SYNTHESIS OF IMIDAZOLE DERIVATIVES FROM α-HYDROXYLAMINO OXIMES (REVIEW)

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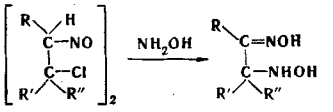
Data on the synthesis of imidazoline N-oxides from α-hydroxylamino oximes and α-amino oximes are collected in this review. The transformations of imidazoline N-oxides into N-oxides of imidazoles and 2H- and 4H-imidazoles and stable iminoxyl radicals and some properties of the compounds formed are examined.

At the start of the 20th century, a number of α-hydroxylamino oximes with an NHOH group attached to a tertiary carbon atom were obtained in a study of compounds of the terpene series [1-3]. A systematic study of such compounds was commenced only after more general methods for the preparation of α-hydroxylamino oximes had been found [4-7]. It was shown that they have peculiarities that are associated with the vicinal orientation of two reactive groups [4, 8], in particular, the ability to form heterocyclic systems with two nitrogen atoms in the ring: imidazoline and imidazole N-oxides [9, 10], 5-hydroxy-5,6-dihydro-4H,1,2,5-oxadiazines [9], and pyrazine N,N-dioxides [11].

On the other hand, recently interest has increased with respect to the chemistry of heterocyclic N-oxides [12, 13], including imidazole and benzimidazole N-oxides [14], which are more reactive than the bases themselves. Some benzimidazole N-oxides display the properties of central nervous system depressants [15]. Since it is difficult to obtain imidazoline, imidazole, and benzimidazole N-oxides by direct oxidation [14, 16, 17], methods based on the heterocyclization of α-substituted oximes and hydroxylamine derivatives are used for their synthesis [12, 14, 18-20]. In the present review, the use of α-hydroxylamino oximes for the synthesis of imidazoline and imidazole N-oxides and some properties and reactions of the compounds obtained are examined.

Preparation of α-Hydroxylamino Oximes

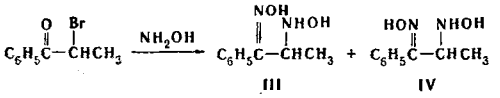
A general method for the synthesis of α-hydroxylamino oximes with an NHOH group attached to a secondary or tertiary carbon atom (I) is the reaction of dimeric olefin nitrosochlorides (II) [21] with hydroxylamine [1, 2, 6, 22].



II I

R=H, Alk, R′, R″=H, Alk, Ar; R—R′=(CH$_2$)$_n$

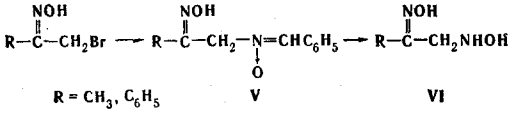
In a number of cases, α-hydroxylamino oximes can be obtained (as a mixture of syn and anti isomers III and IV) by reaction of α-halo ketones with excess hydroxylamine [5].



III IV

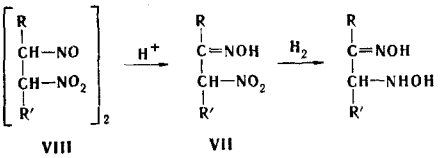
Novosibirsk Institute of Organic Chemistry, Siberian Branch, Academy of Sciences of the USSR. Translated from Khimiya Geterotsiklicheskikh Soedinenii, No. 10, pp. 1299-1310, October, 1973. Original article submitted February 27, 1973.

The introduction of a hydroxylamino group in the protected form [23] into the α-halo ketone oxime molecule makes it possible to obtain primary α-hydroxylamino oximes. Thus the action of anti-benzaldoxime on α-halo ketone oximes in the presence of sodium ethoxide gives nitrones V, which give α-hydroxylamino oximes VI on treatment with hydrazine [7].



R = CH_3, C_6H_5 V VI

Sheinbaum has proposed a method for the synthesis of α-hydroxylamino oximes by catalytic reduction of α-nitro oximes (VII), which are formed during prototropic isomerization of the products (VIII) of addition of N_2O_3 to olefins [11].

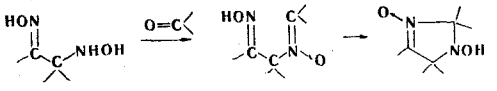


VIII VII

Since the configuration of the oxime group depends mainly on steric factors [24], α-hydroxylamino oximes with an anti configuration of the oxime group are primarily formed in the synthesis. The syn isomer (III) can be converted to the anti isomer (IV) by the action of acid [25].

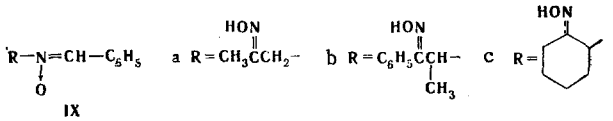
Reaction of α-Hydroxylamino Oximes with Aldehydes, Ketones, and Ethyl Orthoformate. Ring-Chain Tautomerism of 1-Hydroxy-Δ^3-imidazoline 3-Oxides

anti-α-Hydroxylamino oximes react with aldehydes, ketones, and ethyl orthoformate to give N-(2-oximinoalkyl)nitrones (A), 1-hydroxy-Δ^3-imidazoline 3-oxides (B), or tautomeric mixtures of them. Nitrones A are the primary products of these reactions. In the absence of conjugation and steric hindrance, the nitrone grouping interacts with the sterically accessible nitrogen atom of the anti form of the oxime group to give cyclic products B [7, 9, 10].



