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Spin Trapping Chemistry of Iminyl Free Radicals

Edward G. Janzen* and Dale E. Nutter†
Departments of Clinical Studies and Biomedical Sciences, The MRI Facility, Ontario Veterinary College, University of Guelph, Guelph, Ontario N1G 2W1, Canada

The iminyl radicals formed from hydrogen atom abstraction between *tert*-butoxyl radicals and benzylidene-*N*-alkyl- or *N*-arylamines were trapped by 2-methyl-2-nitrosopropane and investigated by EPR spectroscopy. The compounds investigated were benzylidene *N*-methyl, ethyl, 1-propyl, 1-butyl, 2-methylpropyl, 1-methylethyl, 1-methylpropyl, 1-ethylpropyl, 1-methylbutyl and cyclohexyl derivative and also benzylidene *N*-phenyl, 4-tolyl, 4-fluorophenyl, 4-methoxyphenyl, 4-chlorophenyl, 4-nitrophenyl and 4-trifluoromethylphenyl derivatives. In every case the iminyl nitroxide (aminoxyl) was produced in benzene at room temperature. The nitrogen hyperfine splitting constants were in the ranges 3.39–3.56 and 9.68–9.77 G for the iminyl and nitroxyl nitrogens, respectively, for the benzylidene-*N*-alkylamines and 3.60–3.77 and 8.45–9.15 G for the iminyl and nitroxyl nitrogens, respectively, for the benzylidene-*N*-arylamines. Very little evidence was found for hydrogen atom abstraction from the alkyl groups attached to the imine function. The absolute rate constant for hydrogen atom abstraction of the iminyl hydrogen was estimated to be 1.2×10^4 M^{-1} s^{-1} based on competitive experiments with addition of *tert*-butoxyl radicals to 2-methyl-2-nitrosopropane (1.5×10^6 M^{-1} s^{-1}). This value is considerably slower than that for benzaldehyde (2.4×10^7 M^{-1} s^{-1}).

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INTRODUCTION

It is well known that free radical acyl hydrogen abstraction is readily accomplished by various radicals to produce acyl radicals:[1]

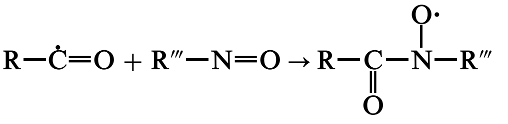
$$\mathrm{R{-}CHO + X\cdot \rightarrow R{-}\dot{C}{=}O + HX} \qquad (1)$$

The question of interest in this paper is whether imines derived from aldehydes undergo the same reaction to form iminyl radicals:[2]

$$\mathrm{R'{-}CH{=}N{-}R'' + X\cdot \rightarrow R'{-}\dot{C}{=}N{-}R'' + HX} \qquad (2)$$

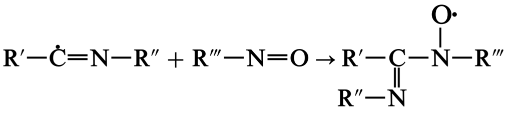
We sought to answer this question by spin trapping. A nitroso spin trap was selected to intercept the iminyl radical so as to produce an EPR distinctive spin adduct in each case.

When acyl are trapped the acyl nitroxide (aminoxyl) spin adduct spectrum usually displays only three lines with about 8 G spacing:[3]

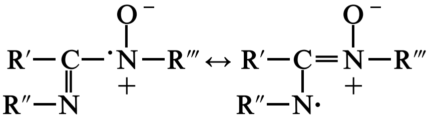


$$\mathrm{R{-}\dot{C}{=}O + R'''{-}N{=}O \rightarrow R{-}\underset{\underset{O}{\Vert}}{C}{-}\overset{\overset{O\cdot}{|}}{N}{-}R'''} \qquad (3)$$

This is because the acyl group does not allow transfer of spin from the nitroxyl function past the carbonyl carbon (a few exceptions exist, however[4]). The iminyl radical spin adduct spectrum of a nitroso spin trap would be expected to show more lines because the spin is delocalized on to the second iminyl nitrogen atom:

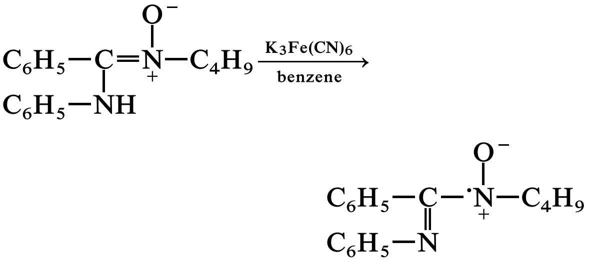


$$\mathrm{R'{-}\dot{C}{=}N{-}R'' + R'''{-}N{=}O \rightarrow R'{-}\underset{\underset{R''-N}{\Vert}}{C}{-}\overset{\overset{O\cdot}{|}}{N}{-}R'''} \qquad (4)$$



$$\mathrm{R'{-}\underset{\underset{R''-N}{\Vert}}{C}{-}{}^{\cdot}\overset{\overset{O^-}{|}}{\underset{+}{N}}{-}R''' \leftrightarrow R'{-}\underset{\underset{R''-N\cdot}{|}}{C}{=}\overset{\overset{O^-}{|}}{\underset{+}{N}}{-}R'''}$$

These iminyl nitroxides (or aminoxyls) have been detected before by EPR spectroscopy.[5] For example, the following amidine *N*-oxide was prepared synthetically and oxidized with a mild oxidizing agent:



$$\mathrm{C_6H_5{-}\underset{\underset{C_6H_5-NH}{|}}{C}{=}\overset{\overset{O^-}{|}}{\underset{+}{N}}{-}C_4H_9 \xrightarrow[\text{benzene}]{K_3Fe(CN)_6} C_6H_5{-}\underset{\underset{C_6H_5-N}{\Vert}}{C}{-}{}^{\cdot}\overset{\overset{O^-}{|}}{\underset{+}{N}}{-}C_4H_9} \qquad (5)$$

In this case three 1:1:1 triplets could be resolved which were assigned to two different nitrogen hyperfine

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* *Correspondence to*: E. G. Janzen.

† Work performed in the Department of Chemistry, University of Georgia, Athens, GA, USA.

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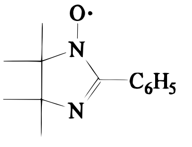
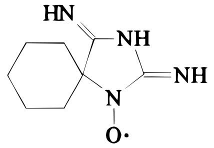
splitting constants (N-HFSCs), plus a complex pattern of multiplets believed to come from the *N*-aryl protons. The larger N-HFSC was assigned to the nitroxyl nitrogen ($a^{N}_{NO} = 8.92$ G) and the smaller to the iminyl nitrogen ($a^{N}_{NC} = 3.87$ G). The remaining HFSCs were attributed to aryl hydrogens assumed to be all approximately magnetically equivalent ($a^{H}_{o=p=m} = 0.45$ G; however, see Results section and Table 3).

Cyclic iminyl aminoxyls also give similar N-HFSCs, e.g.

