soluble in most organic solvents, and decomposes thermally to give hydroxyl and t-butyl radicals at convenient temperatures.[21] The t-butyl radicals produced are rapidly trapped by nitroxide (**1**) to produce the alkoxyamine (**3**) (Scheme 1).

The monomers we chose to examine were of general structure (**4**). These enabled us to examine the effect of the substituent X, and also of methyl substitution at C(1) of the monomer.

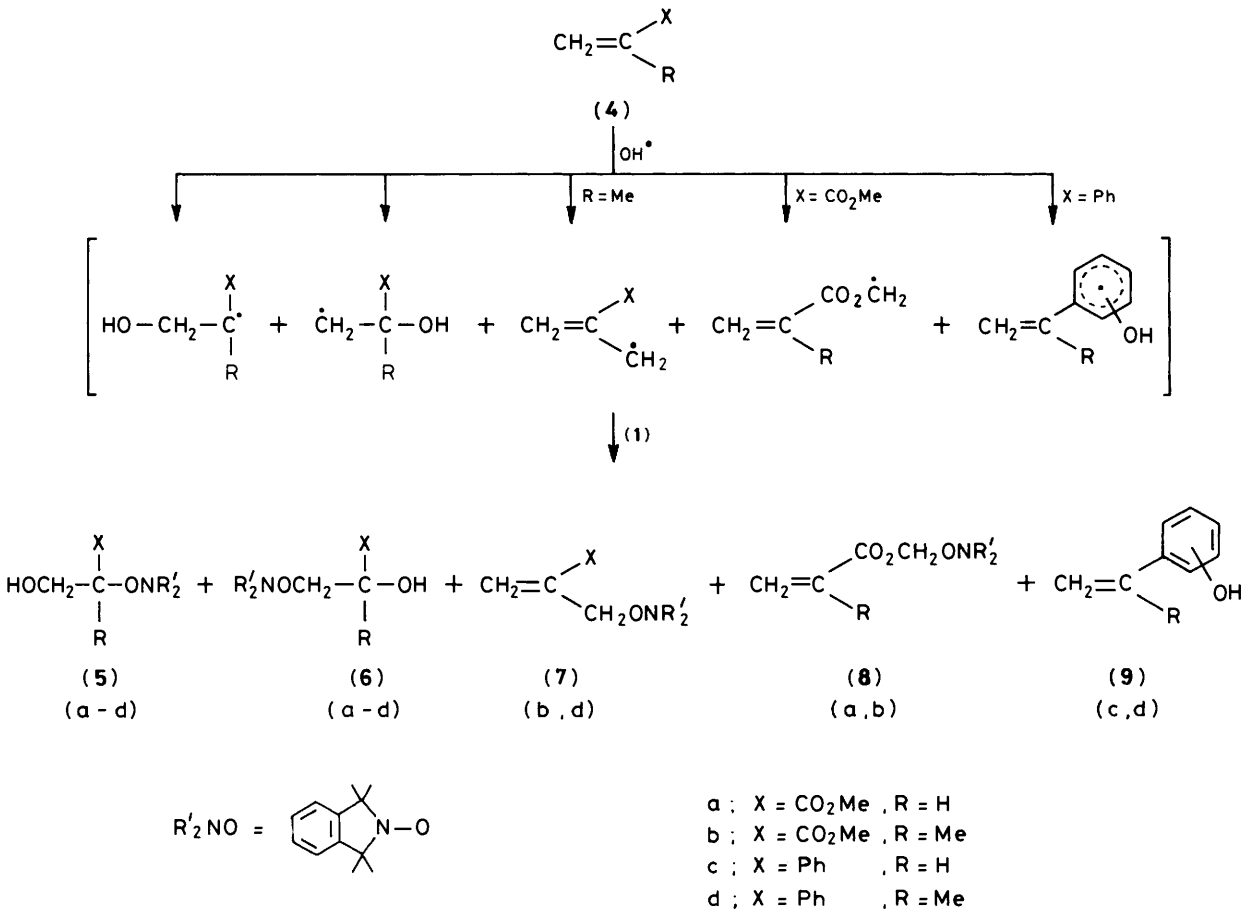
Results

Products.—The experiments were performed by decomposing degassed solutions of 2-(t-butylazo)prop-2-yl hydroperoxide (**2**) (0.17M) and excess of 1,1,3,3-tetramethylisoindolin-2-yloxyl (**1**) (0.43M) in neat monomer, at 60.0 °C. All products, except phenols (**9**) (see below), were quantified and isolated by h.p.l.c.

The various pathways operating in the reaction of hydroxyl radicals with monomers (**4**) are shown in Scheme 2. As was expected from the results of experiments with other radicals,[2–9] the major pathway was addition to the unsubstituted (tail) end of the monomer, leading to products (**5**). Other pathways which were detected include addition to the substituted (head) end of the monomer [products (**6**)], abstraction of an allylic hydrogen atom [products (**7**)], and reaction with the substituent X, either by hydrogen abstraction [products (**8**)] or by aromatic substitution [products (**9**)].

Several of these products [(**7b** and **d**), (**8a** and **b**)] had been characterized in the course of our earlier work,[3,5,12] and were identified by comparison with authentic samples. The structures of previously unknown compounds were assigned on the basis of analytical and spectral data.

