Notes

Structure and Reactivity in the Reduction of Conjugated Dienes by Diimide[1a]

Samuel Siegel,* Michael Foreman, Robert P. Fisher,[1b]
and Susan E. Johnson[1b]

Department of Chemistry, University of Arkansas, Fayetteville, Arkansas 72701

Received April 23, 1975

The reduction of unsaturated groups by the use of hydrazine, or certain of its derivatives, is thought to proceed via the formation of diimide, a reactive intermediate which apparently transfers its two hydrogen atoms to the unsaturated group in a concerted process.[2,3] For simple alkenes and nonconjugated dienes,[4] the relative rate of reduction is a function of the degree of substitution of the double bond attacked but the effect of structure on the reactivity of conjugated dienes is unreported.[5] Such information, we believed, would assist us in identifying a diene whose structure was not resolved on the basis of the spectral evidence available to us.[6] To be valid, the argument required that the possibility of the 1,4 addition of hydrogen be excluded and, although this assumption can be justified by arguments based upon the Woodward–Hoffmann rules, some experimental support seemed in order.[7]

Accordingly three readily available dienes, isoprene (**4**), 2,3-dimethyl-1,3-butadiene (**5**), and 2,5-dimethyl-2,4-hexadiene (**6**), were selected as test compounds which might show marked variations in the rate of the possible 1,4 relative to the 1,2 addition of hydrogen. Thus 1,4 addition to **6** yields an alkene which is less substituted than the product of 1,2 addition while the converse is true for **5**. Further, the 1,4 attack on **6** would be at the more highly substituted carbon atoms whereas the 1,4 attack on **5** would be at the least substituted vinyl carbons. Isoprene (**4**) represents an intermediate situation. 1,3-Cyclohexadiene (**7**) was reduced with dideuteriodiimide to determine whether the cyclic structure had any influence on the orientation of the transfer of hydrogen.

The relative reactivity of these dienes and 1,4-cyclohexadiene (**8**) toward diimide, generated at 80° from benzenesulfonylhydrazide, was determined to extend the structure–reactivity relationships observed by Garbisch et al.[3] Also measured were the relative reactivity of 1,3-cyclopentadiene (**9**), cyclopentene (**10**), and dienes **7** and **8** with diimide which was generated at 25° in methanol from the thermal decomposition of azodicarboxylic acid.[8]

Results and Discussion

There was no evidence of the 1,4 addition of hydrogen to any of the dienes examined. Table I summarizes the results of competitive experiments by listing the average relative rate constant computed from the composition of the reaction mixtures which were sampled at arbitrary intervals of time.[3] For convenience in comparing the results with previous data, the relative reactivity *per double bond,* referred to cyclohexene (**1**) or methylenecyclohexane (**2**), is listed in column 2 of Table II; the k_{rel} for **2** was assumed to be the value given by Garbisch et al.[3] The relative reactivities obtained through our competitive experiments are with reference to either **1**, denoted by A, or to **2**, by B. In the adjacent columns are listed the name and relative reactivity of the

Table I
Results of Competitive Diimide Reductions of Dienes and Reference Compounds[a]

A	B	k_A/k_B
Methylenecyclohexane (2)	4-*tert*-Butylmethylenecyclohexane (3)	0.95 ± 0.05
2,3-Dimethyl-1,3-butadiene (5)	Cyclohexene (1)	6.2 ± 0.2
Isoprene (4)	2,3-Dimethyl-1,3-butadiene (5)	2.2 ± 0.2
2,3-Dimethyl-1,3-butadiene (5)	2,5-Dimethyl-2,4-hexadiene (6)	6.1 ± 0.8
1,3-Cyclohexadiene (7)	4-*tert*-Butylmethylenecyclohexane (3)	8.5 ± 0.2
Methylenecyclohexane (2)	1,4-Cyclohexadiene (8)	1.85 ± 0.08
1,3-Cyclohexadiene (7)	1,4-Cyclohexadiene (8)	13.7 ± 2.1 25[b]
1,3-Cyclohexadiene (7)	Cyclopentadiene (9)	2.0[b]

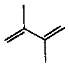
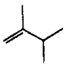
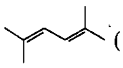
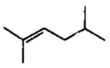
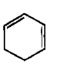
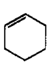
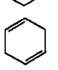
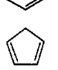
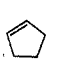
[a] Diimide generated from benzenesulfonylhydrazide in diglyme at 80° except where noted. [b] Diimide from the decomposition of azodicarboxylic acid at 25°.