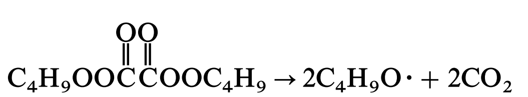


$a^{N}_{NO} = 9.10$; $a^{N}_{NC} = 4.37$ G[6] in benzene



$a^{N}_{NO} = 10.0$ G[7] plus other HFS in water

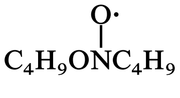
We chose to use *tert*-butoxyl radicals as the hydrogen atom-abstracting radical using di-*tert*-butyl peroxyoxalate (DBPO) as the room-temperature thermal radical source:[8]



$$C_4H_9OO\overset{O}{\overset{\|}{C}}\overset{O}{\overset{\|}{C}}OOC_4H_9 \rightarrow 2C_4H_9O\cdot + 2CO_2 \quad (6)$$

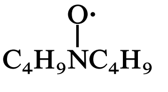
Iminyl radicals have been produced by this method before except that photolysis of *tert*-butyl peroxide at −100 °C in cyclopropane was the radical-generating system.[9]

The nitroso spin trap of choice in hydrocarbon solvents is 2-methyl-2-nitrosopropane (MNP). In this study one could expect to generate iminyl spin adducts of MNP with characteristic EPR spectra consisting of 1:1:1 nitroxyl triplets split into 1:1:1 iminyl triplets with substantially different magnitudes for the HFSCs (as discussed above). In addition, *tert*-butoxyl radicals would add to MNP to give *tert*-butoxyl-*tert*-butylaminoxyl.[10] This spin adduct has a very large N-HFSC ($a^{N}_{NO} \approx 27$ G) and the outer lines would not overlap with the expected spectra. Also present perhaps as impurities would be di-*tert*-butylaminoxyl (DTBA) and acyl-*tert*-butylaminoxyls:[11]



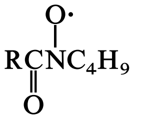
$$C_4H_9O\overset{O\cdot}{\overset{|}{N}}C_4H_9$$

$a^{N}_{NO} = 27$ G



$$C_4H_9\overset{O\cdot}{\overset{|}{N}}C_4H_9$$

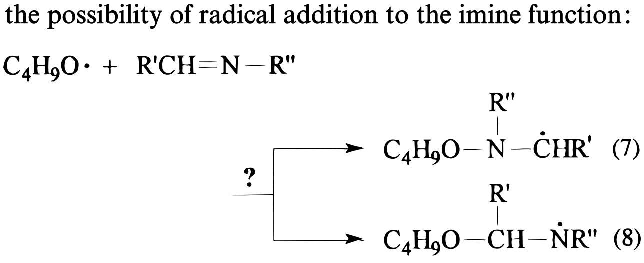
$a^{N}_{NO} = 15.5$ G



$$R\underset{\underset{O}{\|}}{C}\overset{O\cdot}{\overset{|}{N}}C_4H_9$$

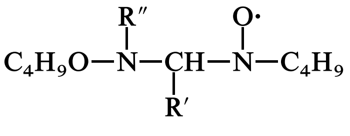
$a^{N}_{NO} = 8.0$ G

An additional question of interest in this study was the possibility of radical addition to the imine function:



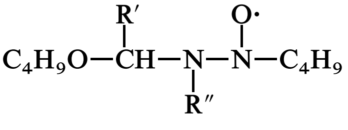
$$C_4H_9O\cdot + R'CH{=}N-R'' \overset{?}{\longrightarrow} \begin{cases} C_4H_9O-\overset{R''}{\overset{|}{N}}-\dot{C}HR' & (7) \\ C_4H_9O-\overset{R'}{\overset{|}{C}H}-\dot{N}R'' & (8) \end{cases}$$

The spin adduct of these addition products would give different EPR spectra with MNP. Reaction (7) should produce a carbon-centered adduct with approximately equivalent *β*-H and *β*-N HFSCs,[12] whereas route (8) should produce a nitrogen-centered adduct with perhaps a very small splitting from the *γ*-hydrogen[13] (see Experimental section for definition of *β*- and *γ*-positions):



$$C_4H_9O-\overset{R''}{\overset{|}{N}}-\underset{\underset{R'}{|}}{\overset{}{CH}}-\overset{O\cdot}{\overset{|}{N}}-C_4H_9$$

$a^{N}_{NO} \approx 15$ G; $a^{N}_{\beta} = a^{H}_{\beta} \approx 3$ G (estimated, not detected)



$$C_4H_9O-\overset{R'}{\overset{|}{C}H}-\underset{\underset{R''}{|}}{N}-\overset{O\cdot}{\overset{|}{N}}-C_4H_9$$

$a^{N}_{NO} \approx 17$ G; $a^{N}_{\alpha} = 2$ G (estimated, not detected)

In cases where R′ or R″ are aliphatic groups, additional sites for hydrogen atom abstraction might be present and spin adducts from these avenues of radical chemistry might be expected. In favourable cases it might be possible to estimate relative reactivities of different hydrogens in the same molecule. This kind of information might be very helpful to biological chemists struggling with identification of possible products resulting from reactions of bioradicals produced in diseased tissue.

EXPERIMENTAL

Chemicals

The imines were prepared in general by using benzaldehyde (or a substituted benzaldehyde) and the primary amine or aniline (or substituted aniline). The imine was vacuum distilled if a liquid or recrystallized from diethyl ether if a solid. The imines were stored in a vacuum desiccator over drying agent at 0.5 mmHg and kept in a refrigerator over nitrogen gas. A general method of preparation is given below for the synthesis of *C*-phenyl-*tert*-butylimine or *N*-benzylidene-*tert*-butylamine. The boiling points and/or melting points for all the imines synthesized are collected in Table 1.

For the preparation of *N*-benzylidnen-*tert*-butylamine, freshly distilled benzaldehyde (44.5 g) was added to 30.0 g of redistilled *tert*-butylamine at 2–3 °C with stirring. The stirring was continued for 30 min and the reaction mixture allowed to stand for 2 days over few grams of NaOH. The aqueous layer was removed and extracted with diethyl ether. The ether extract was added to the water-insoluble material and dried over KOH. After removal of the ether, the product was distilled to give a 60 g yield (90%), b.p. 92 °C/8 mmHg.

MNP was prepared from the oxidation of *tert*-butylamine to make 2-methyl-2-nitropropane followed by reduction to the hydroxylamine and oxidation to the nitroso dimer.[15,16]

A 325 g amount of $KMnO_4$ was stirred into 1.5 l of water and 71.4 g of freshly distilled *tert*-butylamine were added over the course of 15 min. The reaction flask was cooled to 11 °C during the addition. Note that without adequate cooling the reaction mixture can 'explode' with messy consequences. The contents were stirred and allowed to come to room temperature for 8 h, then heated to 55 °C and stirred for 18 h. The mixture was subsequently steam distilled directly from the reaction flask (b.p. 89 °C) and the distillate extracted with four 30 ml portions of diethyl ether. The ether extract was washed with 30 ml of 10% HCl and 30 ml of water and dried over anhydrous $NaSO_4$. The yield of 2-methyl-2-nitrosopropane was 55.3 g (78%) after removal of the ether.

