

# Simple NMR method for assigning relative stereochemistry of bridged bicyclo[3.n.1]-2-enes and tricyclo[7.n.1.0]-2-enes

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**Abstract**—The stereochemistry of *syn* and *anti*-forms of bridged bicyclo[3.n.1]-2-ene, tricyclo[7.n.1.0]-2-ene ( $n=1-3$ ) and bicyclo[4.3.1]dec-7-ene derivatives can be assigned from the  $^{13}\text{C}$  chemical shift difference of the double bond. Both *syn*-9-*R*-bicyclo[3.3.1]non-2-enes and *syn*-13-*R*-tricyclo[7.3.1.0<sup>2,7</sup>]tridec-2(7)-enes have a large shielding difference between  $\text{sp}^2$  carbons, while the corresponding *anti*-forms have a smaller one. In contrast, 8-*R*-bicyclo[3.2.1]oct-2-enes and 12-*R*-tricyclo[7.2.1.0<sup>2,7</sup>]dodec-2(7)-enes have an inverse correlation. The reason of this specificity is the influence of the  $\gamma$ -*gauche* effect on the chemical shift of C(2) atom. The GIAO theory has been applied to investigate the  $^{13}\text{C}$  chemical shifts. The conformational equilibrium in the formamide group of 13-formylamino-tricyclo[7.3.1.0<sup>2,7</sup>]tridec-2(7)-enes has been studied.

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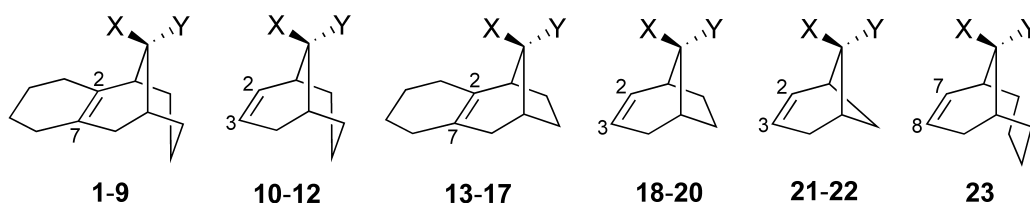
## 1. Introduction

Up to now, the determination of the relative stereochemistry of molecules has been a time consuming and sometimes difficult task. This was solved, as a rule, by X-ray crystallography analysis or NMR methods ( $^1\text{H}$ – $^1\text{H}$  and  $^1\text{H}$ – $^{13}\text{C}$  coupling constants data,  $^1\text{H}$ – $^1\text{H}$  NOE measurements). The most common approach involves  $^1\text{H}$  NMR through the angular dependence of the vicinal coupling constant.<sup>1,2</sup> However, often the coupling information is not available because either the coupling does not exist or the critical lines in the spectrum are masked by superimposed signals. The use of long-range  $^1\text{H}$ – $^{13}\text{C}$  coupling constants in definition of molecular configuration is an increasingly active area, with numerous methods. Recently developed *J*-based configuration analysis<sup>3</sup> is well suited to such measurements, but requires the protons of interest to be sufficiently resolved, and numerous experiments will be required if many  $^nJ_{\text{C,H}}$  values are to be

determined. Therefore, application of conventional 1D  $^{13}\text{C}$  NMR to solve stereochemical problems are sometimes more useful.<sup>4,5</sup> In recent years, efficient techniques for the calculations of NMR parameters by ab initio methods have been developed.<sup>6</sup> The advantage of this approach is the possibility to predict the spectral data in the absence of experimental data. The stereochemistry of substituent placement on a carbon framework is reflected in  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\delta$ -substituent effects. Barfield and co-workers previously examined the capability of ab initio calculations to predict substituent effects by using substituted butanes as model systems.<sup>7</sup>