The tail adducts (**5**) were distinguished from the isomeric head adducts (**6**) by ^{1}H n.m.r. spectroscopy. Thus, in the spectra of compounds (**5b**—**d**), the AB quartet due to the methylene protons (adjacent to an asymmetric centre) was split further by coupling to the OH proton. In several cases this splitting was only observable when the spectrum was run in $(CD_3)_2SO$. The spectrum of adduct (**5a**) in $CDCl_3$, $(CD_3)_2SO$, or C_5D_5N did



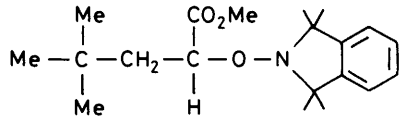
Scheme 2.

not exhibit coupling between the methylene protons and the hydroxyl proton. However, benzoylation of (**5a**) caused the 2-proton doublet to shift downfield by about 1 p.p.m., demonstrating that the hydroxy group of (**5a**) is primary. The regiochemical assignments of the head adducts (**6**) followed from the assignments for compounds (**5**).

It is interesting to note that in the ^{1}H n.m.r. (21 °C, 250 MHz) spectra of the tail adducts (**5**), the signals due to the isoindoline methyl groups appeared as four distinct singlets, whereas in the spectra of the head adducts (**6**) these signals were displayed as a broad hump. This difference is presumably due to steric effects, and appears to be a reliable indicator of the substitution at the carbon attached to the hydroxylamine oxygen atom.

The phenols (**9**) were identified by g.c.–m.s. The *para* isomers of (**9c** and **d**) were synthesized by known methods.[22,23] Their g.c. retention times and fragmentation patterns in the mass spectrometer (c.i. with methane) were shown to be identical with products in the reaction mixtures from styrene (**4c**) and α-methylstyrene (**4d**), respectively. It was assumed in each case that a second, smaller peak, near that from *para*-(**9**) in the chromatogram, was due to another isomer of (**9**), since these compounds were also readily extracted into alkaline solution.

In all our reactions, the t-butoxyamine (**3**) was a major product (Scheme 1). However in the reaction with methyl acrylate, addition of t-butyl radicals to the monomer was sufficiently rapid that the product (**10**) was also formed [29% relative to (**3**)]. This is not surprising since the reaction of a relatively unhindered and electrophilic monomer, such as methyl acrylate, with a nucleophilic radical, such as t-butyl, is expected to be highly favoured.

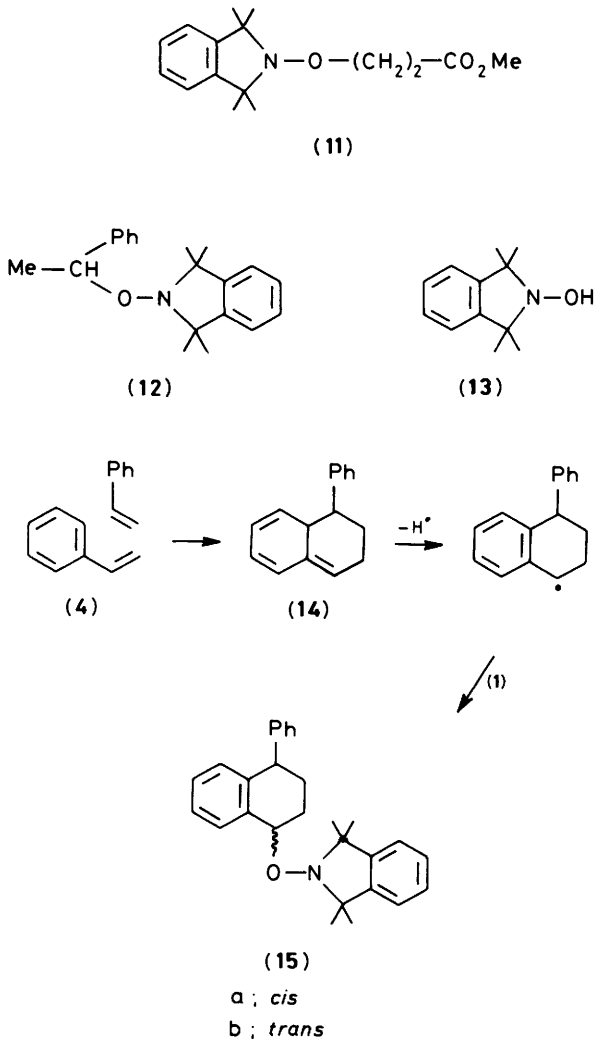


(**10**)

Another minor product (approximately 2%) isolated from this reaction was shown to contain two monomer units (by its n.m.r. and mass spectra) and was considered to be a mixture of diastereoisomers, formed by reaction of the initial hydroxyl/-methyl acrylate adduct radical with a second molecule of monomer, followed by coupling with nitroxide (**1**).