Table 1. Boiling and melting points of *C*-phenyl-*N*-alkyl and *N*-phenylimines R′CH = NR″[a]

R′	R″	Boiling point (°C/mmHg)	Melting point (°C)
Phenyl	Methyl	60/6	
Phenyl	Ethyl	61–62/4	
Phenyl	1-Propyl	80/5	
Phenyl	1-Butyl	100/6.5	
Phenyl	2-Methylpropyl	85.5/5.9	
Phenyl	2-Propyl	88/8	
Phenyl	2-Butyl	95–96/5	
Phenyl	2-pentyl	97–98/8	
Phenyl	3-Pentyl	96–97/8	
Phenyl	Cyclohexyl	137/10	
Phenyl	*tert*-Butyl	92/8	
Phenyl	*tert*-Octyl	99–100/1.7	
Phenyl	Benzyl	130–133/1.7	
Phenyl	α-Methylbenzyl	136–138/1.5	
Phenyl	Phenyl	153–155/10	52–53
Phenyl	4-Fluorophenyl		58–59
Phenyl	4-Chlorophenyl		52–54
Phenyl	4-Methoxyphenyl		71–72.5
Phenyl	4-Tolyl	165–166/9	30–32
Phenyl	4-Trifluoromethylphenyl		51–54
Phenyl	4-Nitrophenyl		94–97
4-Methoxyphenyl	Phenyl		60.5–62
4-Tolyl	Phenyl		41–45
4-Nitrophenyl	Phenyl		42–45

[a] Taken from D. E. Nutter, Jr, Two applications of ESR spin trapping investigation of reaction of *t*-butoxy radicals with benzaldimines and photolysis of alcohol/nitrone solutions, PhD Dissertation, University of Georgia, Athens, GA (1974).

A 25 g amount of 2-methyl-2-nitrosopropane was added to 16.05 g of NH_4Cl dissolved in 300 ml of water in three-necked 500 ml flask fitted with a mechanical stirrer, then 31.7 g of zinc dust were added in small portions over 15 min. Ice was added to keep the temperature below 65 °C. When the temperature had fallen to below 45 °C the precipitated zinc oxide was filtered and the filtrate placed in a two-necked 500 ml flask.

The flask was heated to 70 °C and a solution of 23 g of K_2CrO_4 in 50 ml of 1 M H_2SO_4 were added slowly from an addition funnel. The water-bath temperature may be increased to 95 °C to drive over the nitroso product, which is a blue gas over the reaction mixture. The monomer dimerizes in the condenser and it may be necessary to warm the condenser to move the dimer to a receiving flask (which should be kept cool with an ice–methanol mixture). The white solid dimer of MNP was dried over P_2O_5 in a desiccator and recrystallized from a minimum amount of *n*-pentane. The yield was 9.7 g of MNP dimer.

Di-*tert*-butyl peroxyoxalate (DBPO)[8] was prepared as follows. **Note: DBPO is highly explosive. This material should never be scratched or jarred. DBPO should be stored in very small quantities in a deep-freeze. Do not allow it to melt and refreeze. Wear a protective face shield and gloves.** Further note: no explosion has ever been experienced during the preparation of DBPO or use of fresh DBPO. However, repeated use by removal of small samples from a stored container perhaps with slight warming followed by refreezing, or exposure to humid air and/or room light, has resulted in two violent spontaneous explosions of solid DBPO in the crystalline or glassy state.

Oxalyl chloride (3.3 ml) in 40 ml of pentane was added to a solution of 6.25 ml of pyridine and 5.6 ml of *tert*-butyl hydroperoxide in 60 ml of pentane at 0 °C. The mixture can be allowed to warm to room temperature with continuous stirring. The precipitated pyridine hydrochloride was filterd and washed with pentane. The pentane solutions were combined and washed with 10% $NaHCO_3$ solution, filtered and cooled for 5 h at −20 °C. This cold solution was placed in a dry-ice–acetone bath for 20 min and the DBPO crystals were filtered. The solid was dissolved in pentane, dried over $MgSO_4$ and cooled at −20 °C for 14 h. The crystals were filtered again, washed with cold pentane, dried by suction and stored immediately at −20 °C. The yield was 2.08 g (23.4%).

Equipment

EPR spectra were obtained using a Varian V4502 EPR spectrometer. The calibration of the magnetic field in gauss was effected by use of a Magnion Model G-502 gaussmeter with a manual field marker.

Spin trapping method

The correct amount (by weight) of the imine was placed in one arm of a U-cell[17] and dissolved in benzene. A weighed amount of MNP was added to the benzene solution of the imine. An appropriate amount of DBPO was weighed and placed as dry crystals in the second arm of the U-cell. Dry nitrogen was bubbled through the benzene solution and over the DBPO crystals for 15 min or longer. A round EPR cell was degassed with nitrogen and fitted to the U-cell for the EPR determinations. Vacuum cell preparations did not improve the linewidth of EPR spectra, and were used only for verification purposes. The additional time needed to prepare samples was not warranted for routine samples.

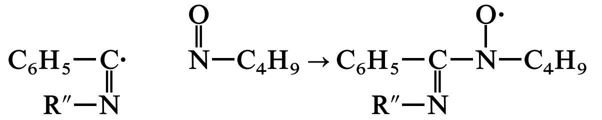
In this type of EPR spectroscopy, α-, β-, γ- or δ-positions are designated for an atom or a group one, two, three or four bonds away from the indicated spin center in the structure of the molecule.

RESULTS

N-Benzylidene-*N*-alkylamines

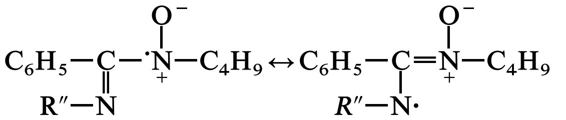
When *N*-benzylidene-*N*-alkylamines reacted with *tert*-butoxyl radicals from room temperature thermal decomposition of DBPO in benzene in the presence of MNP, EPR spectra could be obtained *in situ* for hours. The intensity of the spectra increased to a plateau concentration after about 2–3 h, and thereafter remained at that level for weeks.

The major spectrum obtained was consistent with the conjugated α-iminylaminoxyl structure expected when iminyl radicals are trapped by the nitroso function:

 (9)

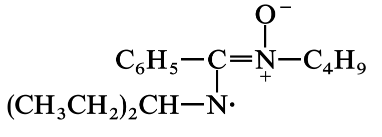
$$C_6H_5\text{—}\underset{R''\text{—N}}{\overset{\|}{C}}\cdot \quad \overset{O}{\overset{\|}{N}}\text{—}C_4H_9 \rightarrow C_6H_5\text{—}\underset{R''\text{—N}}{\overset{\|}{C}}\text{—}\overset{O\cdot}{\overset{|}{N}}\text{—}C_4H_9 \quad (9)$$

A variety of *N*-alkyl groups were investigated and the EPR spectra interpreted in terms of a delocalized π-spin system with two nitrogen hyperfine splitting constants (see Table 2); in general, the values found were as follows: nitroxyl N-HFSC, $a^{N}_{NO} \approx 9.7$ G; iminyl N-HFSC, $a^{N}_{NC} \approx 3.4$ G.