Traditionally, relative stereochemistry determination of 12-*R*-tricyclo[7.2.1.0<sup>2,7</sup>]dodec-2(7)-ene and 13-*R*-tricyclo[7.3.1.0<sup>2,7</sup>]tridec-2(7)-ene systems were carried out either by chemical<sup>8</sup> or by X-ray crystallography analysis.<sup>9,10</sup>

Our objective was to define a simple empirical rule for



**Scheme 1.** 1,10,13,18,21,23: X=H, Y=H; 2: X=H, Y=NHCHO; 3: X=NHCHO, Y=H; 4,14: X=H, Y=NH<sub>2</sub>; 5,15: X=NH<sub>2</sub>, Y=H; 6: X=H, Y=NCHC<sub>6</sub>H<sub>4</sub>OH; 7: X=NCHC<sub>6</sub>H<sub>4</sub>OH, Y=H; 8,11,16,19,22: X=H, Y=OH; 9,12,17,20: X=OH, Y=H.

**Keywords:**  $^{13}\text{C}$  NMR; GIAO-SCF; *Gauche* effect; Bicyclo[3.2.1]octane; Bicyclo[3.3.1]nonane; Tricyclo[7.2.1.0<sup>2,7</sup>]dodecane; Tricyclo[7.3.1.0<sup>2,7</sup>]tridecane; Bicyclo[3.1.1]heptane; Bicyclo[4.3.1]decane.

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assigning relative stereochemistry of 13-*R*-tricyclo[7.3.1.0<sup>2,7</sup>]tridec-2(7)-enes, 9-*R*-bicyclo[3.3.1]non-2-enes, 12-*R*-tricyclo[7.2.1.0<sup>2,7</sup>]dodec-2(7)-enes and 8-*R*-bicyclo[3.2.1]oct-2-enes by visual inspection of <sup>13</sup>C NMR spectra. With this purpose, we have analyzed <sup>13</sup>C NMR spectra for compounds **1–20** (Scheme 1).

## 2. Methodology

All ab initio calculations were performed using the Dalton program package<sup>11</sup> on Beowulf Linux cluster. All geometries employed were fully optimized in the C<sub>1</sub> symmetry at the HF level of theory using the TZ basis set of Ahlrichs and co-workers<sup>12</sup> with two polarization functions. The resulting geometries were characterized at the same levels of theory by performing frequency calculations. The optimal structures were then used to calculate the absolute chemical shielding using the GIAO<sup>13</sup> method, as implemented in

Dalton. The calculated <sup>13</sup>C NMR shielding values were referenced to SiMe<sub>4</sub> ( $\sigma_{\text{C}}=195.11$  ppm at the same computational level).

## 3. Results and discussion

Skeletal <sup>13</sup>C NMR chemical shifts for compounds **1–10**, **13–21**, **23** were calculated and the experimental spectra (where available) are fully assigned (Tables 1 and 2). The experimental assigned spectra for compounds **1**, **18–20** was used for validate computational method. Generally, with the theoretical approach, one isolated molecule in vacuo in its equilibrium geometry is studied. Consequently, the experimental counterparts to the calculated absolute shielding values should be those measured in the gas phase extrapolated to zero density and temperature. Because the NMR experiments for studied compounds had to be carried out on samples in CDCl<sub>3</sub> solutions, the following issues

**Table 1.** Skeletal <sup>13</sup>C NMR chemical shifts (ppm) of tricyclo[7.3.1.0<sup>2,7</sup>]tridec-2(7)-ene and bicyclo[3.3.1]non-2-ene derivatives