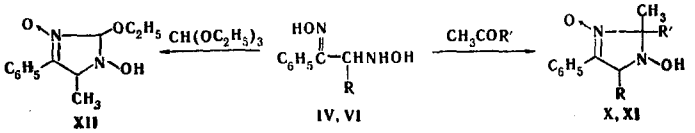
A B

The reaction of α-hydroxylamino oximes with benzaldehyde gives quantitative yields of N-(2-oximinoalkyl)-α-phenylnitrones (IX) [6, 7, 26, 27]. The formation of stable nitrones IX is due to stabilization of the nitrone grouping by conjugation with the benzene ring.



IX

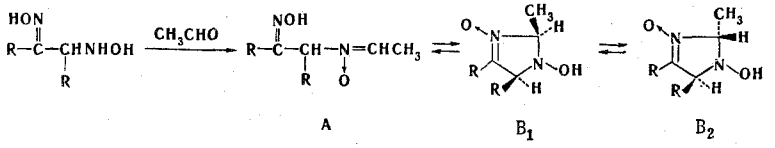
Heating of aliphatic-aromatic α-hydroxylamino oximes IV and VI with acetaldehyde [7, 9], acetone [28], or ethyl orthoformate [29] leads to 1-hydroxy-4-phenyl-Δ^3-imidazoline 3-oxides (X-XII). Formation of a conjugated nitrone grouping as a result of cyclization of the initially formed aliphatic nitrone (A) shifts the reaction to favor cyclic form (B).



XII IV, VI X, XI

IV R=CH_3; VI R=H; X R=H, CH_3, R′=H; XI R=R′=CH_3

Condensation of aliphatic and acyclic α-hydroxylamino oximes with aldehydes and ketones leads to somewhat different results. Thus, acetaldehyde gives condensation products XIII, which exist as a mixture of two tautomeric forms – N-(2-oximinoalkyl)-α-methylnitrone (A) and 1-hydroxy-Δ^3-imidazoline 3-oxide (B) – in solutions [$CHCl_3$, CH_3OH, and dimethyl sulfoxide (DMSO)]. This example of ring–chain tautomerism is interesting in that there are nitrone groupings in both the open and cyclic forms [30].



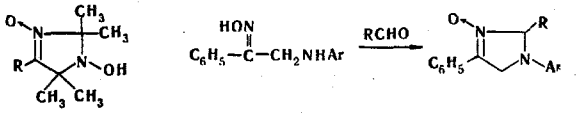
A B_1 B_2

XIII a R = CH_3; b R–R = $(CH_2)_n$

Two forms of signals of the CH_3CH group are observed in the PMR spectra of condensation products XIIIa,b; this attests to participation of two stereoisomeric cyclic forms (B_1 and B_2) [22] in the equilibrium. The ratio of the signals of forms B_1 and B_2 of XIIIa is 2 : 1 and remains unchanged at 30-90°C. As the temperature and polarity of the solvent increase, the amount of the open form increases, and an inverse linear dependence of the logarithm of the constant of tautomeric equilibrium A ⇌ B on temperature is observed. A decrease in the polymethylene chain of XIIIb also leads to an increase in the amount of the open form. On the other hand, the amount of cyclic form B that participates in the equilibrium increases as the number of substituents in the ring increases: when there are four or five substituents present in the ring of 1-hydroxy-Δ^3-imidazoline 3-oxide, the equilibrium is shifted completely to favor the cyclic form, and the formation of a mixture of tautomeric forms is observed when there are fewer substituents.

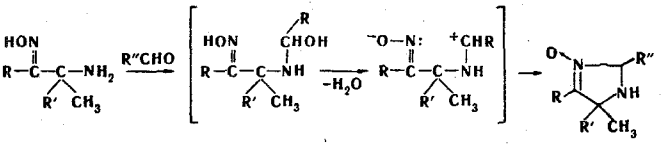
α-Hydroxylamino oximes with a tertiary NHOH group react with acetone to give sterically hindered 1-hydroxy-Δ^3-imidazoline 3-oxides (XIV) only under more severe conditions – on heating in sealed ampules. A more convenient method for the preparation of such compounds is heating hydroxylamino oximes with acetone diethyl acetal [31, 32].

Bush and Strätz have similarly observed that anti-α-(arylamino) oximes (XV) react with benzaldehyde and formaldehyde to give 1-arylimidazoline oxides (XVI) [33].



