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## Steric perturbation of the conjugated triene chromophore. Conformational analysis of (*E*)- and (*Z*)-3-methyl-1,3,5-hexatriene and (*Z*)-3-*tert*-butyl-1,3,5-hexatriene

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**Abstract.** A theoretical and NMR-spectroscopic conformational analysis is presented of the 3-methyl-1,3,5-hexatrienes and of (*Z*)-3-*tert*-butyl-1,3,5-hexatriene. It is shown that (*E*)-3-methyl-1,3,5-hexatriene exists mainly as the *tEt* rotamer and (*Z*)-3-methyl-1,3,5-hexatriene as the *tZt* rotamer. Indications are found for steric strain involving the methyl group of the *E* isomer. In contrast to earlier theoretical predictions, this strain does not lead to detectable amounts of *s-cis* rotamers. *Ab-initio* calculations reported here agree with this experimental finding, but MMP2 calculations underestimate the energy of the *s-cis* form.

<sup>1</sup>H NMR relaxation rates and Nuclear Overhauser Enhancements (NOE) are shown to allow a reliable determination of the predominant ground-state conformation of alkyl-substituted hexatrienes.

NOE experiments on (*Z*)-3-*tert*-butyl-1,3,5-hexatriene reveal that a *tert*-butyl group changes the preferred conformation from *tZt* to *cZt* but, surprisingly, is unable to completely counteract the strong intrinsic preference for a spatially extended *s-trans,s-trans* conformation. We estimate the rotamer population as *cZt*/*tZt* = 80/20 ( $\pm 5$ ).

### 1. Introduction

Conjugated polyenes are generally most stable in planar all-*trans* conformations<sup>1</sup>, allowing maximum conjugation and minimum electron repulsion. The presence of *Z* geometric units, or of substituents, leads to steric crowding, which may result in different preferred conformations of the C–C single bonds. As part of our studies on the photochemistry of hexatrienes, in which the ground-state conformation is a major controlling factor<sup>2</sup>, we found it necessary to establish a general and reliable method for conformational analysis of substituted hexatrienes in solution. Until now, such a method has not been available. In the present paper, we report a combined application of various NMR techniques and molecular structure calculations to establish the conformation of the ground state of the 3-methyl-1,3,5-hexatrienes, and of (*Z*)-3-*tert*-butylhexatriene. For comparison, 2-methyl-1,3-butadiene (isoprene) has been included in the study. The compounds and numbering schemes are shown in Figure 1.

The predominant conformation (about 95% at room temperature) of isoprene is known to be planar *s-trans*<sup>3</sup>. Since the second stable rotamer is present only in a small amount<sup>4</sup>, it is not expected to contribute much to the observed NMR spectra. The geometry of the hexatrienes 3 and 4 has been determined by electron diffraction. (*E*)-

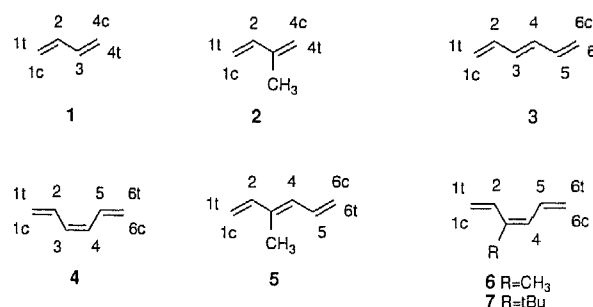


Figure 1. Compounds studied. Numbering scheme. (The unconventional numbering of isoprene 2 was chosen to facilitate comparison to the 3-methyl-1,3,5-hexatrienes.)

-1,3,5-Hexatriene (3) is a planar *tEt* species<sup>5</sup>, while (*Z*)-1,3,5-hexatriene (4) was found to be non-planar, that is, a *tZt* species with a 10°-twisted central double bond<sup>6</sup>. The latter aspect of the structure has been questioned<sup>7</sup>, and UV absorption<sup>8</sup> and vibrational spectra<sup>9,10</sup> of 4 are usually analyzed assuming a planar geometry of  $C_{2v}$  symmetry. The environment of the methyl group in (*Z*)-3-methylhexatriene 6 is sterically not much more restrictive than that in isoprene, so that no change of the predominance of the *tZt* conformation is to be expected. UV absorption

data<sup>11,12</sup> and MMP2 calculations<sup>13</sup> support this idea. In (*E*)-3-methylhexatriene **5**, additional interaction of the methyl group with H-5 is present. MMP2 calculations<sup>13</sup> of (*E*)-3-methylhexatriene suggest that a significant amount of the *cEt* rotamer should be present. However, UV data demonstrate that *tEt* is greatly preferred. The position of the 3-methyl group is comparable to that of the 9-methyl group in all-*trans* and 9-*cis* retinals, which are known to be in *s-trans,s-trans* conformations<sup>14</sup>.