Compound		<sup>1</sup> C	<sup>2</sup> C	<sup>3</sup> C	<sup>4</sup> C	<sup>5</sup> C	<sup>6</sup> C	<sup>7</sup> C	<sup>8</sup> C	<sup>9</sup> C	<sup>10</sup> C	<sup>11</sup> C	<sup>12</sup> C	<sup>13</sup> C
<b>1</b>	Calculated	31.05	138.93	26.76	22.77	22.41	27.62	137.25	34.54	25.67	32.06	18.88	26.70	30.59
	Experimental <sup>a</sup>	34.9	130.8	29.2	23.7	23.3	30.0	130.0	37.7	27.9	34.4	19.0	28.9	32.8
<b>2<sub>Z</sub></b>	Calculated	33.99	138.86	26.55	22.53	22.17	27.24	136.20	35.98	29.01	27.07	17.95	20.80	43.77
	Experimental <sup>b</sup>	38.05	129.88	27.87	23.08	22.99	29.27	129.05	38.25	31.05	28.70	17.46	22.23	48.08
<b>2<sub>E</sub></b>	Calculated	37.89	138.37	26.56	22.39	22.13	27.20	137.37	35.92	31.50	26.81	17.78	21.11	47.37
	Experimental <sup>b,c</sup>	40.35	130.07	27.51	—	22.94	29.21	—	38.36	32.78	—	17.35	21.86	51.88
<b>3<sub>Z</sub></b>	Calculated	36.44	135.12	27.07	22.62	22.41	27.47	139.16	31.24	29.90	31.09	17.80	27.08	44.65
	Experimental <sup>b</sup>	40.05	127.19	28.31	23.20	23.07	29.53	130.85	33.17	31.80	33.13	17.15	29.14	49.40
<b>3<sub>E</sub></b>	Calculated	38.03	135.71	27.04	22.55	22.14	27.33	138.36	30.88	33.27	31.79	17.59	27.21	49.00
	Experimental <sup>b,d</sup>	41.17	127.00	28.39	—	22.92	29.45	131.03	32.82	34.35	33.32	16.91	29.06	53.75
<b>4</b>	Rotamer <i>−sc</i> , $\Delta E=3.75$	5.41	20.82	3.95	3.37	3.32	4.05	20.24	5.38	5.04	3.84	2.69	3.02	7.01
	Rotamer <i>ap</i> , $\Delta E=0$	24.87	93.39	18.03	15.31	15.11	18.44	92.29	24.10	20.90	17.40	12.57	13.65	31.31
	Rotamer <i>+sc</i> , $\Delta E=3.32$	7.01	24.46	4.75	4.01	3.95	4.82	24.30	6.47	5.36	4.57	3.19	3.61	8.32
	Weighted average <sup>f</sup>	37.29	138.67	26.73	22.69	22.38	27.31	136.83	35.95	31.30	25.81	18.45	20.28	46.64
	Experimental	41.55	129.88	28.89	23.23	23.15	29.33	129.64	39.03	33.89	26.90	17.92	21.21	50.80
<b>5</b>	Rotamer <i>−sc</i> , $\Delta E=0$	19.58	63.38	12.93	10.71	10.54	12.86	64.43	14.46	14.78	51.34	8.46	12.79	22.92
	Rotamer <i>ap</i> , $\Delta E=4.36$	3.05	10.77	2.21	1.86	1.81	2.21	11.09	2.56	2.55	2.55	1.47	2.17	3.96