XIV R = C_6H_5, H, CH_3 XV XVI R = C_6H_5, H

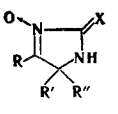
In 1970 Gnichtel demonstrated that primary anti-α-amino oximes XVII react exothermically with acetaldehyde and benzaldehyde in alcohol to give imidazoline oxides (XVIII) [18]. Gnichtel [18] explains their formation by conversion of intermediate amino alcohol XIX to carbonium ion XX, in which electrophilic attack at the nitrogen atom leads to ring closing.



XVII XIX XX XVIII

R = CH_3, C_6H_5; R′ = CH_3, H; R″ = CH_3, C_6H_5

Δ^3-Imidazoline 3-oxide derivatives XXI and XXII are formed in the reaction of α-amino oximes XVII with phosgene [20] and thiophosgene [34].

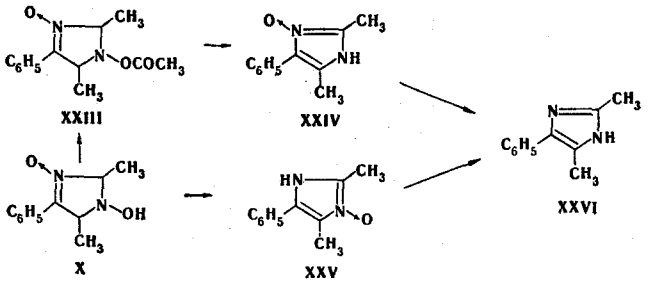


XXI X = O; R, R′, R″ = Alk;
XXII X = S; R, R′ = Alk, Ar; R″ = H

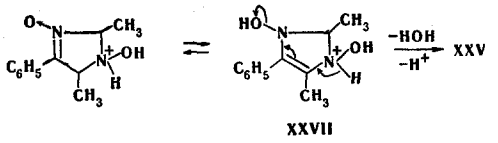
Thus, reaction of α-amino oximes and α-hydroxylamino oximes with carbonyl-containing compounds is a general method for the synthesis of, respectively, Δ^3-imidazoline 3-oxides and 1-hydroxy-Δ^3-imidazoline 3-oxides.

Preparation of Imidazole and 2H-Imidazole N-Oxides from 1-Hydroxy-Δ^3-imidazoline 3-Oxides

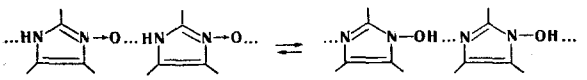
1-Hydroxy-Δ^3-imidazoline 3-oxides that contain one substituent in the 5 position undergo dehydration to give imidazole and 2H-imidazole N-oxides. The process is facilitated on passing to acyl derivatives. Thus acetoxy derivative XXIII on standing, heating, or reaction with hydrogen chloride splits out a molecule of acetic acid to give 2,5-dimethyl-4-phenylimidazole 3-oxide (XXIV) [10, 35]. The action of hydrogen chloride on 1-hydroxy-Δ^3-imidazoline 3-oxide (X) gives 2,4-dimethyl-5-phenylimidazole 3-oxide (XXV), which differs from XXIV only with respect to the position of the N-oxide oxygen atom. Treatment of XXIV and XXV with PCl_3 gives 2,4-dimethyl-5-phenylimidazole (XXVI).



The formation of imidazole oxide XXIV is facilitated by prior acylation, but the formation of isomeric XXV can be explained by the fact that dehydration occurs in the protonated tautomeric N-hydroxy form (XXVII).

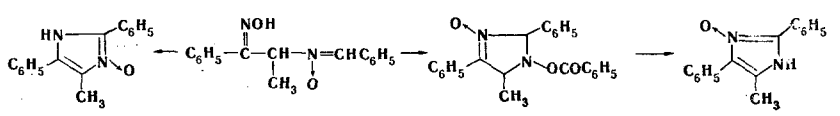


Compounds XXIV and XXV exist in solution as associates consisting of 7-9 monomeric imidazole 3-oxide molecules [10, 14, 36]. The formation of associates is due to the strong hydrogen bond between the N-oxide oxygen atom of one molecule and the hydrogen of the NH group of another molecule or, in the tautomeric form, between the hydrogen of the N-hydroxy group and the basic nitrogen atom [14]. Tautomerism of this form for imidazole and benzimidazole N-oxides depends on the solvents [37].

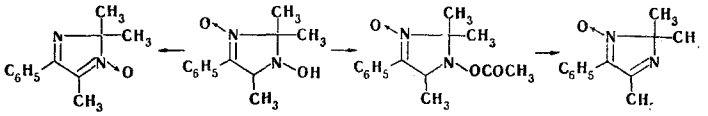


Similarly, the formation of isomeric imidazole N-oxides is observed for the product (XII) of condensation of an α-hydroxylamino oxime with ethyl orthoformate [29].

N-(2-Oximinoalkyl)-α-phenylnitrones IX (see above) can also be the starting compounds for the synthesis of isomeric imidazole N-oxides [25]. 1-Benzoyloxy-5-methyl-2,4-diphenyl-Δ^3-imidazoline 3-oxide (XXVIII) is formed when nitrone IXb is heated with benzoic anhydride. Treatment of this compound with hydrogen chloride leads to 5-methyl-2,4-diphenylimidazole 3-oxide (XXIX), while nitrone IXb under the same conditions gives 4-methyl-2,5-diphenylimidazole 3-oxide (XXX).