In the reactions with methyl acrylate, adduct (**11**) was produced [2.9% relative to (**3**)], and in styrene a related adduct (**12**) was detected [0.5% relative to (**3**)]. These arise from addition of hydroxylamine (**13**) to the respective monomer. The hydroxylamine (**13**) could be formed by transfer of a hydrogen atom to the nitroxide (**1**) from a t-butyl radical. In styrene, the styrene dimer (**14**) or the vinyl hydroxycyclohexadienyl radical (formed by attack of hydroxyl on the aromatic nucleus of styrene) could also serve as sources of hydrogen atoms. The addition of hydroxylamine (**13**) to styrene has been observed previously, and possibly occurs *via* a mechanism involving molecule-assisted homolysis.[24] Both adducts (**11**) and (**12**) were synthesized independently by reaction of the hydroxylamine (**13**) with the appropriate monomer.

The two diastereoisomers (**15a** and **b**) were detected in the



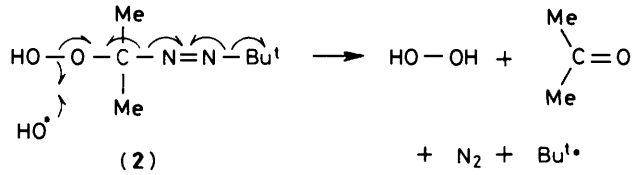
Scheme 3.

reaction in styrene [1% combined yield relative to (3)]. These arise *via* thermal dimerization of the monomer, as shown in Scheme 3.[24]

Product Yields.—Table 1 shows the relative yields of products (5)—(9) produced in the reactions of hydroxyl radicals with monomers (4a—d) in the presence of nitroxide (1). Yields have been normalized so that the total yield of hydroxyl-radical-derived products is 100%. In general, the yields of hydroxyl-derived products were slightly lower than the yields of t-butyl-derived products, possibly due to a small amount of induced decomposition of the initiator, as shown in Scheme 4. When the reaction of 2-(t-butylazo)prop-2-yl hydroperoxide in methyl acrylate was taken to essentially complete conversion of initiator (24 h at 60 °C, 8 half-lives),[21] the yield of identified products, based on initiator consumed, was *ca.* 90%. A slight degree of thermal instability however, was observed for the more sterically crowded alkoxyamine products derived from methyl methacrylate and α-methylstyrene. In particular, 2—3% of (5b and d) were found to decompose over a period of 24 h at 60 °C. Therefore, in order to reduce errors in the relative yields to an insignificant level, the reaction time with all monomers was restricted to 6.0 h and the amount of initiator consumed was calculated from its known rate of decomposition (k = 6.4 × 10^{-5} s^{-1} at 60.0 °C).[21] In these experiments the yield of

Table 1. Normalized yields of products (5)—(9) from the reactions of hydroxyl radicals with monomers (4) at 60 °C

	Product				
Monomer	(5)	(6)	(7)	(8)	(9)
Methyl acrylate (4a)	80	17		3	
Methyl methacrylate (4b)	86	6	6	2	
Styrene (4c)	87	6			7
α-Methylstyrene (4d)	83	3	5		9



Scheme 4.

products was again found to account for approximately 90% of initiator consumed.*

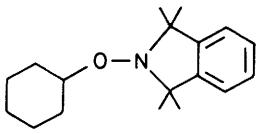
Relative rates of reaction of the four monomers with hydroxyl radicals were determined by repeating the above experiments in the presence of cyclohexane (1:2 cyclohexane to monomer), and then comparing the yields of products (5)—(9) with the yields of adduct (16), formed *via* hydrogen abstraction from cyclohexane by hydroxyl radicals. [Hydrogen abstraction by other radicals is not expected to compete with their coupling with nitroxide (1)]. From these results, the absolute rate constants for the various modes of reaction of monomers (4) with hydroxyl radicals were estimated, using a literature value of 5.42 × 10^9 l mol^{-1} s^{-1} for the rate constant for hydrogen abstraction from cyclohexane by hydroxyl radicals.[25],† These rate constants are shown in Table 2.

* One of the referees of this paper raised the question of the possible instability of phenols (9) under the reaction conditions and the possible formation of peroxyl radicals *via* hydrogen abstraction from the initiator (2). No evidence for these processes was obtained from our experiments and in general it might be expected that significant extent of the reaction of the products or initiator with hydroxyl radicals (or other radicals) would be precluded by the presence of far greater concentrations of highly reactive substrates (monomers). The concentration of styrene or α-methylstyrene is approximately 10^3 times greater than the highest concentration of phenols (9) while the rate constants for reaction of hydroxyl with phenols (9) (addition to double bond, ring attack, hydrogen abstraction) are likely to be of similar magnitude to those of reaction with styrene or α-methylstyrene (1.7 × 10^{10} and 1.4 × 10^{10} l mol^{-1} s^{-1}, respectively, see Table 2). The rate constant for hydroxyl radical attack on phenol, for example, has been estimated at 1.4 × 10^{10} l mol^{-1} s^{-1} (E. J. Land and M. Ebert, *Trans. Faraday Soc.*, 1967, **63**, 1181). Consideration of rate constants and concentrations suggests that hydrogen abstraction from the initiator (2) should also be of minor importance. The concentrations of monomers in these experiments are in the approximate range of 7—10 mol l^{-1} and their rate constants for reaction with hydroxyl radicals are of the order of 6—17 × 10^9 l mol^{-1} s^{-1} (Table 2). The average concentration of initiator (2) is approximately 0.1 mol l^{-1} while the rate constant for its donation of a hydrogen atom to hydroxyl radicals should be similar to that for t-butyl hydroperoxide which has been estimated to be 1.8 × 10^9 l mol^{-1} s^{-1} (C. Anastasi, I. W. M. Smith, and D. A. Parkes, *J. Chem. Soc., Faraday Trans.* 1, 1978, **74**, 1693). Thus, under the conditions of these experiments, the rate of reaction of hydroxyl radicals with monomers (4) is expected to be some 200—1 000 times greater than that for hydrogen abstraction from the initiator (2).