	Rotamer <i>+sc</i> , $\Delta E=0.10$	16.70	61.54	12.22	10.25	10.10	12.34	61.02	13.88	15.72	14.47	8.10	12.41	22.07
	Weighted average	39.33	135.69	27.36	22.82	22.45	27.41	136.54	30.90	33.05	32.36	18.03	27.37	48.95
	Experimental	43.35	126.94	28.86	23.41	23.25	29.50	129.40	32.86	35.19	34.06	17.30	29.57	53.11
<b>6</b>	Calculated	38.42	138.41	26.67	22.60	22.36	27.39	137.28	35.68	32.65	27.11	18.64	21.60	66.67
	Experimental <sup>b</sup>	41.46	130.10	28.32	23.25	23.17	29.46	129.31	38.36	34.25	28.79	18.28	22.72	69.16
<b>7</b>	Calculated	38.82	135.16	27.20	22.89	22.21	27.38	137.81	32.08	33.12	31.75	18.09	26.62	68.27
	Experimental <sup>b</sup>	41.87	126.64	29.37	23.42	23.28	29.61	130.42	34.13	34.57	33.30	17.56	27.89	70.61
<b>8</b>	Rotamer <i>−sc</i> , $\Delta E=0$	19.11	67.34	13.19	11.14	10.99	13.45	68.02	17.49	14.67	12.67	9.01	10.30	31.54
	Rotamer <i>ap</i> , $\Delta E=5.03$	2.37	8.93	1.73	1.46	1.44	1.76	8.88	2.32	1.99	1.67	1.15	1.33	4.13
	Rotamer <i>+sc</i> , $\Delta E=0.27$	15.78	61.09	11.73	9.97	9.86	12.02	60.14	15.56	14.53	11.59	8.08	8.95	28.28
	Weighted average	37.26	137.36	26.65	22.57	22.29	27.23	137.04	35.37	31.19	25.93	18.24	20.58	63.95
	Experimental	41.15	129.83	28.86	23.12	23.12	29.25	128.54	38.47	33.61	27.21	17.87	21.64	70.49
<b>9</b>	Rotamer <i>−sc</i> , $\Delta E=6.06$	2.56	9.42	1.89	1.60	1.56	1.91	9.50	2.20	2.36	2.17	1.25	1.84	4.63
	Rotamer <i>ap</i> , $\Delta E=0$	31.05	109.31	21.92	18.33	18.08	22.18	111.43	24.73	25.73	25.28	14.35	21.56	52.48
	Rotamer <i>+sc</i> , $\Delta E=4.70$	4.86	16.01	3.30	2.78	2.71	3.31	16.86	3.80	3.68	3.75	2.17	3.18	8.00
	Weighted average	38.47	134.74	27.11	22.71	22.35	27.40	137.79	30.73	31.77	31.20	17.77	26.58	65.11
	Experimental	42.81	126.45	29.25	23.31	23.14	29.59	130.60	32.93	34.43	33.03	16.96	28.30	72.41
<b>10</b>	Calculated	27.16	137.72	136.35	30.00	25.19	31.88	18.07	27.44	29.70				
	Experimental <sup>g</sup>	29.6	130.5	129.4	32.4	27.2	34.2	18.2	29.2	31.8				
<b>11</b>	Experimental <sup>h</sup>	36.20	128.01	129.07	33.61	33.30	27.03	17.07	22.20	69.84				
<b>12</b>	Experimental <sup>h</sup>	37.68	125.97	130.30	28.14	34.16	32.91	16.23	28.98	71.58				