$$C_6H_5\text{—}\underset{R''\text{—N}}{\overset{\|}{C}}\text{—}\overset{O^-}{\overset{|}{\underset{+}{\dot{N}}}}\text{—}C_4H_9 \leftrightarrow C_6H_5\text{—}\underset{R''\text{—N}\cdot}{\overset{|}{C}}=\overset{O^-}{\overset{|}{\underset{+}{N}}}\text{—}C_4H_9$$

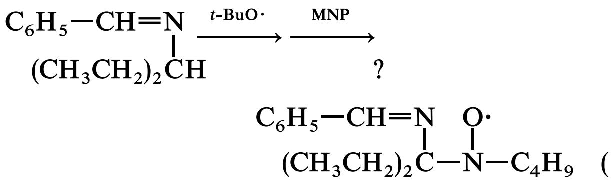
In Fig. 1 is shown the EPR spectrum from *N*-benzylidene-3-pentylamine as an example of an adduct with one hydrogen in the R″ group in the β-position to the iminyl nitrogen atom:



$$C_6H_5\text{—}\underset{(CH_3CH_2)_2CH\text{—N}\cdot}{\overset{|}{C}}=\overset{O^-}{\overset{|}{\underset{+}{N}}}\text{—}C_4H_9$$

Inspection of the main pattern of lines reveals nine groups of multiplets arranged as three 1:1:1 triplets. The larger triplet splitting is assigned to the nitroxyl nitrogen ($a^{N}_{NC} \approx 9.7$ G) and the smaller triplet splitting is assigned to the iminyl nitrogen ($a^{N}_{NC} \approx 3.4$ G). These lines are again split into a doublet of 1:2:1 triplets. This further splitting is assigned to one β-hydrogen [$a^{H}_{R(\beta)} = 0.60$ G] and two γ-hydrogens [$a_{R(\gamma)} = 0.35$ G]. Although there are in total four γ-hydrogens, apparently only two give resolvable hyperfine splitting. This situation could be complicated because the γ-methylene hydrogens are also enantiotopic.

The EPR spectrum in Fig. 1 also shows at least two more triplets, one undoubtedly from di-*tert*-butylaminoxyl (DTBA), $a^{N} = 15.35$ G, and the other perhaps from trapping the carbon-centered radical derived from abstraction of the β-hydrogen in the R″ group:

 (10)

$$\underset{(CH_3CH_2)_2CH}{C_6H_5\text{—CH=}\overset{}{\underset{|}{N}}} \xrightarrow{t\text{-BuO}\cdot} \xrightarrow{\text{MNP}} ? \quad C_6H_5\text{—CH=}\underset{|}{N}\ \ \underset{|}{O}\cdot \atop (CH_3CH_2)_2C\text{—N—}C_4H_9 \quad (10)$$

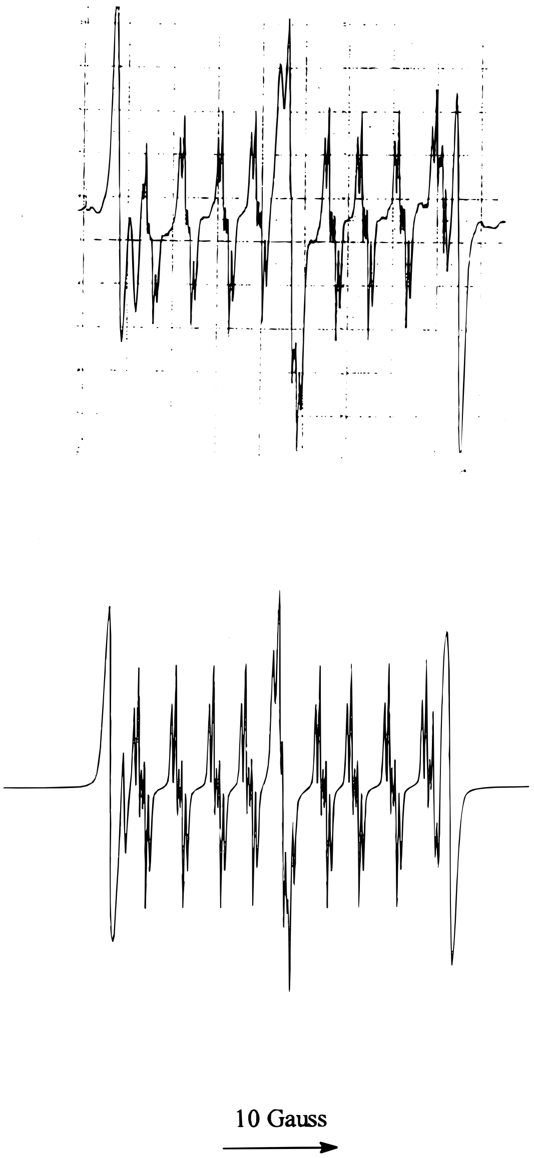


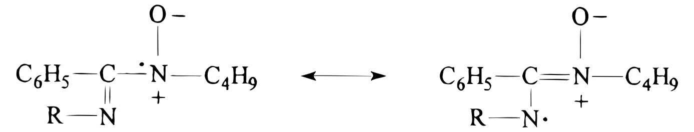
Figure 1. EPR spectrum from 0.005 M DBPO, 1 M *N*-benzylidene-3-pentylamine and 0.01 M MNP in benzene with computer simulation using: main component $a^{N}_{NO} = 9.7$ G; $a^{N}_{NC} = 3.4$ G; $a^{H}_{R(\beta)} = 0.6$ G; $a^{H}_{R(\gamma)} = 0.35$ G (2H); second component $a_N = 15.35$ G; third component $a_N = 14.75$ G; $a^H = 1.3$ G; relative area: 0.53, 0.42, 0.05.

The latter N-HFSC is 14.75 G, which is slightly smaller than the N-HFSC for DTBA. The difference is consistent with the presence of an electron-withdrawing iminyl group in the β-position. However, additional small HFSs would be expected and a 1.3 G doublet provides a good fit in the computer-simulated spectrum. Perhaps the dihedral angle is not favourable for N-HFS in this case. It should be noted that this assignment is speculative and no proof of structure is available at this time.

The other examples of *N*-benzylidene-*N*-alkylamines with one β-hydrogen in the R group give similar EPR spectra (i.e. R″ = isopropyl, *sec*-butyl, *sec*-pentyl and cyclohexyl). The appropriate EPR parameters are given in Table 2.

In Fig. 2 is shown the EPR spectrum from *N*-benzylideneisobutylamine as an example of an adduct

Table 2. Hyperfine splitting constants from MNP spin adducts of *N*-alkyl-*C*-phenyliminyl radicals[a]



R	a^N_{NO}	a^N_{NC}	$a^H_{R(\beta)}$	$a^H_{R(\alpha)}$	Fig.
CH_3	9.70	3.53	5.34 (3H)	—	3
CH_3CH_2	9.68	3.45	4.62 (2H)	—	—
$CH_3CH_2CH_2$	9.73	3.47	5.10 (2H)		
$CH_3CH_2CH_2CH_2$	9.72	3.47	5.03 (2H)	—	—
$(CH_3)_2CHCH_2$	9.84	3.36	5.66 (2H)	—	2
$(CH_3)_2CH$	9.78	3.56	1.08 (1H)	—[b]	—
$CH_3CH_2C(CH_3)H$	9.74	3.39	0.78 (1H)	0.23 (4H)	—
$(CH_3CH_2)_2CH$	9.70	3.40	0.60 (1H)	0.35 (2H)	1
$CH_3CH_2CH_2C(CH_3)H$	9.75	3.44	0.81 (1H)	0.21 (4H)	—
Cyclohexyl	9.75	3.42	0.94 (1H)	—[b]	—

[a] EPR spectra obtained in benzene at room temperature from 1 M *N*-benzylidene-*N*-alkylamine, 0.005 M DBPO and 0.01 M MNP; hyperfine splittings constants measured in gauss.