Table II
Relative Reactivity of Dienes toward Diimide from Competitive Reductions at 80°.
Relative Reactivity per Double Bond (k_{rel}) Is Referred to Either Cyclohexene (A) or Methylenecyclohexane (B)[a]

Diene or monoene	k_{rel}	Monoene	k_{rel}
Cyclohexene (1)	(1.00)	1	(1.00)
Methylenecyclohexane (2)	(3.27)	2	3.27
4-*tert*-Butylmethylenecyclohexane (3)	3.43 (B)		
2-Methyl-1,3-butadiene (4)	13.6 (A)	1-Pentene	20
2,3-Dimethyl-1,3-butadiene (5)	3.1 (A)	2-Methyl-1-pentene	2.04
2,5-Dimethyl-2,4-hexadiene (6)	0.5 (A)	2-Methyl-2-pentene	0.28
1,3-Cyclohexadiene (7)	14.5 (B)	1	(1.00)
1,4-Cyclohexadiene (8)	0.86 (B)	1	(1.00)

[a] Garbisch et al. (ref 3) report k_{rel} for 2 as 3.27. We used two reference compounds, 2 and 1, and assume that their relative rate is 3.27 in order to place the two sets of measured relative reactivities on the same scale. The letter A or B indicates that one can compute the rate relative to 1 or 2, respectively, from the data in Table I.

Table III
Relative Reactivities of Dienes and Product Alkenes Computed from the Distribution of Products as a Function of the Fraction of Diene Transformed[a]

Diene	Product alkene	k_2/k_1[b]
 (5)	 (11)	0.45 ± 0.04
 (6)	 (12)	1.4 ± 0.1
 (7)	 (1)	0.04[c]
 (8)	1	0.45 ± 0.05
 (9)	 (10)	1.75[c,d]

[a] Diimide generated at 80° from benzenesulfonylhydrazide. [b] These are the relative rate constants of eq 1. The rate of reduction *per double bond* of the diene relative to the rate of reduction of its product monoene is 1.1, 0:36, 13., 1.1, and 0.29 for dienes 5, 6, 7, 8, and 9. [c] The result of a single experiment. The precision of the measurement is probably comparable to that reported for the other dienes. [d] Diimide generated at 25° from decomposition of azodicarboxylic acid.

reported alkene which has the same number of alkyl substituents per double bond as the diene in the column to the left. Apparently, the substitution of an alkyl group for a vinyl hydrogen has about the same effect upon the relative reactivity of dienes as it does upon monoenes.

Although the comparison between columns 2 and 4 of Table II indicates that isoprene (4) is less reactive than 1-pentene (presumably the less substituted double bond in 4 is the more reactive), dienes 5 and 6 appear to be more reactive than the equally substituted monoenes 2-methyl-1-pentene and 2-methyl-2-pentene, respectively. However, a direct and more appropriate measure of the effect of conjugation upon the relative reactivity can be obtained from the reductions of the symmetrical dienes. The method employs eq 2, which was derived by Frost and Pearson for consecutive first-order irreversible reactions.[9] The symbols α_1 and α_2 represent the fractions $[A]/[A]_0$ and $[B]/[A]_0$ where $[A]_0$ is the initial concentration of A and κ equals k_2/k_1. Ciola and Burwell have shown that the equation is equally applicable if the transformation of both A and B is the same function of any of the other reaction variables.[10] The results from this method of analysis of the data obtained from dienes 5, 6, 7, 8, and 9 are listed in descending order in Table III; the rate of reduction *per double bond* of each diene relative to the rate of reduction of its product monoene ($k_1/2k_2$) is 1.1, 0.36, 13, 1.1, and 0.29.

$$A \xrightarrow{k_1} B \xrightarrow{k_2} C \qquad (1)$$

$$\alpha_2 = \frac{1}{\kappa - 1}(\alpha_1 - \alpha_1{}^{\kappa}) \qquad (2)$$

With the exception of 1,3-cyclohexadiene (7) and possibly 5, each conjugated diene is less reactive *per double bond* than the monoene produced from it. These direct comparisons are undoubtedly more significant than those determined indirectly through competitive experiments by different investigators. However, the relative reactivities of 1,3- and 1,4-cyclohexadiene against cyclohexene recorded in Table III compare well with the directly measured relative reactivity of these compounds given in Table I and to the values assigned through the indirect comparison (via 2) with Garbisch's standard, cyclohexene.