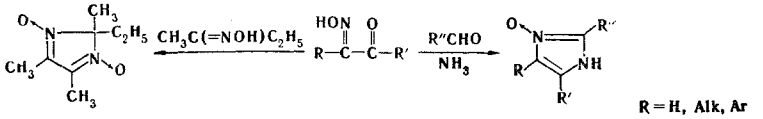


In contrast to acyl derivatives of 2-monosubstituted 1-hydroxy-Δ^3-imidazoline 3-oxides, the 2,2-disubstituted derivatives are more stable and do not change on heating to their melting points, but they are deacylated by the action of hydrogen chloride. For example, 2,2,5-trimethyl-4-phenyl-2H-imidazole 3-oxide (XXXII) is obtained in quantitative yield from acetyl derivative XXXI. Under the same conditions, XI gives the isomeric 2,2,4-trimethyl-5-phenyl-2H-imidazole 3-oxide (XXXIII) [28]. Dehydration apparently occurs in the protonated tautomeric N-hydroxy form, which is similar to N-hydroxy form XXVII.



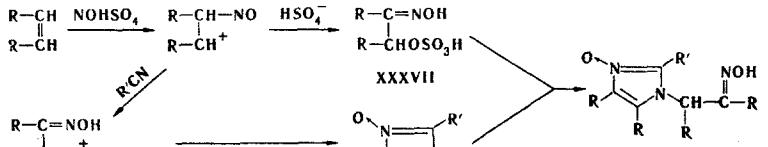
XXXIII XI XXXI XXXII

In recent years the attention of investigators has been drawn to the synthesis of imidazole N-oxides XXXIV by reaction of diketone monooximes with aldehydes and ammonia [38-41]. The formation of 2H-imidazole N,N'-dioxide (XXXV) was observed in the reaction of a diketone monooxime with a ketone oxime [42].



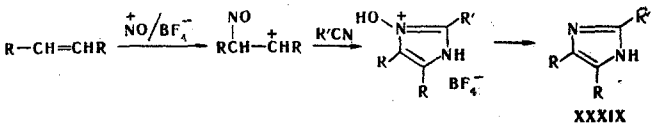
XXXV XXXIV R = H, Alk, Ar; R', R'' = Alk, Ar

In a study of three-component reactions of the Ritter type it was found that the reaction of olefins and nitrosylsulfuric acid in the presence of aliphatic nitriles leads to imidazole N-oxides [43]. The primary reaction products are imidazole N-oxides XXXVI and α-sulfatooximes XXXVII, which then interreact to give 1-(β-oximinoalkyl)imidazole 3-oxides (XXXVIII).



XXXVII XXXVI XXXVIII R = Alk; R' = Alk, Ar

A similar method is the reaction of olefins with nitrosyltetrafluoroborate in the presence of nitriles [36]. The subsequent action of lithium aluminum hydride leads to imidazole XXXIX.



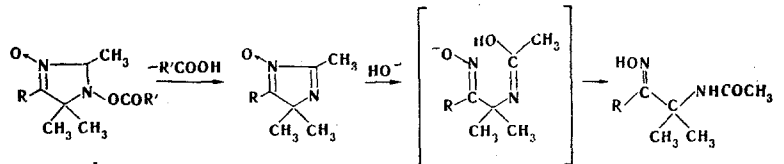
XXXIX

Thus, in contrast to other methods, the use of 1-hydroxy-Δ^3-imidazoline 3-oxides makes it possible to obtain isomeric pairs of imidazole and 2H-imidazole N-oxides from a single compound.

Preparation and Covalent Hydration of 4H-Imidazole N-Oxides

1-Hydroxy-Δ^3-imidazoline 3-oxides have also been used for the synthesis of 4H-imidazole N-oxides [44]. The dehydration of 5,5-disubstituted 1-hydroxy-Δ^3-imidazoline 3-oxides by the action of hydrogen chloride or alkali could not be accomplished. However, heating of acyl derivatives XLa,b in vacuo leads to 2,4,4-trimethyl-5-phenyl- and 2,4,4,5-tetramethyl-4H-imidazole 1-oxides (XLIa,b).

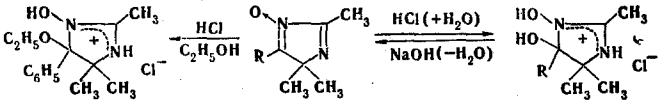
4H-Imidazole N-oxides XLIa,b react with aqueous alkalies with ring opening to give α-acylamino ketone oximes XLIIa,b, apparently through a step involving the enol form (XLIII) of the amide [44].