<sup>a</sup> Data taken from Ref. 14.

<sup>b</sup> Data are identically published.<sup>9</sup>

<sup>c</sup> Signals of the C(4), C(7) and C(10) atoms are masked by superimposed signals of the more stable conformer.

<sup>d</sup> Signal of the C(4) atom is masked by superimposed signals of the more stable conformer.

<sup>e</sup> Values in kJ mol<sup>−1</sup>, relative to the most stable rotamer.

<sup>f</sup> Weighted average for each carbon was calculated based on the sum of the GIAO predicted chemical shift values for each rotamers weighted by the distribution coefficient.

<sup>g</sup> Data taken from Ref. 15.

<sup>h</sup> Data taken from Ref. 16.

**Table 2.** Skeletal  $^{13}\text{C}$  NMR chemical shifts (ppm) of tricyclo[7.2.1.0<sup>2,7</sup>]dodec-2(7)-ene and bicyclo[3.2.1]oct-2-ene derivatives, bicyclo[3.1.1]hept-2-ene and bicyclo[4.3.1]dec-7-ene

Compound		<sup>1</sup> C	<sup>2</sup> C	<sup>3</sup> C	<sup>4</sup> C	<sup>5</sup> C	<sup>6</sup> C	<sup>7</sup> C	<sup>8</sup> C	<sup>9</sup> C	<sup>10</sup> C	<sup>11</sup> C	<sup>12</sup> C
<b>13</b> <sup>a</sup>	Calculated	37.08	143.84	27.30	22.75	22.41	27.20	132.33	38.52	31.53	28.36	32.02	33.82
<b>14</b> <sup>a</sup>	Rotamer –sc, $\Delta E^b=5.34$	3.88	13.36	2.51	2.08	2.06	2.48	12.11	3.60	3.75	2.38	2.66	5.11
	Rotamer ap, $\Delta E=0$	34.31	114.01	21.69	18.05	17.83	21.52	105.20	30.58	30.13	21.55	23.82	42.96
	Rotamer +sc, $\Delta E=4.84$	5.17	16.21	3.10	2.56	2.52	3.05	14.99	4.48	4.12	2.95	3.25	6.27
	Weighted average <sup>c</sup>	43.36	143.58	27.30	22.69	22.41	27.05	132.30	38.66	38.00	26.88	29.73	54.34
<b>15</b>	Rotamer –sc, $\Delta E=0$	23.79	76.17	15.38	12.49	12.34	14.83	73.03	18.45	18.65	14.72	16.26	28.08
	Rotamer ap, $\Delta E=6.29$	1.80	5.91	1.20	0.99	0.97	1.16	5.76	1.47	1.51	1.19	1.31	2.17
	Rotamer +sc, $\Delta E=0.71$	16.76	57.85	11.38	9.35	9.23	11.12	53.96	13.89	14.71	11.26	12.12	21.18
	Weighted average	42.35	139.93	27.96	22.83	22.54	27.11	132.75	34.01	34.87	27.17	29.69	51.43
	Experimental <sup>d</sup>	45.9	131.4	30.0	23.2	23.1	29.2	125.0	36.4	37.0	29.6	32.0	55.4
<b>16</b> <sup>a</sup>	Rotamer –sc, $\Delta E=0$	22.02	69.75	13.44	11.13	10.98	13.28	65.71	18.90	17.97	13.11	14.65	35.26
	Rotamer ap, $\Delta E=5.49$	2.30	7.70	1.47	1.21	1.20	1.44	7.14	2.09	2.02	1.37	1.53	3.89
	Rotamer +sc, $\Delta E=0.21$	18.96	64.98	12.32	10.24	10.12	12.20	59.76	17.27	17.93	12.11	13.40	32.47
	Weighted average	43.28	142.43	27.23	22.58	22.30	26.92	132.61	38.26	37.92	26.59	29.58	71.62
<b>17</b>	Rotamer –sc, $\Delta E=7.86$	1.49	5.15	1.03	0.85	0.83	1.00	4.92	1.27	1.30	0.97	1.05	2.51
	Rotamer ap, $\Delta E=0$	36.27	123.72	24.62	20.15	19.92	24.12	119.14	29.83	29.59	22.95	24.81	59.45
	Rotamer +sc, $\Delta E=6.14$	3.16	10.16	2.08	1.71	1.68	2.02	10.10	2.54	2.48	1.93	2.14	5.02
	Weighted average	40.92	139.03	27.73	22.71	22.43	27.14	134.16	33.64	33.37	25.85	28.00	66.98
	Experimental	44.96	130.95	29.80	23.19	23.02	29.26	126.55	36.40	35.90	28.26	30.16	74.38
<b>18</b>	Calculated	32.76	142.21	131.58	34.49	31.15	28.43	33.38	33.30				
	Experimental <sup>e</sup>	35.6	134.7	123.8	37.5	33.6	30.6	35.5	35.5				
<b>19</b>	Rotamer –sc, $\Delta E=0$	20.84	72.15	68.42	17.76	18.76	13.79	16.04	36.75				
	Rotamer ap, $\Delta E=5.72$	1.97	7.23	6.75	1.79	1.92	1.31	1.52	3.68				
	Rotamer +sc, $\Delta E=0.44$	16.27	61.01	56.47	14.70	16.99	11.57	13.30	30.68				
	Weighted average	39.08	140.39	131.64	34.25	37.67	26.67	30.86	71.11				
	Experimental <sup>e</sup>	42.3	132.6	124.2	37.5	40.7	28.3	32.6	78.1				
<b>20</b>	Rotamer –sc, $\Delta E=8.27$	1.13	4.29	4.13	0.95	1.09	0.82	0.93	2.10				
	Rotamer ap, $\Delta E=0$	32.30	121.65	118.44	26.30	29.06	25.89	29.31	58.52				
	Rotamer +sc, $\Delta E=5.81$	3.22	11.39	11.45	2.57	2.80	2.20	2.55	5.64				
	Weighted average	36.65	137.33	134.02	29.82	32.95	28.91	32.79	66.26				
	Experimental <sup>e,f</sup>	39.8	129.9	126.6	31.5	35.7	28.4	32.2	73.5				
<b>21</b> <sup>a</sup>	Calculated	29.71	145.91	130.34	31.59	30.59	31.87	31.87					
<b>23</b> <sup>a</sup>	Calculated	25.73	33.13	24.67	27.35	32.13	30.64	139.23	133.46	31.40	28.52		