In addition, we have studied (*Z*)-3-*tert*-butylhexatriene **7**, in which the bulky alkyl substituent is expected to shift the conformational equilibrium from planar *tZt* to (non-planar) *cZt*, as shown in Figure 2. This hypothesis is supported by UV absorption spectroscopy<sup>11</sup>. Interestingly, the conformational perturbation of the chromophore in **7** is similar to that in the C5-C10 fragment of retinal, which is usually found in the 6-*s-cis* conformation although, in the protein environment of bacteriorhodopsin, a 6-*s-trans* conformation prevails<sup>15</sup>.



Figure 2. Conformational equilibrium in (*Z*)-3-*tert*-butyl-1,3,5-hexatriene **7**.

Earlier NMR studies of conjugated dienes<sup>16,17</sup> and trienes<sup>18,19,20</sup> have focussed mainly on <sup>1</sup>H chemical shifts and <sup>1</sup>H-<sup>1</sup>H coupling constants of compounds with a predominant planar *s-trans* structure. The effect of non-planarity or cisoid geometry<sup>21,22</sup> has not been very well established for these parameters. The available data are surprisingly scarce. For example, satisfactory analysis of the <sup>1</sup>H NMR spectrum of (*E*)-1,3,5-hexatriene **3** has not yet been reported. <sup>13</sup>C NMR data of (*Z*)-hexatriene **4** and of substituted hexatrienes have not been published.

In this paper, we present the first study in the field of the short polyenes of the application of relaxation data ( $T_1$ ) and Nuclear Overhauser Enhancements (NOE)<sup>23,24</sup> in a semi-quantitative fashion to establish the structure of the predominant rotamers. It will be shown that, with the usual

assumptions of nearly complete dipole-dipole relaxation and isotropic tumbling, good agreement is obtained between the observed NOE and values derived from calculations of molecular structure using molecular mechanics and *ab-initio* calculations. The conformational energies from the calculations will be compared to the experimental results and to earlier published values.

## 2. Results and discussion

### 2.1 <sup>1</sup>H NMR spectral data

The chemical shifts of the 3-alkylhexatrienes **5**, **6** and **7** are presented in Table I, together with published data for reference compounds **1-4**.

Table I <sup>1</sup>H chemical shifts (in ppm, relative to TMS).

H	Compound						
	1 <sup>a</sup>	2 <sup>b</sup>	3 <sup>c</sup>	4 <sup>d</sup>	5 <sup>e</sup>	6 <sup>e</sup>	7 <sup>e</sup>
1 <sub>c</sub>	5.13	5.104	5.18	5.165	5.246	5.269	5.113
1 <sub>t</sub>	5.02	4.977	5.05	5.085	5.157	5.166	5.364
2	6.23	6.393	6.30	6.739	6.409	6.950	6.260
4 <sub>c</sub>	5.13	4.911	6.16	—	6.084	—	—
4 <sub>t</sub>	5.02	4.919	—	5.933	—	6.007	6.043
5	—	—	6.30	6.739	6.700	6.823	6.734
6 <sub>c</sub>	—	—	5.18	5.165	5.266	5.190	5.198
6 <sub>t</sub>	—	—	5.05	5.085	5.065	5.091	4.999
CH <sub>3</sub>	—	1.79	—	—	1.872	1.901	1.086

<sup>a</sup> Ref. 21, CCl<sub>4</sub>/C<sub>6</sub>H<sub>12</sub>. <sup>b</sup> Ref. 16, neat, 100 MHz. <sup>c</sup> Ref. 19, neat, 100 MHz. <sup>d</sup> Ref. 19, 50% v/v in CCl<sub>4</sub>. <sup>e</sup> This work, 297 K, about 3% v/v in CDCl<sub>3</sub>, 300 MHz, accuracy ± 0.002 ppm.