XL a, b XLI a, b XLIII XLII a, b

R' = CH_3, C_6H_5; a R = C_6H_5; b R = CH_3

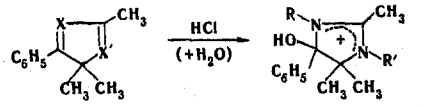
When hydrogen chloride is passed into an ether solution of XLIa,b, a molecule of water is added to give substituted 1,5-dihydroxy-2-imidazolinium chlorides (XLIVa,b). Traces of moisture are apparently sufficient for their formation [45]. Under the same conditions in alcohol solution, XLIa adds a molecule of alcohol.



XLIV c XLI XLIV

a R = C_6H_5; b R = CH_3

Similarly, the action of hydrogen chloride on 4H-imidazole XLV, 4H-imidazole 3-oxide XLVI, and 4H-imidazole 1,3-dioxide XLVII gives hydration products – 2-imidazolinium chlorides XLVIII-L [45].

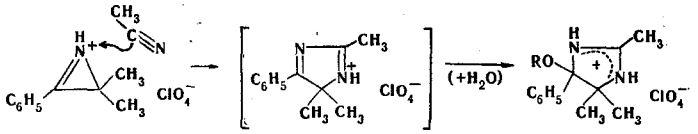


XLV X = X′ = N; XLVIII R = R′ = H;

XLVI X = N, X′ = N→O; XLIX R = H, R′ = OH;

XLVII X = X′ = N→O; L R = R′ = OH

The well-known phenomenon of covalent hydration of heterocyclic cations [46, 47] has not been previously observed in imidazole derivatives. Recently, in a study of ring-expansion reactions, Leonard observed that 3,3-dimethyl-2-phenyl-1-azirine (LI) reacts with acetonitrile in the presence of perchloric acid to give, rather than 2,4,4-trimethyl-5-phenyl-4H-imidazole perchlorate (LII), the hydration product, i.e., 5-hydroxy-2,4,4-trimethyl-5-phenyl-2-imidazolinium perchlorate (LIIIa) [48]. When LIIIa is heated in alcohol, ethoxy derivative LIIIb, which is similar to XLIVc, is formed.

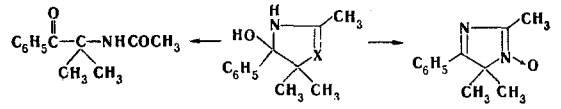


LI LII LIII a R = H; b R = C_2H_5

The hydration reaction begins with the formation of a heterocyclic cation (LII, for example), which then adds a water molecule to give a structure that is stabilized by charge delocalization in the amidinium fragment of the molecule [47].

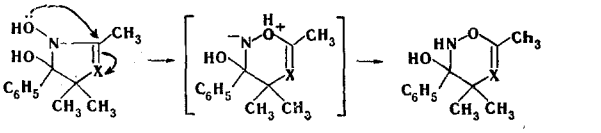
Depending on the conditions, the isolation of the free base from salt XLIVa gives different products. When the salt is added to a sodium hydroxide solution, 4H-imidazole 1-oxide XLIa is regenerated. Careful neutralization of an alcohol or aqueous solution of salt XLIVa at −5 to 0° gives a covalent-hydration product in the free state – 1,5-dihydroxy-2,4,4-trimethyl-5-phenyl-2-imidazoline (LIVa). Similar compounds (LIVb-d) are formed when salts XLVIII-L are neutralized under the same conditions [49]. The imidazolinium chlorides are regenerated by the action of hydrochloric acid on LIVa-d.

Hydroxyimidazolines LIVa-d are relatively stable in the crystalline state. Refluxing a solution of LIVb in ethyl acetate–alcohol (10 : 1) does not lead to changes, while 2-acetamido-2-methyl-1-phenyl-1-propanone (LV) is formed in aqueous solution. When LIVc is allowed to stand or is heated, a water molecule is split out, and 4H-imidazole 3-oxide XLVI is regenerated.



LV LIV b X = N; c X = N→O XLVI

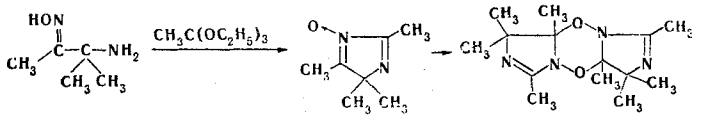
When solutions of 1,5-dihydroxy-2-imidazolines LIVa,d are heated briefly or are allowed to stand for a few hours at 20°, the ring is expanded to give 3-hydroxy-4,4,6-trimethyl-3-phenyl-2,3-dihydro-4H-1,2,5-oxadiazine and -oxadiazine 5 oxides (LVIa,b) [49]. The reaction apparently commences with attack on the 2-position of the imidazoline by the oxygen of the N-hydroxy group with synchronous cleavage of the C–N bond.



LIV a X = N; d X = N→O LVI a X = N; b X = N→O

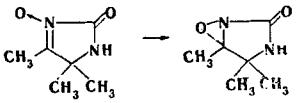
Thus covalent hydration is apparently characteristic for 4H-imidazoles and their mono- and N,N'-dioxides. However, the properties of the hydration products depend substantially on the presence and position of an oxygen-containing function.