[b] Additional splittings observed but not resolved.

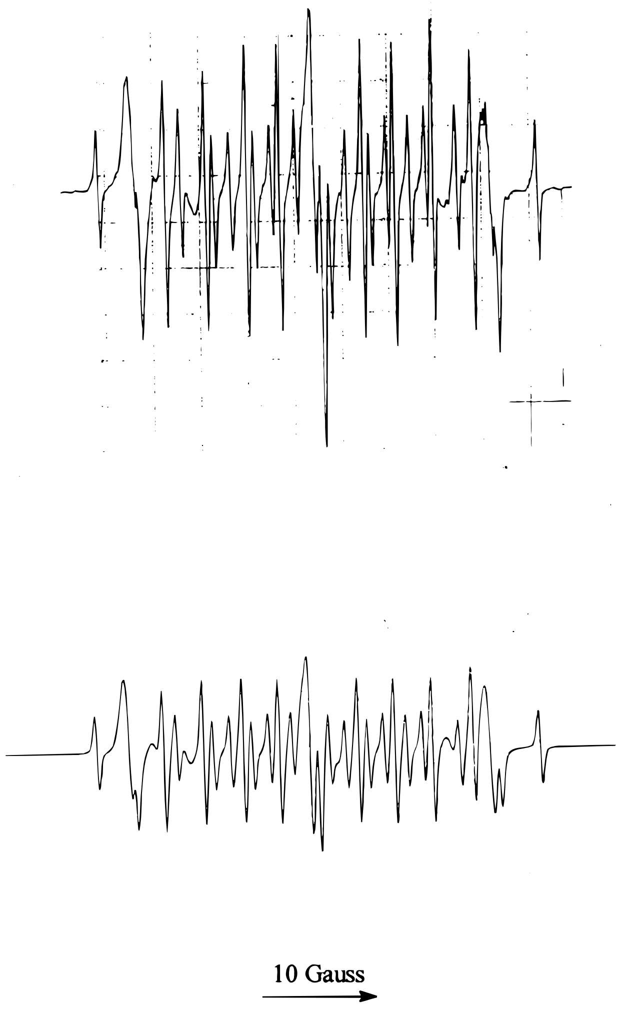
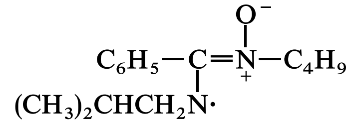


Figure 2. EPR spectrum from 0.005 M *N*-benzylideneisobutylamine and 0.01 M MNP in benzene with computer simulation using: main component a^N_{NO} = 9.84 G; a^N_{NC} = 3.36 G; $a^H_{R(\beta)}$ = 5.66 G (2H); second component a_N = 15.36 G; third component a_N = 12.60 G; a^H = 2.50 G (1H); relative area: 0.50, 0.39, 0.11.

with two hydrogens in the R″ group present in the *β*-position to the iminyl nitrogen atom:

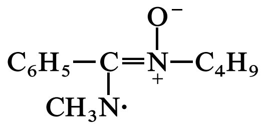


$$C_6H_5-C(=N^+(O^-)-C_4H_9)-\dot{N}CH_2CH(CH_3)_2$$

The spectrum looks complicated but if the large DTBA triplet is ignored, the remaining 24 lines are reasonably well resolved into intensity '1' and intensity '2' lines. In fact, three groups of 1 : 2 : 1 triplets of 1 : 1 : 1 triplets can be found consistent with two magnetically equivalent *β*-methylene hydrogens, $a^H_{R(\beta)} = 5.66$ G (2G), and one iminyl nitrogen, $a^N_{NC} = 3.36$ G (27 lines total expected; three lines lost under the large DTBA triplet). Other lines near the DTBA triplet hint at additional adducts produced by MNP [$a^N = 12.60$; $a^H = 2.50(1H)$ G], but these products were not investigated further. A computer simulation under the spectrum in Fig. 2 accounts for all the components described.

The other examples of *N*-benzylidene-*N*-alkylamines with two *β*-hydrogens in the R″ group gave similar EPR spectra (i.e. R = ethyl, *n*-propyl and *n*-butyl). The appropriate EPR parameters are given in Table 2.

In Fig. 3, the EPR spectrum from *N*-benzylidenemethylamine is shown. Here there are three *β*-hydrogens in the R″ group next to the iminyl nitrogen atom:



$$C_6H_5-C(=N^+(O^-)-C_4H_9)-\dot{N}CH_3$$

In this case 33 of the possible 36 lines are visible. The resolution is adequate for recognition of 1 : 3 : 3 : 1 multiplets. In addition to the large triplet due to DTBA, another triplet with a smaller N-HFSC, namely $a_N \approx 8.0$ G due to benzoyl-*tert*-butylaminoxyl is detected. This nitroxide comes from benzaldehyde impurity in the

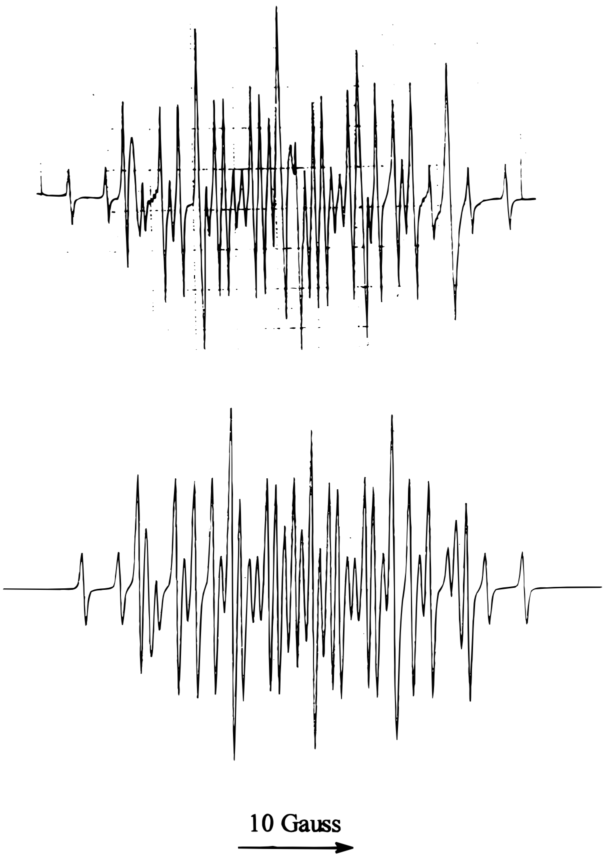
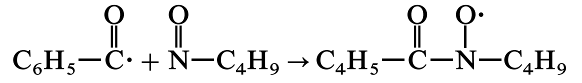


Figure 3. EPR spectrum from 0.005 M DBPO, 1 M *N*-benzylidenemethylamine and 0.01 M MNP in benzene with computer simulation using: main component $a^{\mathrm{N}}_{\mathrm{NO}} = 9.70$ G; $a^{\mathrm{N}}_{\mathrm{NC}} = 3.53$ G; $a^{\mathrm{H}}_{\mathrm{R}(\beta)} = 5.34$ G (3H); second component $a_{\mathrm{N}} = 15.36$ G; third component $a_{\mathrm{N}} = 8.01$ G; relative area: 0.75, 0.14, 0.1.