Only a few generalizable effects of methyl substitution on the <sup>1</sup>H chemical shifts in dienes and trienes emerge from the data. H-2 is shifted downfield in the methyl-substituted compounds, while H-4<sub>c</sub> in **2** and **5** are moved to higher field. H-4<sub>t</sub> (in **6**), on the other hand, appears to be subject to counteracting electronic and steric interactions with the methyl group, resulting in a small net shift. These results do

Table II <sup>1</sup>H-<sup>1</sup>H coupling constants (Hz).

J	Compound							
	2 <sup>a</sup>	2 <sup>b</sup>	3 <sup>c</sup>	4 <sup>c</sup>	4 <sup>b</sup>	5 <sup>d</sup>	6 <sup>d</sup>	7 <sup>d,e</sup>
<sup>2</sup> J <sub>11</sub>	1.20	-1.20	1.9	1.91	-1.87	1.10	1.40	2.50
<sup>2</sup> J <sub>66</sub>	1.70 <sup>f,g</sup>	-1.85 <sup>g</sup>	1.9	1.91	-1.87	2.05	2.05	2.15
<sup>3</sup> J <sub>1c2</sub>	17.52	17.35	15.2 <sup>f</sup>	16.77	17.05	17.30	17.25	17.50
<sup>3</sup> J <sub>1t2</sub>	10.76	10.80	9.5 <sup>f</sup>	10.15	10.17	10.60	10.80	11.30
<sup>3</sup> J <sub>45</sub>	—	—	10.5	11.14	11.15	11.15	11.30	10.60
<sup>3</sup> J <sub>56c</sub>	—	—	15.2 <sup>f</sup>	16.77	17.05	16.75	16.70	17.00
<sup>3</sup> J <sub>56t</sub>	—	—	9.5 <sup>f</sup>	10.15	10.17	10.15	10.15	10.15 <sup>h</sup>
<sup>4</sup> J <sub>24t</sub>	-0.42	-0.80	—	-1.04	-1.0	—	1.00	—
<sup>4</sup> J <sub>24c</sub>	-0.78	-0.70	-0.8	—	—	0.80	—	—
<sup>4</sup> J <sub>34c</sub>	-0.8	-1.30	16.2	—	—	1.37	—	—
<sup>4</sup> J <sub>34t</sub>	-1.2	-1.71	—	10.77	10.45	—	1.13	—
<sup>4</sup> J <sub>46t</sub>	—	—	-0.8	-0.77	-0.80	0.70	0.90	0.80
<sup>4</sup> J <sub>46c</sub>	—	—	-0.8	-0.71	-0.70	0.95	0.95	0.70
<sup>5</sup> J <sub>1c4c</sub>	0.68	0.69	0.7	—	—	0.65	—	—
<sup>5</sup> J <sub>1c4t</sub>	0.80	0.60	—	0.56	0.70	—	0.90	0.50
<sup>5</sup> J <sub>1t4c</sub>	0.63	0.60	0.7	—	—	0.65	—	—
<sup>5</sup> J <sub>1t4t</sub>	1.22	1.25	—	1.36	1.3	—	1.55	0

<sup>a</sup> Ref. 16. <sup>b</sup> Ref. 20. <sup>c</sup> Ref. 19. <sup>d</sup> This work (absolute values of *J*, accuracy ± 0.1 Hz; unresolved long range couplings <sup>n</sup>*J* (*n* > 5) of 0.2-0.4 Hz exist among the olefinic protons and between the methyl group and H-6<sub>c</sub> and H-6<sub>t</sub>. <sup>e</sup> <sup>6</sup>J<sub>2,6c</sub> = <sup>6</sup>J<sub>2,6t</sub> = 0.6 Hz. <sup>f</sup> Uncertain, cf. references. <sup>g</sup> In this case <sup>2</sup>J<sub>44</sub>. <sup>h</sup> Unresolved. <sup>i</sup> <sup>3</sup>J for **3** and **4**, <sup>4</sup>J for **2**, **5** and **6**.

not confirm the trends derived from work on the penta- and hexadienes<sup>17</sup>. The difference in the influence of the methyl group on the chemical shifts of H-1c and H-5 in (E)-3-methylhexatriene **5**, +0.07 and +0.40 ppm, respectively, is noteworthy. Such downfield shifts have been related to steric interactions<sup>17</sup>. Other changes in chemical shifts are small and of no diagnostic value.