In 1972, there appeared a communication by Gnichtel and co-workers regarding the formation of 4H-imidazole 1-oxide XLIb on reaction of α-amino oxime XVII with ethyl orthoformate [19]. Compound XLIb is readily dimerized.



XVII XLI b

When 2-oxo-Δ^3-imidazoline 3-oxide LVII is heated it gives oxaziridine derivative LVIII [20].

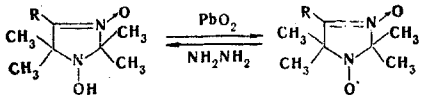


LVII LVIII

Synthesis and Properties of Stable Iminoxyl Radicals of Δ^3-Imidazoline 3-Oxides

The extensive development of the chemistry of stable iminoxyl radicals, the functional derivatives of which find application as spin labels for biological systems [50, 51], began 60 years ago. The stability of radicals of this form makes it possible to use them as stabilizers, antioxidants, paramagnetic standards, etc. [50]. The methods for the synthesis of these compounds are based on catalytic oxidation of sterically hindered amines under relatively severe conditions; this leads to destruction of the reactive functional groups. Oxidation of sterically hindered hydroxylamine derivatives is a milder method for the generation of such radicals, but up until now direct methods for the synthesis of such compounds have not been worked out.

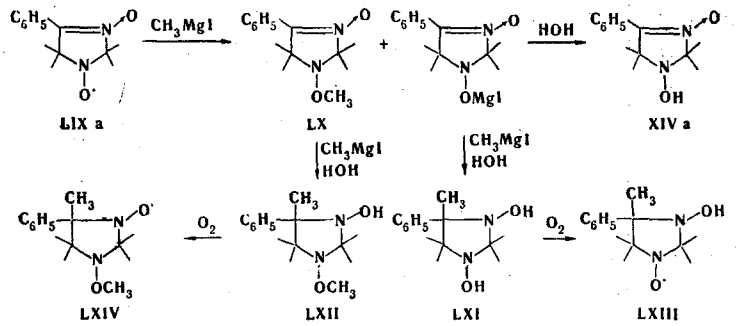
Oxidation of sterically hindered 1-hydroxy-Δ^3-imidazoline 3-oxides XIVa-c with lead dioxide in benzene or ether, silver oxide in ammonium hydroxide, or other suitable oxidizing agents proceeds smoothly to give stable iminoxyl radicals LIXa-c [31, 32, 52]. Radicals LIXa-c are stable with respect to aqueous alkali solutions, are decomposed by acids, and are reduced with hydrazine to the starting compounds.



XIV a-C LIX a-C

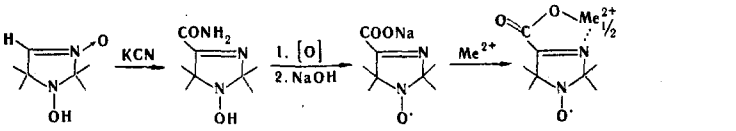
a R = C_6H_5; b R = CH_3; c R = H

1,3-Addition reactions are characteristic for the nitrone grouping [27]. The addition of a Grignard reagent to radicals LIXa,b, which contain this grouping, should have led, with retention of free valence [50], to radicals with a higher degree of substitution. Reaction of radical LIXa with an equimolecular amount of methylmagnesium iodide gave 1-methoxy-2,2,5,5-tetramethyl-4-phenyl-Δ^3-imidazoline 3-oxide (LX) and (XIVa). The use of excess Grignard reagent and carrying out the reaction and isolation of the products in an inert atmosphre gives 1,3-dihydroxy-2,2,4,5,5-pentamethyl-4-phenylimidazolidine (LXI) and 1-hydroxy-3-methoxy-2,2,4,4,5-pentamethyl-5-phenylimidazolidine (LXII) [53]. The reaction commences with attack on the radical center by the Grignard reagent [54] with subsequent addition at the nitrone grouping. The hydroxy derivatives are oxidized to radicals LXIII and LXIV on standing in air and during chromatographic purification. Reaction of radical LIXb with methylmagnesium iodide gives similar products.

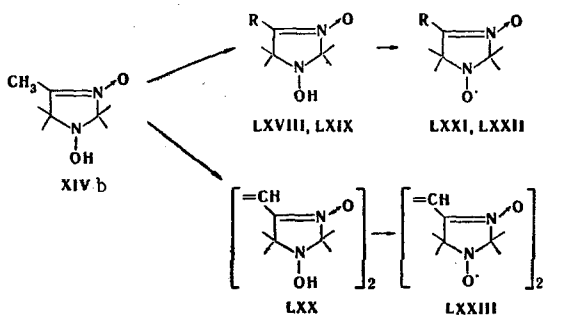


The presence in XIVb,c of a nitrone grouping was used to obtain Δ^3-imidazolines and Δ^3-imidazoline 3-oxides with different functional groups, the oxidation of which gives a new series of stable iminoxyl radicals [55, 56].