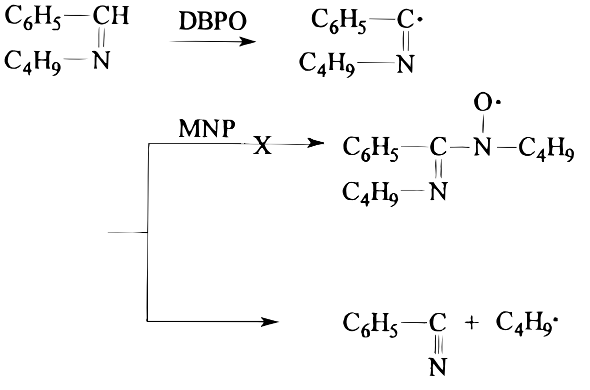
imine reacting with the *tert*-butoxyl radicals followed by addition to MNP:



$$C_6H_5-\overset{\overset{\displaystyle O}{\|}}{C}\cdot + \overset{\overset{\displaystyle O}{\|}}{N}-C_4H_9 \rightarrow C_4H_5-\overset{\overset{\displaystyle O}{\|}}{C}-\overset{\overset{\displaystyle O\cdot}{|}}{N}-C_4H_9 \quad (11)$$

The computer simulation under the spectrum in Fig. 3 accounts for the *N*-methylimine adduct using the EPR parameters shown in Table 2, plus DTBA and benzoyl-*tert*-butylaminoxyl in small amounts.

The compounds where R″ is *N*-*tert*-butyl, *N*-benzyl and *N*-α-methylbenzyl constitute a special case. In the first example when *N*-benzylidene-*N*-*tert*-butylamine was reacted with *tert*-butoxyl radical in the presence of MNP, no spectrum consistent with the 'normal' spin adduct was detected [Eqn (12)]:

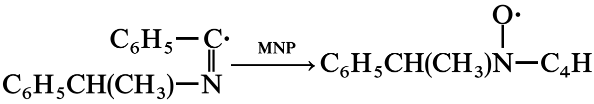


(12)

(13)

Instead, a very strong EPR spectrum due to DTBA was detected, indicating that β-cleavage of the intermediate iminyl radical occurs [eqn (13)] to produce *tert*-butyl radicals and benzonitrile (cyanobenzene) before spin trapping with MNP can be accomplished (spectrum not shown). Also, when *N*-benzylidene-*N*-*tert*-octylamine was subjected to the same conditions, a triplet pattern consistent with *tert*-octyl-*tert*-butylaminoxyl was produced, with little else. This kind of β-cleavage of iminyl radicals has been proposed by Ohta and Tokumaru[18] to account for their observations.

When *N*-benzylidene-*N*-α-methylbenzylamine was investigated, a strong EPR spectrum composed of a triplet of doublets was detected with DBPO and MNP. By allowing ethylbenzene in a different experiment to react with *tert*-butoxyl radicals from DBPO in the presence of MNP, the same spectrum was obtained. Therefore, the assignment of α-methylbenzyl-*tert*-butylaminoxyl to the first EPR spectrum could be verified (spectra not shown):



$$\begin{matrix} C_6H_5-C\cdot \\ \| \\ C_6H_5CH(CH_3)-N \end{matrix} \xrightarrow{\text{MNP}} C_6H_5CH(CH_3)\overset{\overset{\displaystyle O\cdot}{|}}{N}-C_4H_9$$

$a^{\mathrm{N}} = 14.95$; $a^{\mathrm{H}}_{\beta} = 3.59$ G

$$C_6H_5CH_2CH_3 \xrightarrow{\text{DBPO}} \xrightarrow{\text{MNP}} \qquad (14)$$

$a^{\mathrm{N}} = 14.87$; $a^{\mathrm{H}}_{\beta} = 3.58$ G

This spin adduct is also the product of spin trapping methyl radical by *C*-phenyl-*N*-*tert*-butylnitrone (PBN):[19] $a^{\mathrm{N}} = 14.81$; $a^{\mathrm{H}}_{\beta} = 3.48$ G.

When *N*-benzylidene-*N*-benzylamine was subjected to *tert*-butoxyl radicals from DBPO in benzene in the presence of MNP, a relatively weak EPR spectrum was observed. The strongest components after 10 min were DTBA, *tert*-butoxyl-*tert*-butylaminoxyl ($a^{\mathrm{N}} = 27.1$ G), an unknown triplet with $a^{\mathrm{N}} \approx 10.38$ G (see later) and a small amount of benzyl-*tert*-butylaminoxyl ($a^{\mathrm{N}} = 14.8$; $a^{\mathrm{H}}_{\beta} = 7.4$ G). After 8 h the benzyl-*tert*-butylaminoxyl pattern was still discernible as a weak set of lines dwarfed by a large DTBA triplet. During the interim period (e.g. after 1 h), spectra were obtained which contained more patterns of lines but the signal intensity and resolution were insufficient for good spectral analysis to be accomplished (spectra not shown).

In comparing the last three compounds, it is clear that the release of the R″ group as an MNP detectable free radical produced from β-cleavage of the *N*-benzylidene-*N*-alkyliminyl radical follows the following order: *tert*-butyl > α-methylbenzyl > benzyl.

The question of hydrogen atom abstraction from a site remote from the iminyl position is also of interest. Inspection of the EPR spectra obtained from the *N*-alkylimines indicated that typically another smaller triplet of moderate intensity was present which could be due to the MNP adduct of an alkyl adduct with very small β-H HFSs. The following data were gleaned from the spectra but estimates are very approximate:

	$a^{\mathrm{N}}_{\mathrm{NO}}$(G)	Notes
methyl	—	only a small amount of DTBA
ethyl	—	very little evidence; perhaps only DTBA

propyl	14.1	~4 × weaker than iminyl spin adduct
isobutyl	15.5	~9 × weaker than iminyl adduct
2-butyl	14.2	~3 × weaker than iminyl adduct
3-pentyl	14.1	~9 × weaker than iminyl adduct

Although these spectra cannot be assigned with certainty at this time, it is likely that spin adducts from alkyl group hydrogen atom abstraction occurred. All but the *n*-propyl case are examples where a tertiary hydrogen exists in this group. The peak heights are comparable in size but the fact that the iminyl adduct has many more lines makes this nitroxide stronger in molar concentration.