<sup>a</sup> Experimental data are absent.<sup>b</sup> Values in  $\text{kJ mol}^{-1}$ , relative to the most stable rotamer.<sup>c</sup> Weighted average for each carbon was calculated based on the sum of the GIAO predicted chemical shift values for each rotamers weighted by the distribution coefficient.<sup>d</sup> Data taken from Ref. 10.<sup>e</sup> Data taken from Ref. 17.<sup>f</sup> Ref. 18.

complicated comparison of the theoretical and experimental data. Gas-to-liquid transition and solvation effects generate a large shift in shieldings. In general, vibrational motion perturbs chemical shifts,<sup>19</sup> but for many cases, this correction may be negligible.

It should be noted that the calculated chemical shifts for all compounds tend, as a rule, to be underestimated for the saturated carbons (0.13–7.4 ppm) and overestimated for the olefinic carbons (6.95–9.06 ppm) than the observed ones. It can be traced back to the neglect of electron correlation contribution in the SCF approach. However, we find fairly reasonable linear correlations ( $0.994 < R^2 < 0.999$ ) between

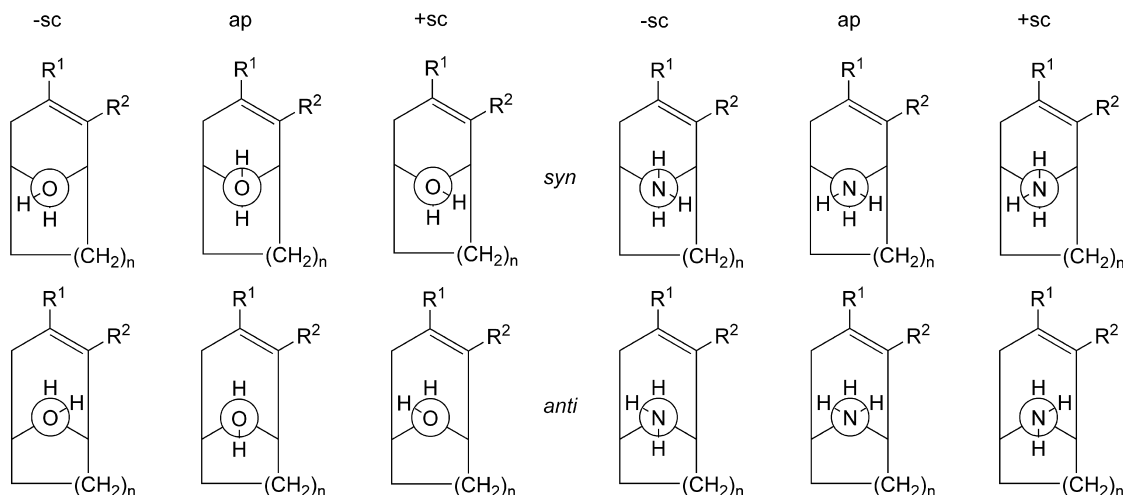
**Table 3.** Correlation parameters (slope, intercept and  $R^2$  factor) between experimental assigned and theoretical chemical shifts for compounds **1**, **18**–**20**<sup>a</sup>