Introduction of the *tert*-butyl group leads to greater changes of chemical shifts. The upfield shift of the resonance of H-2 in **7** compared to **6** may be associated with the expected conformational change. The differences observed among the <sup>1</sup>H chemical shifts in **4**, **6** and **7** do not allow detailed conclusions on the conformation of **7**.

On the whole, there is very close correspondence of the <sup>1</sup>H-<sup>1</sup>H coupling constants in the methyl hexatrienes with those in the reference compounds, as seen from Table II. Conservation of the predominant *s-trans,s-trans* conformation of the hexatrienes in the 3-methyl derivatives is thus established beyond doubt. Some of the minor variations in  $J_{HH}$  can easily be related to small structural changes, according to previously derived generalizations<sup>16-22</sup>. For example, the rather large  $^3J_{4,5}$  in **5** is consistent with in-plane deformation of the C3=C4-C5 and C4-C5=C6 angles. The value of  $^5J_{1,4}$  in **6** is close to that in (Z)-pentadiene, where the large value of this coupling constant has been related to in-plane deformation<sup>17</sup>. The coupling constants in the C4-C6 fragment of **7** indicate the presence of a (slightly distorted) *s-trans* conformation. The long-range coupling constants in the C1-C4 part are consistent with a non-planar *s-cis* conformation, although they are different from those in 2-*tert*-butyl-1,3-butadiene<sup>21</sup>. A surprising finding is the long-range coupling of 0.6 Hz of H-6c and H-6t with H-2. Such a coupling is absent in planar trienes.

## 2.2 <sup>13</sup>C NMR spectral data

In alkenes, the changes in <sup>13</sup>C chemical shifts are predicted with reasonable accuracy by application of additivity rules, with corrections for steric factors where appropriate<sup>25</sup>. Analysis of the data presented in Table III shows that transfer of the increment values used for alkenes to dienes and

trienes is not justified. In particular, steric effects appear to be greater than expected. The high frequency of the resonances of C-2(5) in **3** compared to **4**, the upfield shift of C-1 in the methyl substituted compounds and of C-5 in **5** are typical examples of sterically induced shielding.

The upfield shift of C-6 in **6**, which is absent in **5**, is presumably caused by polarization of the electron density, which is different in the geometric isomers. This effect is also found in (E)- and (Z)-1,3-pentadiene<sup>26,27</sup>.

There is a large difference in the chemical shift of the methyl groups of the 3-methylhexatrienes. In (E)-3-methylhexatriene **5**, the methyl group is in a strained position, flanked by two  $\gamma$ -hydrogens. The high-field <sup>13</sup>C resonance is one of the indications of this considerable steric strain.

The one-bond <sup>13</sup>C-<sup>1</sup>H couplings, given in Table III, have little value for conformational analysis, but long-range couplings  $^nJ_{CH}$  have been used to obtain stereochemical information<sup>28</sup>. In particular, the methyl groups occupy a position adjacent to a single bond, which would otherwise offer a useful <sup>1</sup>H-<sup>1</sup>H coupling. Experience has shown that a linear relationship often exists between  $^3J_{CH}$  and  $^3J_{HH}$  with a similar coupling path<sup>28</sup>. Unfortunately, a more extensive analysis<sup>12</sup> of some of the long-range <sup>13</sup>C-<sup>1</sup>H coupling constants forced us to conclude that these do not offer a reliable tool for conformational analysis of substituted polyenes.