† Calculated from Arrhenius parameters given in ref. 25: A = $10^{13.15}$ cm^3 mol^{-1} s^{-1}, E_a = 634 cal mol^{-1}; for T = 333 K. These parameters were evaluated using cyclohexane and hydrogen peroxide in the vapour phase. Small changes in these values could result on using mixtures of cyclohexane and monomers (4) in the liquid phase.

Table 2. Rate constants for major reaction pathways in the reaction of hydroxyl radicals with monomers (**4**) at 60 °C

	$10^8 k_2$/l mol^{-1} s^{-1}				
Monomer	Tail addition	Head addition	Allylic abstraction	Ester abstraction	Aromatic substitution
Methyl acrylate (**4a**)	47	9.9		1.9	
Methyl methacrylate (**4b**)	93	6.5	5.3	2.0	
Styrene (**4c**)	143	13			14
α-Methylstyrene (**4d**)	120	4.8	7.4		11



(**16**)

Discussion

The results described above demonstrate that the reactions of hydroxyl radicals with monomers (**4**) are extremely rapid (Table 2), in some cases occurring at rates approaching diffusion control. This is consistent with earlier results for these monomers[19,20] (although no reaction temperatures were specified in those publications) and indeed with the known rates of hydrogen abstraction[25–27] and addition to double bonds[27,28] by hydroxyl in other systems.

Despite its extremely high rates of reaction with monomers (**4**), hydroxyl exhibits considerable selectivity in its reactions with these substrates. Thus hydroxyl radicals reacted primarily by tail addition to each monomer investigated. This was expected both from the results with other oxy-radicals such as t-butoxyl with monomers (**4**)[1–7] and from earlier work on the reactions of hydroxyl with a variety of olefins[18] including the monomers examined in the present work.[19] Head addition and hydrogen abstraction have been observed only rarely in the reactions of hydroxyl radicals with monomers (**4a**—**d**),[15] possibly due to the fact that the techniques (u.v. and e.s.r. spectroscopy) used in earlier studies are less sensitive to minor reaction pathways than our radical trapping technique. These processes have however been detected using e.s.r. spectroscopy in the reactions of hydroxyl with several allyl monomers.[18]

Addition of hydroxyl radicals to the aromatic rings of styrene and α-methylstyrene has been found in several studies to be a major reaction pathway.[15,19] It is difficult to reconcile these results with the low yields of phenols (**9**) obtained in the present work. Possibly part of the discrepancy is due to the different reaction solvents used (earlier experiments were performed in aqueous media), although a solvent effect of this magnitude would be remarkable for a free-radical reaction. However, since the method of detection used in these earlier experiments (measurement of transient absorption spectra) measures only the relative concentrations of free radicals, it may not accurately yield the relative rates of formation of those radicals, as the concentration depends not only on the rates of formation, but also on the rates of decay of the radicals.

A comparison of the relative yields and rates of formation of the various products formed in the reaction between hydroxyl radicals and monomers (**4a**—**d**) allows some comments to be made about the factors which influence these reactions. Thus the fact that tail addition is the predominant reaction for olefins with electron-withdrawing as well as electron-donating substituents is in accord with the proposition that the orientation of free-radical addition is principally controlled by steric factors[29–31] despite, in this case, the relatively small size of hydroxyl radicals. The importance of steric factors in these reactions is also shown by the slower rate of head addition to 1,1-disubstituted monomers (**4b** and **d**) relative to the corresponding, less hindered mono-substituted monomers (**4a** and **c**), respectively.

Electronic factors do however influence the reactivity of hydroxyl radicals. Thus hydroxyl reacts more rapidly with electron-rich monomers (**4c** and **d**) than with electron-deficient monomers (**4a** and **b**), in agreement with its known electrophilic nature.[13c,30] The fact that there is a higher proportion of head addition relative to tail addition for electron-deficient monomers (**4a** and **b**) than for the corresponding electron-rich monomers (**4c** and **d**) may be due to electronic factors (since the head end of the electron-deficient monomers has a higher electron density than the tail end[9]), although steric factors probably contribute to this effect (as phenyl is considered to be more bulky than methoxycarbonyl[32]). Reaction of hydroxyl with the functional substituent X of monomers (**4**) seems relatively unaffected by the presence of an α-methyl substituent. The rates of hydrogen abstraction from the ester methyls of (**4a** and **b**) are almost identical.