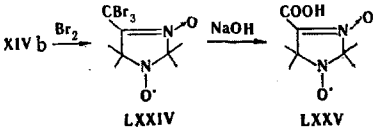
Reaction of 1-hydroxy-Δ^3-imidazoline 3-oxide XIVc with aqueous potassium cyanide solution gives 1-hydroxy-2,2,5,5-tetramethyl-3-imidazoline-4-carboxamide (LXV). Oxidation of amide LXV gives a stable radical, the hydrolysis of which with alkali gives a radical acid, which was isolated as salt LXVI. Complexes with Cu^{2+}, Ni^{2+}, $CrCl^{2+}$ with retention of the radical center were obtained when this compound was used as a ligand [55, 57].



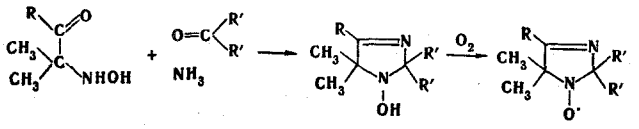
A methyl group in the 4 position of Δ^3-imidazoline 3-oxide, i.e., in the α-position of the nitrone grouping, has properties that are similar to those of methyl groups in the o- and p-positions of aromatic N-oxides, which are capable of reacting with electrophilic reagents in the presence of bases [12, 13]. Treatment of XIVb in alkaline solution with benzaldehyde gives styryl derivative LXVIII [56]. Reaction of XIVb with amyl nitrite in the presence of sodium amide gives a nitrosation product – 4-oximinomethyl-2,2,5,5-tetramethyl-Δ^3-imidazoline 3-oxide (LXIX). Under the same conditions, reaction with nitrobenzene gives the ethylene derivative (LXX), possibly through a step involving the formation of a carbene [13]. Oxidation of LXVIII-LXX generates stable iminoxyl radicals LXXI-LXXIII.



Treatment of XIVb with alkaline bromine solution gives tribromomethyl derivative LXXIV, which gives acid LXXV on alkaline hydrolysis [56].



It should be noted that reaction of α-hydroxylamino ketones, formed in the acid hydrolysis of α-hydroxylamino oximes [58], with ketones and ammonia makes it possible to obtain 1-hydroxy-Δ^3-imidazolines LXXVI without an N-oxide oxygen; oxidation of LXXVI gives stable iminoxyl radicals LXXVII [59].



R = C_6H_5, CH_3; R′ = Alk LXXVI LXXVII

Thus the accessibility of α-hydroxylamino oximes and the simplicity of their conversion to 1-hydroxy-Δ^3-imidazoline 3-oxides, which are the starting materials for the preparation of isomeric imidazole and 2H- and 4H-imidazole N-oxides and iminoxyl radicals, opens up new possibilities for research on imidazole and imidazoline derivatives and stable radicals.