## 2.3 Relaxation studies and Nuclear Overhauser Enhancements (NOE)

The dominant contribution to longitudinal relaxation in rapidly tumbling, small molecules is provided by intramolecular dipole-dipole interactions<sup>23,24,29,30</sup>. Usually, the effects of anisotropy of motion and of additional internal motion can be neglected in the analysis of <sup>1</sup>H-relaxation processes<sup>30</sup>. These assumptions will not hold for the relaxation behaviour of the protons in the methyl groups, for which the rapid methyl rotation leads to a different effective correlation time. Moreover, spin-rotation relaxation may be effective in this case. We have measured  $T_1$  for isoprene in methylcyclohexane-*d*<sub>14</sub> (MCH-*d*<sub>14</sub>) at 203 K,

Table III <sup>13</sup>C chemical shifts [ppm (relative to TMS) and  $^1J_{CH}$  (Hz) (in parentheses;  $\pm 3$  Hz, or  $\pm < 1$  Hz when four digits are given)].

C	Compound						
	1 <sup>a</sup>	2 <sup>b</sup>	3 <sup>b</sup>	4 <sup>b</sup>	5 <sup>b</sup>	6 <sup>b</sup>	7 <sup>c</sup>
1	116.6 (159.2, 154.9) <sup>d</sup>	113.3 (158.9, 154.5)	117.7 (159.8, 155.2)	118.4 (159.8, 155.2)	113.0 (159.2, 154.9)	114.6 (159.1, 155.1)	115.9
2	137.2	139.6 (153.1)	136.8 (153)	131.9 (154)	141.1 (152.7)	133.1 (152)	135.5
3	137.2	142.2 -	133.7 (153)	130.4 (156)	135.7 -	134.3 -	e
4	116.6	116.5 (156.1)	133.7 (153)	130.4 (156)	131.8 (152)	130.3 (152)	123.6
5	-	-	136.8 (153)	131.9 (154)	133.0 (152)	131.8 (152)	134.1
6	-	-	117.7 (159.8, 155.2)	118.4 (159.8, 155.2)	117.8 (159.6, 155.5)	116.8 (160.6, 154.8)	119.9
CH <sub>3</sub>	-	17.6 (126.3)	-	-	11.9 (126.3)	19.7 (126.1)	29.4 <sup>f</sup>

<sup>a</sup> Ref. 27. <sup>b</sup> This work, 75 MHz, CDCl<sub>3</sub>. <sup>c</sup> This work, 50 MHz, CDCl<sub>3</sub>; coupling constants not determined. <sup>d</sup> G. Schrumpp, G. Becher and W. Lüttke, J. Magn. Reson. 10, 90 (1973) (the greater coupling is with H-1r). <sup>e</sup> C-3 not observed. <sup>f</sup> *t*Bu-C:  $\delta$  35.5 ppm.

and for the 3-alkylhexatrienes in CDCl<sub>3</sub> at 295 K. The results are listed in Table IV.

Table IV <sup>1</sup>H relaxation times (s) (estimated accuracy < ±5%).

H	Compound			
	2 <sup>a</sup>	5 <sup>b</sup>	6 <sup>b</sup>	7 <sup>b</sup>
1c	5.7	9.4	9.5	7.1
1t	6.6	10.2	10.1	7.5
2	10.1	13.5	10.6	12.5
4c	6.4	13.4	—	—
4t	5.9	—	16.0	7.5
5	—	14.2	10.6	12.9
6c	—	9.7	10.1	5.7
6t	—	10.3	10.1	6.1
CH <sub>3</sub>	3.0	9.5	5.7	2.9

<sup>a</sup> MCH-d<sub>14</sub>, 203 K. <sup>b</sup> CDCl<sub>3</sub>, 295 K.

First inspection of the  $T_1$  values reveals a good agreement with structural features. For example, in isoprene (2), the relaxation of the terminal CH<sub>2</sub> protons is rapid, being dominated by the short-distance geminal interaction. H-1c and H-4t further interact significantly with the methyl group, while H-1t and H-4c experience an interaction with H-2 instead. The former interaction is clearly larger. H-2 relaxes most slowly, because it lacks the short-range geminal interaction. In a similar manner, considering only nearest-neighbour interactions, the  $T_1$  values of the 3-methylhexatrienes are easily rationalized in a qualitative sense. A semi-quantitative evaluation is given by Brouwer<sup>12</sup>. The marked difference in the  $T_1$  values of the methyl groups (which is also found for the corresponding <sup>13</sup>C atoms<sup>12</sup>) is ascribed to more rapid rotation of the methyl group in (*E*)-3-methylhexatriene 5 than in 6: in 5 the effective  $\tau_c$  for the short-distance intra-methyl interactions is relatively short, reducing the effectiveness of an important relaxation pathway. This is confirmed by semi-quantitative NOE experiments in which clear enhancements of the methyl signal upon irradiation at H-5 have been observed. Apparently, the 1,3 interactions with H-1c and with H-5 raise the energy of stable staggered-like conformations in 5, which leads to a small barrier to rotation. Similar steric considerations apply when comparing rotational barriers of methyl groups in 1-methylnaphthalene and 9-methylanthracene<sup>31</sup>. The <sup>1</sup>H-relaxation times of (*Z*)-3-*tert*-butylhexatriene 7 confirm that its conformation is different from that of 6. The strong interaction which leads to a short relaxation time of H-2 and H-5 in 6 is alleviated in 7, resulting in increased (relative)  $T_1$  values.