A recent paper reports the relative rates of reaction of *cis*-diimide in the gas phase with the alkenes as ethylene (1.0), *trans*-2-butene (0.33), *cis*-2-butene (0.11), 1,3-butadiene (0.065), 1,3-cyclohexadiene (~0.05), and 2,3-dimethyl-2-butene (~0.02).[5] The effect of structure upon reactivity thus displayed compares well with the results of competitive experiments in solution.[3] One should note that 1,3-butadiene is less reactive than either *cis*- or *trans*-2-butene, which, judged by the results of Garbisch (in the liquid phase),[3] are likely to be less reactive than 1-butene. Clearly conjugation reduces the reactivity of a double bond toward diimide.

The exceptional reactivity of 1,3-cyclohexadiene (7) compared to the other conjugated dienes illustrates the importance of the release of torsional strain as a driving force for this reaction.[3,11] The lack of planarity in the ground state of 7 results from the partial relief of bond angle and eclipsing strain involving the 5,6-methylene groups which opposes the π-conjugative interaction; the later is at a maximum for the planar molecule.[11] The stabilizing influence of conjugation which exists in the ground state will be partially lost at the transition state (rate retarding) and some of the torsional strain is released (rate enhancing); apparently the latter change is overriding. In comparison 1,3-cyclopentadiene (9) may owe its appreciably lower reactivity than cyclopentene to its greater energy of conjugation, although its torsional strain also would be relieved in part on reduction.[11] Similarly, acyclic dienes are stabilized through conjugation, but to a lesser extent than in 9, and indeed the effect may be reduced markedly if rotation about the central bond is required to relieve torsional strain as in 5, where nonbonding interactions involving the 2- and 3-methyl groups would increase the potential energy of the planar conformation about the central bond (compare 5 and 6, Table III).[12]

The apparent equal reactivity per double bond of 1,4-cyclohexadiene and cyclohexene seems curious when one recalls that 1,4- and 1,3-cyclohexadienes have almost the same heats of formation.[11,13] If correct, it implies that the 1,4-diene derives stability from some interaction which involves the double bonds[14] and because this interaction must be lost upon reduction, the effect should retard this reaction. Experimental evidence and theory indicate that the molecules of the 1,4-diene are planar, oscillating between boatlike conformations.[15,16] Apparently, the transition state is attained with a smaller increase in torsional strain than for cyclohexene and this compensates for the stabilizing effect noted. Thus the almost equal reactivity per double bond of 1 and 8 results from different proportions of the opposing effects of changes of homoconjugation (not present in 1) and torsional or bond angle bending strain.

From this qualitative argument it seems clear that the general approach of Garbisch et al. for estimating the contributions of resonance, torsional strain, and bond angle strain to the relative reactivities of alkenes may be extended to the dienes by an appropriate estimate of the conjugation energy as a function of the nonplanarity of the conjugated system.[16] A further advance in developing these structure–reactivity relationships into a more quantitative theory probably will require the incorporation of more accurate measures of changes in torsional and bond angle bending strain, from ground to transition state, perhaps through the use of calculations based upon molecular mechanics.[11,17]

Experimental Section

Dienes and Alkenes. Isoprene (4), 2,3-dimethyl-1,3-butadiene (5), and 2,5-dimethyl-2,4-hexadiene (6) were used as obtained from Aldrich Chemical Co. Cyclohexene (**1**), methylenecyclohexane (**2**), 1,3-cyclohexadiene (**7**), and 1,4-cyclohexadiene (**8**) were purchased from Chemical Samples Co. Each of the preceding materials was at least 99% pure by GLC. 4-*tert*-Butylmethylenecyclohexane (**3**) was prepared from 4-*tert*-butylcyclohexanone via the Wittig reaction.[18] Cyclopentadiene (**9**), obtained from the dedimerization of dicyclopentadiene, was redistilled before use (99.8% by GLC).

Other alkenes which were used as authentic reference compounds for GLC analyses were obtained from Chemical Samples Co.

Other Materials. Benzenesulfonylhydrazide (from Aldrich Chemical Co.) and triethylamine and diglyme (from Matheson Coleman and Bell) were used in diimide reductions as obtained. Potassium azodicarboxylate was prepared by the hydrolysis of azodicarbonamide (Aldrich Chemical Co.).[4] Deuteriomethanol and deuterioacetic acid (99% *O-D*) were obtained from Diaprep Inc.