From the results presented here, it is possible to predict the nature, and hence the reactivity, of the end-groups which would be introduced into a polymer during initiation by hydroxyl radicals. For all four monomers discussed here, the predominant (*ca.* 80—90%) initiation-derived end-group would be HO–CH_2–. This is a versatile group, which can be readily converted into a wide variety of other functionalities. In addition, chains with hydroxyl end-groups could be used as reactive oligomers, for the synthesis of block copolymers. A small proportion of chains would contain residues derived from head addition. Those from monosubstituted monomers (**4a** and **c**) would be readily oxidisable, and may act as sites for radical attack on the polymer. Hydrogen abstraction (from methyl acrylate, methyl methacrylate, and α-methylstyrene) and hydroxylation of aromatic rings (in styrene and α-methylstyrene) lead to new unsaturated species, which could copolymerize with the original monomer, and thus alter the nature of the polymer.

Experimental

H.p.l.c. was performed using either a Waters Associates instrument fitted with a Du Pont SIL column, or a Du Pont Instruments 850 liquid chromatograph fitted with an Altex Ultrasphere ODS column, connected to a variable-wavelength u.v. detector set at 270 nm. G.c. was carried out using a Varian 4600 gas chromatograph equipped with a flame-ionization detector. The column used was 3% Silar 10C on Chromosorb Q (100—200 mesh), and helium was used as carrier gas. Peak integration for both h.p.l.c. and g.c. was performed using a Varian Vista 401 chromatography data system.

N.m.r. spectra were recorded on a Varian EM-390 (90 MHz) or Bruker WM250 (250 MHz) spectrometer, using deuteriochloroform as solvent and tetramethylsilane as internal

standard unless otherwise specified. I.r. spectra were recorded on a Unicam SP1000 or Perkin-Elmer 783 instrument, and u.v. spectra on a Unicam SP1700 spectrometer. Mass spectra were measured on a Finnigan 3300 mass spectrometer using chemical ionization with methane as reagent gas unless otherwise stated. High-resolution mass spectra were obtained on a VG Micromass 70-70 instrument coupled to an Incos 2400 data system (Dr. S. Middleton, Monash University, Melbourne). Accurate mass determinations were only made for compounds of which insufficient material was available for elemental analysis. Such compounds were shown to be pure by n.m.r. spectroscopy and by h.p.l.c. Elemental analyses were performed by the Australian Microanalytical Service, AMDEL, Melbourne. Melting points were determined using an Electrothermal apparatus or a Kofler hot-stage and are uncorrected.

Materials.—Cyclohexane and monomers (**4a**—**d**) were each passed through a short column of alumina and then distilled under nitrogen. Light petroleum refers to that fraction boiling at 60—70 °C. 1,1,3,3-Tetramethylisoindolin-2-yloxyl (**1**) was prepared by the literature procedure.[33]

2-(*t-Butylazo*)*prop*-2-*yl Hydroperoxide* (**2**).—A solution of acetone t-butylhydrazone (180 mg) in pentane (5 ml) was stirred under oxygen until oxygen uptake ceased. The solvent was removed by a stream of oxygen. The residual oil, which solidified at −20 °C, was used without further purification. It was shown to be almost pure hydroperoxide (**2**) by its n.m.r. spectrum: δ (90 MHz) 1.23 (9 H, s, Bu^t), 1.44 (6 H, s, CMe_2), and 9.4—9.7 (1 H, br, O_2H).

Reactions of Hydroxyl Radicals with Monomers (**4**).—A solution of freshly prepared hydroperoxide (**2**) (80 mg, 0.5 mmol) and nitroxide (**1**) (500 mg, 2.6 mmol) in either neat monomer (6.0 ml) or a mixture of monomer (4.0 ml) and cyclohexane (2.0 ml) was degassed using three successive freeze–pump–thaw cycles to 2 Pa, and the vessel was then sealed under vacuum. The reaction mixture was then heated at 60 °C for 6 h, and subsequently analysed by reversed-phase h.p.l.c. and by g.c.

Conditions used for h.p.l.c. analysis were: flow-rate 3.0 ml min^{-1}, 60—100% methanol in water over 60 min (for reactions of methyl acrylate); flow-rate 3.0 ml min^{-1}, 70—100% methanol in water over 45 min (for reactions of methyl methacrylate); flow-rate 2.5 ml min^{-1}, 65—100% ethanol in water over 52.5 min (for reactions of styrene); and flow-rate 3.0 ml min^{-1}, 70—100% acetonitrile in water over 45 min (for reactions of α-methylstyrene).

Preparative reactions were performed using the same proportions of reagents as described above. The crude reaction mixtures were concentrated under reduced pressure, and the residue sublimed at 60 °C and 2 Pa for 4 h, to remove the majority of the excess of nitroxide (**1**) and t-butoxyamine (**3**). The residue was then fractionated by reversed-phase h.p.l.c. as described above. The isomeric pairs (**5**) and (**6**) were more readily separated by normal-phase h.p.l.c. Thus mixtures of (**5**) and (**6**) isolated by reversed-phase h.p.l.c. were separated on normal-phase h.p.l.c. eluting with the following solvent mixtures: 17% ethyl acetate in light petroleum [adducts (**5a**) and (**6a**)], 12% ethyl acetate in light petroleum [adducts (**5b**) and (**6b**)], 9% ethyl acetate in light petroleum [adducts (**5c**) and (**6c**)], and 7% ethyl acetate in light petroleum [adducts (**5d**) and (**6d**)].