The steady-state NOE is expected to be determined by the cross-relaxation rate of the observed and irradiated nucleus

(or set of nuclei) and by the population of the rotamer in which the dipole-dipole interaction is effective. The rate at which the NOE grows to its maximum value<sup>24,29,30,32</sup> can be used as a more direct method for the determination of (relative) intramolecular distances, as it depends only on the cross-relaxation rate. In Table V, we have compiled the results of quantitative dynamic Overhauser experiments (DOE), in which we have saturated the signals of the methyl groups using a variable saturation time. The comparison of experimental results to calculated values from molecular models will follow below.

Table V Dynamic Overhauser Experiments (DOE) with saturation of methyl groups. Maximum enhancements ( $\eta$ , %) and ratio  $r_{rel}$  of growth rates for NOE at H-1c and the other H as indicated. Calculated values from MM2-optimized molecular structures.

Compound	H	Experiment		Model A		Model B	
		$\eta$	$r_{rel}$	$\eta$	$r_{rel}$	$\eta$	$r_{rel}$
2 <sup>a</sup>	1c	13.6	1.7	12.9	1.23	16.1	2.07
	4t	8.2	—	11.3	—	9.8	—
5 <sup>b</sup>	1c	15.1	1.4	13.9	0.71	16.8	1.28
	5	26.9	—	32.3	—	27.9	—
6 <sup>b</sup>	1c	14.6	1.5	13.9	1.07	17.1	1.77
	4	24.7	—	29.0	—	26.7	—
7 <sup>b</sup>	1c	4.0	2.8	—	—	—	—
	2	23.6	0.7	—	—	—	—
	4	30.2	—	—	—	—	—

<sup>a</sup> MCH-d<sub>14</sub>, 203 K. <sup>b</sup> CDCl<sub>3</sub>, 295 K.

#### 2.4 Theoretical calculations

In view of the contradictory results from MMP1 and MMP2 calculations on (*E*)-3-methylhexatriene<sup>13</sup>, we have performed geometry optimizations of 5, 6 and 7 at the *ab-initio* level<sup>33</sup> and using a recent version of MM2<sup>34</sup>. Some results are presented in Table VI.

Reasonable geometries for isoprene and hexatriene have been obtained from *ab-initio* calculations employing the 3-21G, 6-31G or 6-31G\* basis sets<sup>35</sup>. We initially optimized the structure of the two methyl rotamers of *tEt* and *tZt*-3-methylhexatriene under C<sub>s</sub> symmetry at the 3-21G level. A force constant calculation showed that the 1-eclipsed form was a transition state in both cases, while the minima were found to be 4- and 5-eclipsed rotamers, respectively.

The energy of the (non-planar) *cEt* rotamer was clearly above that of the *tEt* form. Hartree-Fock calculations employing a larger basis set (6-31G\*) and correlation corrections using MP2 do not alter the overall picture. It can

Table VI Calculated relative energies (kcal/mol) of isomers, in parentheses the torsion angle (degrees) of the *s-cis* species.