Reductions with Diimide. The procedure for generating diimide from benzenesulfonylhydrazide was similar to that described by Garbisch et al.[3] Solutions consisting of benzenesulfonylhydrazide (ca. 1.0 g), diglyme (10 ml), triethylamine (ca. 10 g), and either one or two of the unsaturated hydrocarbons (ca. 0.20 g each) were prepared. Eight 1-ml aliquots of the reaction solution were sealed in 8 mm × ca. 15 cm Pyrex tubes. The tubes were kept at 80° by suspending them in either a constant-temperature oil bath or refluxing reagent grade benzene. At appropriate times a tube was removed from the constant-temperature apparatus, cooled in dry ice–2-propanol, and carefully opened. The contents were poured into ca. 1.0 ml of pentane and the pentane extracts were washed twice with 1-ml portions of 5% sulfuric acid, 5% sodium hydroxide, and finally with water. The extracts were dried over magnesium sulfate, sodium sulfate, or Linde 3A molecular sieve and stored in a freezer until analysis by GLC. In those instances where pentane interfered with the product analysis, other solvents such as benzene, toluene, or xylene were used.

Competitive reductions with diimide generated from the decarboxylation of azodicarboxylic acid in methanol at 25° followed the procedure of Baird, Franzus, and Surridge.[4] Reaction solutions consisting of 50 ml of methanol, ca. 1.0 g of a mixture of the two unsaturated hydrocarbons and the internal standard (benzene or toluene), and ca. 3.5 g of potassium azodicarboxylate was stirred in a three-necked flask equipped with a vibrating stirrer (Vibro Mischer), a pressure equalizing addition funnel, and a outlet through which a positive pressure of nitrogen was maintained. A solution of 1.2 g of glacial acetic acid in methanol (15 ml) was added dropwise to the bright yellow reaction mixture. For analysis, a 1-ml portion of the mixture was removed, added to 1 ml of xylene, and washed with small portions of 5% sodium hydroxide and water. The xylene extracts were dried over Linde 3A molecular sieve and analyzed by GLC.

Analytical Procedure. The mixtures were analyzed by GLC (flame ionization detector) on either a 45 ft × 0.125 in. column of 2.5% Carbowax 600 and 2.5% Carbowax 750 on Chromosorb W (AW) 60/80 mesh (for the cyclic dienes and products) or a 25 ft × 0.25 in. column of 30% silver nitrate in triethylene glycol on 60/80 mesh Chromosorb P, which was used for the separations of the alicyclic dienes and products. All peaks were identified by comparison with synthetic mixtures of authentic standards and the molar response factor of each component was determined.[19] The columns were not able to separate 2-methyl-1-butene from 3-methyl-1-butene; however, this did not impair the ability to distinguish 1,2 and 1,4 addition to isoprene (**4**) because in the analysis on the $AgNO_3$ column 2-methyl-2-butene, the result of 1,4 addition, is cleanly separated from the other components of the reaction mixture.

Reduction of 1,3-Cyclohexadiene with N_2D_2. The deuteriodiimide was generated at 10° in CH_3OD (50 ml) containing the diene (0.4 g) from potassium azodicarboxylate (3.5 g) and deuterioacetic acid (1.2 g) as described by Baird et al.[4] Upon completion of the reaction, the mixture was diluted with water (100 ml) and extracted with three 40-ml portions of pentane. The solution was concentrated to a volume of ca. 5 ml and the concentrate was subjected to preparative chromatography. The ^1H NMR spectrum (Varian A-60) of the cyclohexene which was isolated was integrated and gave a ratio of 2.0:3.1:3.1 for the relative areas of the signals for the vinyl, allyl, and homoallyl protons. The ratio compares well with the value 2:3:3 expected for the product of 1,2 addition and not with the value 2:2:4 expected for 1,4 addition.

Calculations of Relative Rate Constants. A. Competitive Reductions. With the exceptions noted in Table I, the composition of the mixtures from three to six different conversions of the alkenes or dienes were used to compute the relative reactivities, k_A/k_B, from the equation $k_A/k_B = (\log [A]_0 - \log [A])/(\log [B]_0 - \log [B])$ where $[A]_0$ and $[B]_0$ represent the initial mole fractions of A and B, respectively, and [A] and [B] are the fractions when the mixture was sampled.[3]

B. Consecutive Reactions of a Diene. The value of k_2/k_1 (κ), the relative rate constants of the consecutive reactions of a diene → ene → ane, was computed using eq 2 in the form of $(\kappa - 1)\alpha_2 = \alpha_1[1 - \alpha_1^{\kappa-1}]$.[9,10] The value of κ was obtained through successive approximations using a hand-held calculator; the number reported is that for which the ratio of the right- to the left-hand side of the above equation is 1.000 ± 0.002. The precision of the values obtained for different conversions (average deviations) is indicated in Table III.