New compounds isolated in the above manner were as follows.

2-*t-Butoxy*-1,1,3,3-*tetramethylisoindoline* (**3**), m.p. 33—35 °C (from aqueous methanol) (Found: C, 77.4; H, 10.15; N, 5.5. $C_{16}H_{25}NO$ requires C, 77.7; H, 10.2; N, 5.65%); $\nu_{max.}$ (Nujol) 1 360, 1 190, 1 160, and 750 cm^{-1}; δ (90 MHz) 1.3 (9 H, s, Bu^t), 1.35, 1.5 (6 H, 2 × br s, isoindoline Me), and 7.0—7.4 (4 H, m, ArH); *m/z* (g.c.–m.s. using Dexil 300 3% on Chromosorb W) 248 (*M* + 1), 192, 176, 147, and 119.

Methyl 3-*hydroxy*-2-(1,1,3,3-*tetramethylisoindolin*-2-*yloxy*)-*propanoate* (**5a**), m.p. 70.5—71 °C (from 1:1 CCl_4–light petroleum) (Found: C, 65.55; H, 8.05; N, 5.0. $C_{16}H_{23}NO_4$ requires C, 65.5; H, 7.9; N, 4.8%); $\nu_{max.}$ (Nujol) 3 600—3 200 (OH), 1 755 (C=O), 1 205, 1 110, 1 060, and 750 cm^{-1}; δ (250 MHz) 1.42, 1.48, 1.49, 1.60 (4 × 3 H, 4 × s, isoindoline Me), 2.75 (1 H, br, OH), 3.81 (3 H, s, CO_2Me), 4.04 (2 H, d, $J_{2,3}$ 5 Hz, 3-H), 4.68 (1 H, t, $J_{2,3}$ 5 Hz, 2-H), and 7.06—7.16, 7.21—7.31 (4 H, 2 × m, ArH); *m/z* 322 (*M* + 29), 294 (*M* + 1), 278, 190, 174, 160, 147, and 119.

Methyl 3-*hydroxy*-2-*methyl*-2-(1,1,3,3-*tetramethylisoindolin*-2-*yloxy*)*propanoate* (**5b**), m.p. 90—92 °C (from light petroleum) (Found: C, 66.65; H, 8.45; N, 4.35. $C_{17}H_{25}NO_4$ requires C, 66.45; H, 8.2; N, 4.55%); $\nu_{max.}$ (Nujol) 3 500—3 100 (OH), 1 740 (C=O), 1 050, and 755 cm^{-1}; δ (250 MHz) 1.44, 1.48, 1.52, 1.56, 1.60 (5 × 3 H, 5 × s, isoindoline Me and 2-Me), 3.83 (3 H, s, CO_2Me), 4.08 (2 H, d, J_{OH} 5 Hz, 3-H), 4.37 (1 H, br d, J_3 5 Hz, OH), and 7.05—7.15, 7.2—7.3 (4 H, 2 × m, ArH); *m/z* 336 (*M* + 29), 308 (*M* + 1), 190, 174, 160, 147, and 119.

2-*Phenyl*-2-(1,1,3,3-*tetramethylisoindolin*-2-*yloxy*)*ethanol* (**5c**), m.p. 64—65 °C (from aqueous methanol, −20 °C) (Found: C, 77.1; H, 8.0; N, 4.45. $C_{20}H_{25}NO_2$ requires C, 77.15; H, 8.1; N, 4.5%); $\nu_{max.}$ (Nujol) 3 500—3 150 (OH), 1 510, 755, and 700 cm^{-1}; δ (250 MHz) 1.40, 1.45, 1.49, 1.74 (4 × 3 H, 4 × s, isoindoline Me), 3.85 (1 H, dd, $J_{1,1}$ 12 Hz, $J_{1,2}$ 2.5 Hz, 1-H), 4.20 (1 H, dd, $J_{1,1}$ 12 Hz, $J_{1,2}$ 9 Hz, 1-H), 4.65 (1 H, br, OH), 5.20 (1 H, dd, $J_{1,2}$ 9 Hz, $J_{1,2}$ 2.5 Hz, 2-H), and 7.03—7.20, 7.20—7.46 (9 H, m, ArH); *m/z* 340 (*M* + 29), 312 (*M* + 1), 192, 174, 147, and 119.

2-*Phenyl*-2-(1,1,3,3-*tetramethylisoindolin*-2-*yloxy*)*propan*-1-*ol* (**5d**), m.p. 63—65 °C (from aqueous methanol) (Found: C, 77.65; H, 8.55; N, 4.25. $C_{21}H_{27}NO_2$ requires C, 77.5; H, 8.35; N, 4.3%); $\nu_{max.}$ (Nujol) 3 600—3 150 (OH), 1 520, 1 090, 765, 755, and 710 cm^{-1}; δ (250 MHz) 1.18, 1.36, 1.47, 1.59 (3 H, 6 H, 3 H, 3 H, 4 × s, isoindoline Me and 3-H_3), 4.03 (1 H, br d, $J_{1,1}$ 13 Hz, 1-H), 4.19 (1 H, br d, $J_{1,1}$ 13 Hz, 1-H), 4.8 (1 H, br, OH), and 6.94—7.11, 7.11—7.43, 7.57—7.71 (9 H, 3 × m, ArH); *m/z* (NH_3 reagent gas) 326 (*M* + H), 208, 192, and 190.