Compound	3-21G//3-21G	6-31G*//3-21G	6-31G*//6-31G*	MP2/6-31G*//6-31G*	MMP2
5 <i>tEt</i> -A	0 <sup>a</sup>	0 <sup>b</sup>	0 <sup>c</sup>	0 <sup>d</sup>	0.2
5 <i>tEt</i> -B	1.5	1.7	1.1	1.5	0
5 <i>cEt</i>	2.9 (33)	3.5	2.9 (34)	3.2	0.3 (11)
6 <i>tZt</i> -A	0.6	0.6	0.1	0.6	0.3
6 <i>tZt</i> -B	3.5	e	e	e	1.4
7 <i>cZt</i>	0 <sup>f</sup> (60)	e	e	e	0 (56)
7 <i>tZt</i>	2.7	e	e	e	3.4

<sup>a</sup> -269.33677 a.u. <sup>b</sup> -270.84194 a.u. <sup>c</sup> -270.84127 a.u. <sup>d</sup> -271.76287 a.u. <sup>e</sup> Not determined. <sup>f</sup> -385.78667 a.u.

be seen that the methyl group reduces the energy difference of the isomers to 0.6 kcal/mol or less, compared to 1.9 kcal/mol for the parent hexatrienes (6–31G)<sup>10</sup>. A corresponding steric effect is operative in the lowest excited triplet state of the 3-methylhexatrienes and there leads to a relatively high population of the *tZt* form<sup>36</sup>.

The MMP2 calculations show only small differences between the configurational and conformational isomers, and the results are less satisfactory.

Distances between the hydrogen atoms of compounds **2**, **5** and **6** were obtained from the MM2 calculations, since this method is considered to give structural data pertaining to experimental conditions at room temperature, whereas *ab-initio* calculations give  $r_e$  values, with somewhat shorter bonds. In each case, model A is the structure of minimum energy and model B is the "1-eclipsed" rotamer of the methyl group, the transition structure for rotation.

The experimental DOE results (Table V) of the methyl compounds **2**, **5** and **6** demonstrate that, in each case, H-1c has a greater effective interaction with the methyl group than the other neighbouring hydrogen atom. This is surprising, since the corresponding structures are not those of the lowest energy. A simplified model, in which the distances of protons to those of the rapidly rotating methyl group are taken to be the distance to the centre of the H<sub>3</sub> triangle<sup>14</sup>, gives results similar to those of model B for isoprene and (*Z*)-3-methylhexatriene, but predicts a smaller difference in the interactions of the methyl group of (*E*)-3-methylhexatriene with H-1c and H-5. The results give no indication for the presence of minor cisoid rotamers. At least 90% occurs in the *s-trans,s-trans* conformation.

In (*Z*)-3-*tert*-butylhexatriene **7** enhancements upon saturation of the *tert*-butyl protons are found of H-1c, H-2 and H-4. The latter is to be expected regardless of the conformation, but the former two indicate the presence of two rotamers, as shown in Figure 3.



Figure 3. Nuclear Overhauser Enhancements (NOEs) detected for compound **7**. The arrows point from saturated to observed spin systems.

The strong enhancement of H-2 confirms the predominance of the *cZt* conformation. The small enhancement of H-1c, associated with a rapid growth of the NOE, proves that the minor *tZt* conformation, in which the *tert*-butyl-H-1c distance is small, must also be present. A semi-quantitative evaluation<sup>24,30</sup> using steady-state NOEs, growth rates and relaxation times leads to the estimate that 15–25% of **7** exists in the *tZt* form. This is the first case where direct NMR spectroscopic evidence has been found for the coexistence of two rotamers of a substituted polyene in solution. Moreover, the NOE method allows a conclusion to be drawn about the structures involved. At present, we can only describe these in a global sense as *tZt* and *cZt* but, in principle, much more detailed information could be obtained from extensive studies at different temperatures. It would be useful to be able to detect the dipolar interactions among the olefinic protons, but this is very difficult to achieve by selective saturation. We have attempted such experiments with (*E*)-3-methylhexatriene **5**, but it turned out that sufficient selectivity and a sufficient degree of saturation could not be reconciled. In following papers, we shall, therefore, make use of isotopically labelled

compounds and compare their relaxation times and NOEs. The finding that a significant amount of **7** exists in the apparently strained *tZt* conformation shows an intrinsic preference for an extended conformation which is stronger than expected.