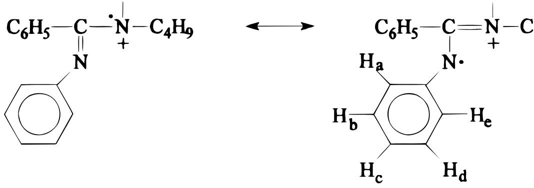
N-Benzylideneanilines

After mixing *N*-benzylideneanilines or substituted *N*-benzylideneanilines in benzene with MNP and DBPO, rich EPR spectra were obtained *in situ* in the EPR spectrometer cavity. Although the splitting patterns are complex, they could be analyzed in terms of one aminoxyl N-HFS of about 9 G (a^{N}_{NO} = 8.45–9.15 G, see Table 3) and another nitrogen triplet with HFS ≈ 3.7 G (a^{N}_{NC} 3.6–3.77 G, see Table 3). Further splitting is difficult to resolve completely.

By substitution in the anilino phenyl ring it could be determined that the detected multiplets originate from proton hyperfine splitting in this ring. However, the assignment to specific positions in the ring is not possible. It is assumed that limited rotation of this phenyl ring may make the positions in the *ortho* and *meta* positions unequal. Thus in *N*-benzylidene aniline the spin adduct might have five different aryl hydrogen HFSs:

In this work, the EPR spectrum obtained from the MNP adduct of the unsubstituted *N*-benzylideneaniline was computer simulated and the best fit was found when three aryl protons were assumed to have the same HFS (namely $a^{H} = 0.52$ G, see Table 3) plus two additional smaller but equal aryl HFSs (almost half, namely $a^{H} = 0.31$ G, see Table 3). The EPR spectrum due to this aminoxyl has been published before by Aurich *et al.*[20] but the aryl hydrogen splittings were given as 0.45 G and all positions equal (see Table 3). Since Aurich *et al.*'s value is the average between the larger and smaller numbers we report, perhaps with slightly better resolution obtained in this work, the differences between the HFSs from different positions in the ring could be distinguished. This makes it unnecessary to theorize about the possibility that both π- and σ-delocalization of spin at the same time produces equal HFS in all positions of the *N*-aryl ring in these aminoxyl radicals.[20]

In the case of *N*-benzylidene-4-fluoroaniline, the EPR spectrum was obtained was considerably different. Aurich *et al.*[20] also reported this spectrum and the assignments of these spectra (theirs and ours) agree well (see Table 3). In this case, because the hyperfine splitting patterns are consistent with one relatively large HFS (1.1 G), two medium-sized HFSs (but similar to the larger HFS found in the unsubstituted example, namely 0.52 G) and two relatively small HFSs (0.31 G), it is suggested that the HFSs from the *ortho* and *para* positions are approximately equal ($a^{N}_{o-p} \approx 0.55$ G) and the HFSs from the meta positions are smaller and also approximately equal ($a^{H}_{m} \approx 0.38$ G).



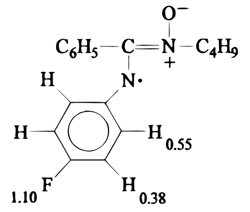
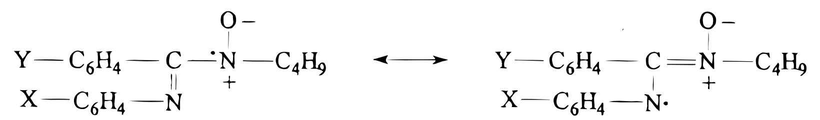


Table 3. Hyperfine splitting constants from MNP spin adducts of *N*-aryl-*C*-phenyliminyl radicals[a]



$$\mathrm{Y{-}C_6H_4{-}\underset{\underset{X{-}C_6H_4{-}N}{\|}}{C}{-}\overset{\overset{O^-}{|}}{\dot{N}}^{+}{-}C_4H_9 \longleftrightarrow Y{-}C_6H_4{-}\underset{\underset{X{-}C_6H_4{-}N\cdot}{|}}{C}{=}\overset{\overset{O^-}{|}}{N}^{+}{-}C_4H_9}$$

X	Y	a^{N}_{NO}	a^{N}_{NC}	$a^{H}_{N-C_6H_4-X}$	Ref.
H	H	8.97	3.64	0.52 (3H); 0.32 (2H)	—
H	H	8.92	3.68	0.45 (5H)	—
F	H	9.1	3.66	0.56 (2H); 0.315 (2H); 1.06 (1F)	20
F	H	8.84	3.68	0.55 (2H); 0.3 (2H); 1.10 (1F)	—
CH_3	H	8.96	3.66	0.47 (7H)	—
CH_3	H	8.96	3.68	0.5 (7H)	—
CH_3O	H	8.95	3.60	0.68 (2H); 0.34 (2H)	—
Cl	H	8.78	3.66	0.53 (2H); 0.36 (2H)	—
NO_2	H	8.45	3.77	0.41 (multiplet spacing)[b]	—
CF_3	H	8.70	3.72	0.40 (2H + 3F); 0.35 (2H)	—
H	CH_3	9.04	3.68	0.41 (multiplet spacing)[b]	—
H	CH_3O	9.15	3.70	0.40 (multiplet spacing)[b]	—

[a] EPR spectra obtained in benzene at room temperature from 1 M *N*-benzylidene-*N*-arylamine, 0.005 M DBPO and 0.01 M MNP; hyperfine splittings are measured in gauss.

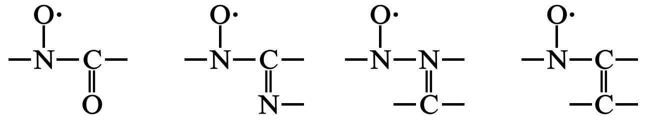
[b] Spacing of peaks in multiplet; resolution inadequate for analysis.

Similar conclusions can be reached about the 4-methyl, 4-methoxy, 4-chloro and 4-nitroaniline derivatives (see Table 3), although sufficient resolution was not available in every case to distinguish between *ortho* and *meta* positions.

Unassigned EPR spectra

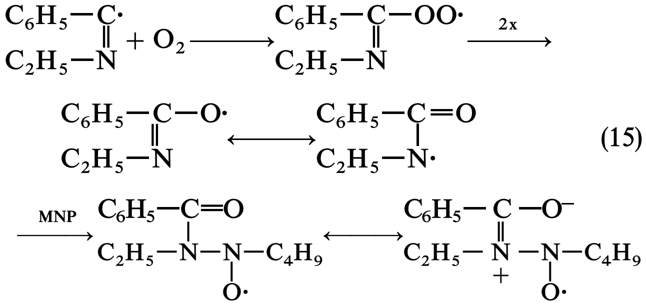
In all the experiments described so far an additional EPR component was present in the spectrum when oxygen was incompletely removed from the solution or when oxygen was purposely added by bubbling through the benzene solution. This spectrum was characterized by a 10–11 G triplet with a very broad linewidth, sometimes revealing some extra splittings. A total of 23 benzylideneamines including those in Tables 2 and 3 plus the *N*-*tert*-butyl, *N*-*tert*-octyl, *N*-benzyl and *N*-(α-methylbenzyl) derivatives showed this kind of triplet with $a^N = 10.2$–10.96 G. In some cases evidence of additional splitting could be resolved which reflected the number of magnetically equivalent hydrogens in the *N*-alkyl group, e.g. 0.8 G quartets from *N*-methyl and 0.5 G triplets from *N*-ethyl and *N*-propyl groups.