LITERATURE CITED

1. G. Cusmano, Gazz. Chim. Ital., 40, I, 602 (1910).
2. G. Cusmano, Gazz. Chim. Ital., 40, II, 122 (1910).
3. G. Cusmano, Gazz. Chim. Ital., 40, II, 525 (1910).
4. V. A. Koptyug, L. B. Volodarskii, and N. N. Vorozhtsov, Jr., Zh. Obshch. Khim., 32, 1613 (1962).
5. L. B. Volodarskii, V. A. Koptyug, and A. N. Lysak, Zh. Organ. Khim., 2, 114 (1966).
6. L. B. Volodarskii and Yu. G. Putsykin, Zh. Organ. Khim., 3, 1686 (1967).
7. L. B. Volodarskii and A. Ya. Tikhonov, Zh. Organ. Khim., 6, 307 (1970).
8. L. B. Volodarskii (Volodarsky) and V. A. Koptyug, Tetrahedron Lett., 2659 (1964).
9. L. B. Volodarskii, V. A. Koptyug, and A. N. Lysak, Khim. Geterotsikl. Soed., 766 (1966).
10. L. B. Volodarskii (Volodarsky), V. A. Koptyug, and A. N. Lysak, Tetrahedron Lett., 1565 (1965).
11. M. L. Sheinbaum, J. Org. Chem., 35, 2790 (1970).
12. A. R. Katritzky and J. M. Lagowsky, Chemistry of the Heterocyclic N-Oxides, Vol. 3, Academic Press (1971), p. 99.
13. E. Ochiai, Aromatic Amine Oxides, Vol. 4, Am. Elsevier (1970), p. 347.
14. H. Lettau, Z. Chem., 6, 211 (1970).
15. G. Desstevens, A. B. Brown, D. Rose, and H. J. Chernov, J. Med. Chem., 10, 211 (1967).
16. R. Kuhn and W. Blau, Ann, 615, 99 (1958).
17. G. W. Stacy, T. E. Wollner, and T. R. Oakes, J. Heterocycl. Chem., 3, 51 (1966).
18. H. Gnichtel, Ber., 103, 2411 (1970).
19. H. Gnichtel, W. Griebenow, and W. Lowe, Ber., 105, 1865 (1972).
20. H. Gnichtel, R. Walentowski, and K. E. Shuster, Ber., 105, 1701 (1972).
21. P. P. Kadzyauskas and N. S. Zefirov, Usp. Khim., 37, 1243 (1968).
22. Yu. G. Putsykin and L. B. Volodarskii, Izv. Sibirsk. Otd. Akad. Nauk SSSR, No. 9, 86 (1969).
23. E. Buehler, J. Org. Chem., 32, 261 (1967).
24. P. A. S. Smith, The Chemistry of the Open-Chain Nitrogen Compounds, Vol. 2, W. A. Benjamin (1966), p. 29.
25. L. B. Volodarskii and A. N. Lysak, Khim. Geterotsikl. Soed., 904 (1967).
26. V. A. Koptyug, L. B. Volodarskii, and I. K. Baeva, Zh. Obshch. Khim., 34, 151 (1964).
27. J. Hamer and A. Macaluso, Chem. Rev., 64, 474 (1964).
28. L. B. Volodarskii, A. N. Lysak, and V. A. Koptyug, Khim. Geterotsikl. Soed., 334 (1968).
29. L. B. Volodarskii and E. I. Vityaeva, Zh. Organ. Khim., 8, 1887 (1972).
30. G. R. Delpierre and M. Lamchen, Quart. Rev., 19, 329 (1965).
31. L. B. Volodarskii (Volodarsky), G. A. Kutikova, R. Z. Sagdeev, and Yu. N. Molin, Tetrahedron Letters, 1065 (1968).
32. L. B. Volodarskii and G. A. Kutikova, Izv. Akad. Nauk SSSR, Ser. Khim., 937 (1971).
33. M. Bush and F. Strätz, J. Prakt. Chem., 150, 1 (1937).
34. H. Gnichtel, S. Exner, H. Bierbuss, and M. Alterdinger, Ber., 104, 1512 (1971).
35. L. B. Volodarskii and A. N. Lysak, Khim. Geterotsikl. Soed., No. 1, 109 (1967).
36. M. L. Sheinbaum and M. B. Dines, Tetrahedron Lett., 2205 (1971).
37. S. O. Chua, M. J. Cook, and A. R. Katritzky, J. Chem. Soc., B, 2350 (1971).
38. O. Diels, Ber., 51, 965 (1918).
39. H. Lettau, Z. Chem., 10, 338 (1970).
40. H. Lettau, Z. Chem., 10, 441 (1970).
41. K. Akagane, F. G. Allan, G. G. Allan, T. Friberg, and S. O. Mnircheartaigh, Bull. Chem. Soc. Japan, 42, 3204 (1969).
42. J. E. Baldwin and N. H. Rogers, Chem. Commun., 524 (1965).

43. J. Beger, J. Prakt. Chem., 311, 746 (1969).
44. L. B. Volodarskii, V. S. Kobrin, and Yu. G. Putsykin, Khim. Geterotsikl. Soed., 1241 (1972).
45. L. B. Volodarskii, L. A. Fust, and V. S. Kobrin, Khim. Geterotsikl. Soed., 1246 (1972).
46. A. Albert, Angew. Chem., 79, 913 (1967).
47. A. R. Katritzky (editor), Physical Methods in Heterocyclic Chemistry, Academic Press (1963).
48. N. Leonard and B. Zwanenberg, J. Am. Chem. Soc., 89, 4456 (1967).
49. V. S. Kobrin, L. B. Volodarskii, L. A. Tikhonova, and Yu. G. Putsykin, Khim. Geterotsikl. Soed., 1087 (1973).
50. É. G. Rozantsev, Free Iminoxyl Radicals [in Russian], Khimiya, Moscow (1970).
51. S. L. Hamilton and H. M. McConnell, Usp. Khim., 39, 531 (1970).
52. R. Z. Sagdeev, Yu. N. Molin, G. A. Kutikova, and L. B. Volodarskii, Teor. i Éksperim. Khim., 6, 220 (1970).
53. G. A. Kutikova and L. B. Volodarskii, Zh. Organ. Khim., 6, 1505 (1970).
54. V. D. Sholle, V. A. Golubev, and É. G. Rozantsev, Dokl. Akad. Nauk SSSR, 200, 137 (1971).
55. L. B. Volodarskii, G. A. Kutikova, V. S. Kobrin, R. Z. Sagdeev, and Yu. N. Molin, Izv. Sibirsk. Otd. Akad. Nauk SSSR, No. 7, 101 (1971).
56. L. B. Volodarskii, I. A. Grigor'ev, and G. A. Kutikova, Zh. Organ. Khim., 9, No. 8 (1973).
57. Yu. N. Molin, R. S. Sagdeev, G. A. Kutikova, and L. B. Volodarskii (Volodarsky), J. Magn. Res., 9, 13 (1973).
58. L. B. Volodarskii and T. K. Sevast'yanova, Zh. Organ. Khim., 7, 1687 (1971).
59. T. K. Sevast'yanova and L. B. Volodarskii, Izv. Akad. Nauk SSSR, Ser. Khim., 2359 (1972).