### 3. Conclusions

The conformation of the ground state of the (*E*)- and (*Z*)-3-methyl-1,3,5-hexatrienes has been established experimentally on the basis of <sup>1</sup>H–<sup>1</sup>H coupling constants which are comparable to those in isoprene, the 1,3-pentadienes and the 1,3,5-hexatrienes, and dynamic NOE experiments which allow determination of the relative distances of the methyl group to the nearest-neighbour protons. Unlike the application of coupling constants, the NOE method does not require reference data, which makes it a general tool for analysis of non-planar compounds, for which coupling constants are not well known.

Chemical-shift data, relaxation times and <sup>13</sup>C–<sup>1</sup>H coupling constants support the conclusions.

The expected predominance of the *cZt* conformation of (*Z*)-3-*tert*-butyl-1,3,5-hexatriene has been confirmed, but the dynamic NOE measurements provide evidence for the existence of as much as 20 ± 5% of the *tZt* rotamer.

*Ab-initio* RHF calculations correctly predict that the *cEt* rotamer of 3-methyl-1,3,5-hexatriene is not populated to a significant extent at room temperature. The presence of the methyl group leads to a smaller *E*–*Z* energy difference than in the unsubstituted hexatriene. The energy difference between the rotameric forms of (*Z*)-3-*tert*-butyl-1,3,5-hexatriene seems to be overestimated both by MM2 and RHF/3–21G calculations.

### 4. Experimental

An isomer mixture of the hexatrienes (3/4 = 60/40) was prepared by CuSO<sub>4</sub>-catalyzed dehydration of 1,5-hexadiene-3-ol<sup>12,37</sup>. The 3-methylhexatrienes were synthesized by dehydrobromination of 3-bromo-3-methyl-1,5-hexadiene using KOtBu in DMSO<sup>12</sup>. This method constitutes a significant practical improvement over the original procedure of Spangler et al.<sup>11</sup>. Isoprene was purchased from Janssen Chimica and distilled prior to use. (*Z*)-3-*tert*-Butylhexatriene was obtained by photolysis at 254 nm of 2-*tert*-butyl-1,3-cyclohexadiene<sup>38</sup>.

Samples (10–50% v/v for <sup>13</sup>C, 3% v/v for <sup>1</sup>H NMR) were degassed using freeze-pump-thaw cycles and sealed. CDCl<sub>3</sub> was used as solvent, except for the <sup>1</sup>H NMR measurements on isoprene, in which MCH-*d*<sub>4</sub> was preferred because it produced better separation of the relevant signals and because of its low melting point. Temperatures were as indicated in the Tables. The FT-NMR spectrometer used was a Bruker WM 300, operating at 300 MHz for <sup>1</sup>H and 75 MHz for <sup>13</sup>C (the <sup>13</sup>C NMR spectrum of **7** was recorded on a Jeol FX 200 spectrometer at 50 MHz). The number of data points of the FID was 16K for high resolution measurements, 8K or 16K for *T*<sub>1</sub> and NOE experiments. Analysis of <sup>1</sup>H NMR spectra (resolution enhanced zero-filling to 32K and Gaussian multiplication) was supported by computer simulation. The coupling constants of the olefinic protons were determined from a spectrum recorded with decoupling of the methyl groups. The assignments are straightforward and agree with NOE measurements. <sup>1</sup>H–<sup>13</sup>C correlated spectra were obtained to ascertain the assignments of the <sup>13</sup>C signals. For measurement of the <sup>1</sup>H–<sup>13</sup>C coupling constants, separate parts of the spectra were recorded, and zero-filling was to 64K data points. *T*<sub>1</sub> (inversion-recovery method) and <sup>1</sup>H-NOE measurements were carried out using relaxation delays of about 5 or 9 times the longest *T*<sub>1</sub> of the system and a variable presaturation period. For the determination of *T*<sub>1</sub>, 8 to 10 different delays were sufficient; for dynamic Overhauser measurements, 10 to 20 points were used. Peak heights

(after exponential multiplication) from these experiments were fitted to a mono-exponential equation using the standard Bruker software for  $T_1$  experiments. Values of  $T_1$  and of the NOE growth rates reported are averages over a number of lines of a multiplet, where appropriate. Effective and selective saturation could only be achieved for the isolated methyl signals. Broad multiplets could be saturated with reasonable selectivity using multiple-frequency pre-saturation<sup>39</sup>, but then the saturation was not complete. These experiments have been used to confirm assignment but are not suited for quantitative analysis.

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