Methyl 2-*hydroxy*-3-(1,1,3,3-*tetramethylisoindolin*-2-*yloxy*)-*propanoate* (**6a**), m.p. 64—65 °C (from pentane, −20 °C) (Found: C, 65.35; H, 7.7; N, 4.7. $C_{16}H_{23}NO_4$ requires C, 65.5; H, 7.9; N, 4.75%); $\nu_{max.}$ (Nujol) 3 650—3 300 (OH), 1 720 (C=O), 1 410, 1 230, 1 065, and 765 cm^{-1}; δ (250 MHz) 1.15—1.8 (12 H, br, isoindoline Me), 3.5 (1 H, br, OH), 3.87 (3 H, s, CO_2Me), 4.24 (1 H, dd, $J_{2,3}$ 3.1 Hz, $J_{3,3}$ 12 Hz, 3-H), 4.27 (1 H, dd, $J_{2,3}$ 3.7 Hz, $J_{3,3}$ 12 Hz, 3-H), 4.47 (1 H, br, 2-H: on irradiation at δ 3.52 give br t, $J_{2,3}$ 3.5 Hz), and 7.04—7.15, 7.15—7.3 (4 H, 2 × m, ArH); *m/z* 294 (*M* + 1), 204, 192, 190, 176, 174, 160, 131, and 119.

Methyl 2-*hydroxy*-2-*methyl*-3-(1,1,3,3-*tetramethylisoindolin*-2-*yloxy*)*propanoate* (**6b**), m.p. 70—72 °C [Found: $M^{+\bullet}$(e.i.) 307.181. $C_{17}H_{25}NO_4H^+$ requires 307.178]; δ (250 MHz) 1.05—1.7 (16 H, br, isoindoline Me, OH, and 2-Me), 3.86 (3 H, s, CO_2Me), 3.98 (1 H, d, $J_{3,3}$ 9 Hz, 3-H), 4.19 (1 H, d, $J_{3,3}$ 9 Hz, 3-H), and 7.05—7.19, 7.19—7.37 (4 H, 2 × m, ArH); *m/z* 336 (*M* + 29), 308 (*M* + 1), 248 (*M* − CO_2Me), 190, 176, 174, 160, 147, and 119.

1-*Phenyl*-2-(1,1,3,3-*tetramethylisoindolin*-2-*yloxy*)*ethanol* (**6c**), m.p. 73—74.5 °C (from aqueous methanol, −20 °C) [Found: $M^{+\bullet}$(e.i.) 311.188. $C_{20}H_{25}NO_2^{+\bullet}$ requires 311.189]; δ (250 MHz) 1.3—1.9 (12 H, br, isoindoline Me), 3.99 (1 H, dd, $J_{1,2}$ 2.5 Hz, $J_{2,2}$ 12 Hz, 2-H), 4.08 (1 H, dd, $J_{1,2}$ 9 Hz, $J_{2,2}$ 12 Hz, 2-H), 4.37 (1 H, br, OH), 5.16 (1 H, dd, $J_{1,2}$ 2.5 Hz, $J_{1,2}$ 9 Hz, 1-H), and 7.08—7.23, 7.23—7.55 (9 H, m, ArH); *m/z* 312 (*M* + 1), 294 (*M* − OH), 234 (*M* − Ph), 190, 171, 160, 147, and 119.

2-*Phenyl*-1-(1,1,3,3-*tetramethylisoindolin*-2-*yloxy*)*propan*-2-*ol* (**6d**), m.p. 63—66 °C [Found: $M^{+\bullet}$ (e.i.) 325.206. $C_{21}H_{27}NO_2^{+\bullet}$

requires 325.204]; δ (250 MHz) 1.07—1.55 (13 H, br, isoindoline Me and OH), 1.60 (3 H, s, 3-H), 4.11 (1 H, d, $J_{1,1}$ 10 Hz, 1-H), 4.20 (1 H, d, $J_{1,1}$ 10 Hz, 1-H), and 7.01—7.15, 7.15—7.48, 7.48—7.65 (9 H, 3 × m, ArH); *m/z* 326 (*M* + 1), 308 (*M* − OH), 248 (*M* − Ph), 190, 174, 160, 147, 131, 121, and 119.

Methyl 4,4-*dimethyl*-2-(1,1,3,3-*tetramethylisoindolin*-2-*yloxy*)*pentanoate* (**10**), colourless oil [Found: $M^{+\bullet}$ (e.i.) 333.232. $C_{20}H_{31}NO_3$ requires 333.230]; $\nu_{max.}$(film) 1 755 (C=O), 1 165, and 755 cm^{-1}; δ (250 MHz) 1.00 (9 H, s, Bu^t), 1.35, 1.40, 1.42, and 1.49 (4 × 3 H, 4 × s, isoindoline Me), 1.80 (1 H, dd, $J_{2,3}$ 5.5 Hz, $J_{3,3}$ 15 Hz, 3-H), 1.82 (1 H, dd, $J_{2,3}$ 8 Hz, $J_{3,3}$ 15 Hz, 3-H), 3.72 (3 H, s, CO_2Me), 4.51 (1 H, dd, $J_{2,3}$ 5.5 Hz, $J_{2,3}$ 8 Hz, 2-H), and 7.04—7.14, 7.2—7.29 (4 H, 2 × m, ArH); *m/z* 334 (*M* + 1), 318 (*M* − Me), 216, 190, 174, 160, 147, and 119.