Registry No.—**1**, 110-83-8; **2**, 1192-37-6; **3**, 13294-73-0; **4**, 78-79-5; **5**, 513-81-5; **6**, 764-13-6; **7**, 592-57-4; **8**, 628-41-1; **9**, 542-92-7; **10**, 142-29-0; **11**, 563-78-0; **12**, 3404-78-2.

References and Notes

(1) (a) The support of this research by the National Science Foundation is gratefully acknowledged (NSF GP-15719 and NSF GP-3619X). (b) R. P. Fisher and S. E. Johnson were undergraduate research participants (NSF GY-53 and NSF GY-10017).

(2) S. Hünig, H. R. Müller, and W. Thier, *Angew. Chem., Int. Ed. Engl.*, **4**, 271 (1965).

(3) E. W. Garbisch, Jr., S. M. Schildcrout, D. B. Patterson, and C. M. Sprecher, *J. Am. Chem. Soc.*, **87**, 2932 (1965).

(4) W. C. Baird, Jr., B. Franzus, and J. H. Surridge, *J. Am. Chem. Soc.*, **89**, 410 (1967).

(5) S. K. Vidyarthi, C. Willis, R. A. Back, and R. M. McKitrick, *J. Am. Chem. Soc.*, **96**, 7647 (1974).

(6) S. Siegel and J. R. Cozort, *J. Org. Chem.*, accompanying paper in this issue.

(7) R. Hoffmann and R. B. Woodward, *Acc. Chem. Res.*, **1**, 17 (1968).

(8) E. E. van Tamelen, R. S. Dewey, and R. J. Timmons, *J. Am. Chem. Soc.*, **83**, 3725 (1961).

(9) A. A. Frost and R. G. Pearson, "Kinetics and Mechanism", 2nd ed, Wiley, New York, N.Y., 1961, p 166.

(10) R. Ciola and R. L. Burwell, Jr., *J. Phys. Chem.*, **65**, 1158 (1961).

(11) N. L. Allinger and J. T. Sprague, *J. Am. Chem. Soc.*, **95**, 3893 (1973).

(12) M. J. S. Dewar and G. J. Gleicher, *J. Am. Chem. Soc.*, **87**, 692 (1965).

(13) S. W. Benson, F. R. Cruickshank, D. M.golden, R. Haugen, H. E. O'Neal, A. S. Rodgers, R. Shaw, and R. Walsh, *Chem. Rev.*, **69**, 279 (1969).

(14) R. B. Bates, R. H. Carnighan, and C. E. Staples, *J. Am. Chem. Soc.*, **85**, 3030 (1963).

(15) E. W. Garbisch, Jr., and M. G. Griffith, *J. Am. Chem. Soc.*, **90**, 3590 (1968).

(16) N. L. Allinger and J. T. Sprague, *J. Am. Chem. Soc.*, **94**, 5734 (1972).

(17) A qualitative argument does not carry the weight of a quantitative, though approximate theoretical calculation based upon the same ideas. See, for example, D. I. Schuster and C. W. Kim, *J. Org. Chem.*, **40**, 505 (1975).

(18) S. Siegel, G. M. Foreman, and D. Johnson, *J. Org. Chem.*, accompanying paper in this issue.

(19) H. M. McNair and E. J. Bonelli, "Basic Gas Chromatography", Varian, Walnut Creek, Calif., 1969, Chapters 8 and 9.

Direct Dehydrogenation of Aporphine Alkaloids

Michael P. Cava,* Dennis L. Edie, and José M. Saá

Department of Chemistry, University of Pennsylvania, Philadelphia, Pennsylvania 19174

Received June 23, 1975

The dehydrogenation of aporphines to the corresponding dehydroaporphines, some of which are naturally occurring alkaloids, has been accomplished by the use of various chemical oxidants, including permanganate, DDQ, mercuric salts, and iodine.[1]

We now report the direct catalytic dehydrogenation of a number of aporphines to dehydroaporphines in high yield and under remarkably mild conditions. The reaction proceeds particularly well in refluxing acetonitrile, using 10% palladium on charcoal catalyst. Under these conditions, nuciferine (**1**) afforded dehydronuciferine (**4**) in 90% yield after 15 min reaction time. Other examples of this reaction