Proposals speculating about a structure for this aminoxyl must take into account the peculiar size of the nitrogen triplet hyperfine splitting and the lack of additional significant splitting from another nucleus. The range of N-HFS as one considers possible aminoxyl structures might be as follows:



a^N_{NO} 7.8–8.0 G a^N_{NO} 9.7–9.9 G 10–11 G? 12.5 G[21]

A possible suitable structure might be produced if a nitrogen-centered radical which has been trapped by MNP has a double bond to carbon in its most prevalent resonance form. A reaction sequence which could create this kind of aminoxyl is shown below:

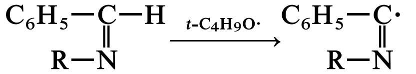


(15)

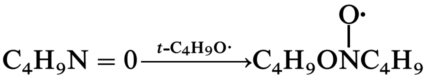
The β-position to the nitroxyl function in acyl nitroxides is known to have very little (if any) spin and the small spin on the α-nitrogen atom in the proposed structure might also give only a very small hyperfine splitting from the methyl or ethyl methylenic hydrogens in the other β-position (0.8–0.5 G). The iminyl radical should react with oxygen rapidly to form the peroxyl radical. Peroxyl radicals are known to couple, and the tetraoxides produced dissociate to give oxyl radicals and oxygen. In this case the oxyl radical proposed is actually the acylamino radical, which should be readily trapped by MNP to give the spin adduct indicated.

Relative rate constants

Since MNP adducts of the iminyl and *tert*-butoxyl radicals are produced simultaneously in benzene the relative rate constants of hydrogen atom abstraction can be determined if the addition of *tert*-butoxyl radicals to MNP is known, i.e. if reactions (16) and (17) are in competition:



$$C_6H_5-C(H)=N-R \xrightarrow{t\text{-}C_4H_9O\cdot} C_6H_5-\dot{C}=N-R \quad (16)$$



$$C_4H_9N=0 \xrightarrow{t\text{-}C_4H_9O\cdot} C_4H_9ON(O\cdot)C_4H_9 \quad (17)$$

the following equation applies:

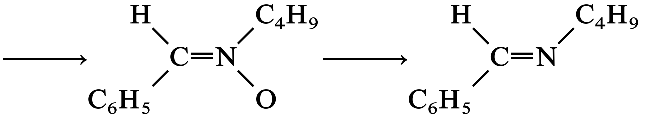
$$\frac{d(SA_{17})/dt}{d(SA_{16})/dt} = \frac{k_{17}[C_4H_9NO]}{k_{16}[\text{imine}]}$$

where SA = spin adduct.

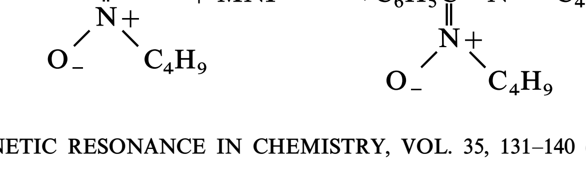
Using the equation $A = bhw^2$, where A = area of peak, h = peak height, w = linewidth measured horizontally from maximum to minimum of the first derivative peak and b is the line multiplicity of the splitting pattern (e.g. $b = 3$ for a 1:1:1 triplet), the change in spin adduct intensity for the imine where R'' = methyl can be monitored in an experiment performed in the normal way. For the MNP *tert*-butoxyl adduct $b = 3$, $w^2 = 0.36$ and $k_{17} = 1.5 \times 10^6$ M^{-1} s^{-1};[22] therefore, for the MNP iminyl adduct, $b = 27$, $w^2 = 0.058$ and $k_{16} = 1.2 - 10^4$ M^{-1} s^{-1} (calculated). This estimate for iminyl hydrogen atom abstraction is considerably slower than for the same reaction with benzaldehyde. With benzaldehyde, *tert*-butoxyl radicals abstract the acyl hydrogen at a rate of 2×10^7 M^{-1} s^{-1}.[11]

Hydrogen atom abstraction from nitrones

It was of interest to compare the possibility of hydrogen atom abstraction from the nitronyl function with the same hydrogen atom in the iminyl compound of similar structure:



If some radical species was capable of abstracting a nitronyl hydrogen, the resulting radical would give a nitronyl nitroxide spin adduct with MNP:[23]



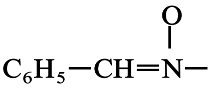
(18)

Since these nitronyl nitroxides have considerable stability, one would expect the presence of even a small amount of nitronyl hydrogen abstraction to be detectable.

Experiments in which DBPO was reacted with *C*-phenyl-*N*-*tert*-butylnitrone in the presence of MNP showed no evidence of nitronyl nitroxide formation even after several days. Only *tert*-butoxyl addition to form the spin adduct occurred.[22]

DISCUSSION

The special energetics of radical approach to a nitrone function have been explored recently in the case of a nitrone[24] and the route towards carbon bond formation through additions has been clearly delineated theoretically. When *tert*-butoxyl radicals react with styrene the process also seems to be addition.[25] However, with benzaldehyde and benzylidene imines the reaction is only hydrogen atom abstraction, as illustrated in this work. No evidence for addition was found:



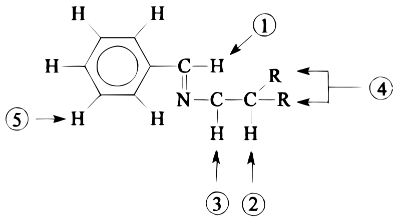
$C_6H_5{-}CH{=}CH_2$	$C_6H_5{-}CH{=}\overset{\overset{O}{\vert}}{N}{-}$	radical addition only
$C_6H_5{-}CH{=}O$	$C_6H_5{-}CH{=}N{-}$	hydrogen atom abstraction only

This subtle difference would seem to warrant further study. Perhaps the transition states for the two former cases are polarized as the *tert*-butoxyl radical approaches so that addition is favored over hydrogen atom abstraction. If polar transition states do not develop, perhaps the only other route remaining is hydrogen atom abstraction.

The fact that hydrogen atom abstraction from the *N*-alkyl group occurs is also interesting. That the amount of spin adduct formed is comparable to the amount from iminyl radicals might not have been expected. This would indicated that similar absolute rate constants apply. Thus, the absolute rate constant for hydrogen atom abstraction from toluene and cyclohexane has been estimated at 2×10^4 and 1×10^5 M^{-1} s^{-1}, respectively.[26] The value for iminyl hydrogen abstraction in this work is 1.2×10^4 M^{-1} s^{-1}. The estimate from EPR spectral intensity comparison would place abstraction from remote hydrogens in the *N*-alkyl group at about 3–9 times less. However, trapping bulky tertiary alkyl radicals might be slower than trapping iminyl radicals. Therefore, these values may be underestimated.

CONCLUSIONS

This study has contributed information about the probability of abstracting a hydrogen atom from a given site in a series of benzylidene-*N*-alkylamines using spin trapping methodology. On the basis of this work, it is possible to predict that *tert*-butoxyl radicals will react by hydrogen atom abstraction in the following order (1 is the fastest, 5 is the slowest):



However, this prediction is speculative for hydrogens at positions 2, 3 and 4 because the EPR spectra for secondary adducts were not explicitly analyzed and assigned. No EPR spectra consistent with aryl radical adducts were found; therefore, position 5 must be the least likely.

Acknowledgements

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