Methyl 3-(1,1,3,3-*tetramethylisoindolin*-2-*yloxy*)*propanoate* (**11**), m.p. 95—97 °C (from light petroleum) (Found: C, 69.55; H, 8.6; N, 4.9. $C_{16}H_{23}NO_3$ requires C, 69.3; H, 8.35; N, 5.05%); $\nu_{max.}$ (Nujol) 1 730 (C=O), 1 190, 1 060, and 760 cm^{-1}; δ (250 MHz) 1.23—1.65 (12 H, br, isoindoline Me), 2.66 (2 H, t, $J_{2,3}$ 7 Hz, 2-H), 3.74 (3 H, s, CO_2Me), 4.19 (2 H, t, $J_{2,3}$ 7 Hz, 3-H), and 7.05—7.19, 7.19—7.34 (4 H, 3 × m, ArH); *m/z* 278 (*M* + 1), 262, 246 (*M* − Me), 192, 174, 160, 147, 119, and 87.

An authentic sample of this material was synthesized as follows: a solution of nitroxide (**1**) (50 mg) in ethyl acetate (10 ml) was hydrogenated at 1.5 atm over platinum oxide catalyst for 15 min. The resultant colourless solution was filtered rapidly and methyl acrylate (10 ml) added immediately to the filtrate. This solution was then degassed, and heated at 60 °C for 1 h. The solvent was removed, and the residue crystallized from light petroleum to give *the adduct* (**11**) as colourless crystals, identical (mixed m.p., n.m.r. spectrum, and h.p.l.c. retention volume) to the material isolated above.

The following known compounds were also identified, by comparison with authentic samples: methyl 2-[(1,1,3,3-tetramethylisoindolin-2-yloxy)methyl]propenoate[5] (**7b**), δ (250 MHz) 1.2—1.7 (12 H, br, isoindoline Me), 3.82 (3 H, s, CO_2Me), 4.66 (2 H, nm, 2-CH_2), 4.97, 5.36 (2 × 1 H, 2 × s, 3-H), and 7.05—7.17, 7.17—7.30 (4 H, 2 × m, ArH); 2-phenyl-3-(1,1,3,3-tetramethylisoindolin-2-yloxy)prop-1-ene[12] (**7d**); (1,1,3,3-tetramethylisoindolin-2-yloxy)methyl propenoate[3] (**8a**), δ (250 MHz) 1.35, 1.55 (12 H, 2 × br s, isoindoline Me), 5.66 (2 H, s, CO_2CH_2), 5.94 (1 H, dd, $J_{2,3}$ 10.5 Hz, $J_{3,3}$ 1.5 Hz, 3-H *trans* to ester), 6.21 (1 H, dd, $J_{2,3}$ 17 Hz, $J_{2,3}$ 10.5 Hz, 2-H), 6.54 (1 H, dd, $J_{2,3}$ 17 Hz, $J_{3,3}$ 1.5 Hz, 3-H *cis* to ester), and 7.06—7.19, 7.22—7.31 (4 H, 2 × m, ArH); (1,1,3,3-tetramethylisoindolin-2-yloxy)methyl 2-methylpropenoate[5] (**8b**), δ (250 MHz) 1.3—1.7 (12 H, br, isoindoline Me), 2.02 (3 H, nm, 2-Me), 5.68 (3 H, nm, CO_2CH_2 and 3-H), 6.27 (1 H, nm, 3-H), and 7.07—7.16, 7.21—7.32 (4 H, 2 × m, ArH); 1-phenyl-1-(1,1,3,3-tetramethylisoindolin-2-yloxy)ethane[24] (**12**), *E*- and *Z*-1-(1,1,3,3-tetramethylisoindolin-2-yloxy)-4-phenyl-1,2,3,4-tetrahydronaphthalene[24] (**15a** and **b**), and 2-cyclohexyloxy-1,1,3,3-tetramethylisoindoline[12] (**16**).

p-Hydroxystyrene (**9c**) was synthesized from *p*-acetoxyacetophenone by the method of Corson *et al.*[22] The crude product was sublimed (2 Pa, 55—65 °C) to yield the desired product as colourless crystals, m.p. 69—71 °C (lit.,[22] m.p. 68—69 °C). *p*-Hydroxy-α-methylstyrene (**9d**) was produced by vacuum pyrolysis of 2,2-bis-(4-hydroxyphenyl)propane (bisphenol A) in the presence of a catalytic amount of sodium hydroxide.[23] The crude product was purified by chromatography on a column of silica, and then crystallized from benzene–light petroleum to give the pure phenol, m.p. 83.5—84 °C (lit.,[23] m.p. 85—86 °C).

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