Compound	Slope	Intercept	$R^2$ factor
<b>1</b>	1.0917	–4.675	0.9988
<b>18</b>	1.1060	–6.120	0.9998
<b>19</b>	1.1078	–6.410	0.9995
<b>20</b>	1.1081	–4.908	0.9937

<sup>a</sup> Data are plotted as  $\delta(\text{GIAO}) = \text{intercept} + \text{slope} \times \delta(\text{exp})$ .

experimental assigned and theoretical chemical shifts for compounds **1**, **18**–**20** (Table 3). The correct order of shifts is given with just one exception for C(1) atom in hydrocarbons **1** and **18**, but its assignment can be easily corrected by NMR experiments with  $J$ -modulated spin-echo sequence. That procedure was used for correction of C(1) atom assignment for hydrocarbons **10** and **13** also. We proceeded with our work using the assumption that calculated intramolecular chemical shift differences for the two olefinic carbons using identical levels of theory and basis sets can greatly reduce this type of systematic error, and achieve much higher accuracy than chemical shifts calculated relative to a standard.

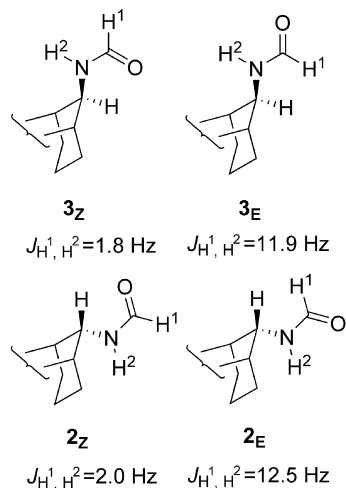
Alcohols and amines introduce the problem of conformational mobility of substituent on a fixed bicyclic framework. The observed chemical shifts at ambient temperature are time-averaged values from weighted average of contributing conformations. It has been recently shown that to reproduce the experimental  $^{13}\text{C}$  NMR results for isomeric 2-norbornanols, the conformational-averaged values are used in calculations of chemical shifts.<sup>20</sup> The hydroxyl or amino proton(s) can occupy three different positions associated with the energy minima in rotation about



**Scheme 2.4,5:**  $n=2$ ,  $R^1+R^2=(CH_2)_4$ ; **8,9:**  $n=2$ ,  $R^1+R^2=(CH_2)_4$ ; **11,12:**  $n=2$ ,  $R^1=R^2=H$ ; **14,15:**  $n=1$ ,  $R^1+R^2=(CH_2)_4$ ; **16,17:**  $n=2$ ,  $R^1+R^2=(CH_2)_4$ ; **19,20:**  $n=1$ ,  $R^1=R^2=H$ .

the C–O or C–N bond, shown as ap(antiplanar) and  $\pm$ sc(synclinal) rotamers with respect to the relationship between H–H or H–lone pair moieties (Scheme 2). The ab initio energies of all rotamers were computed in order to estimate the rotamer populations at 298 K based on the Boltzmann's equation. On the basis of the populations of the rotamers, the weighted average chemical shifts were obtained for compounds **4**, **5**, **8**, **9**, **14–17**, **19**, **20**. The conformational behavior of methyl-substituted hydrocarbon chains does not depend on solvation, as has been demonstrated by the analysis of  $^3J_{C,C}$  coupling constants for certain model compounds.<sup>21</sup> It can thus be expected that the energetic order of the rotamers does not change significantly when going from the gas phase to a  $CDCl_3$  solution.

Experimental  $^{13}C$  NMR spectra of formylamines **2** and **3** have double sets of signals.<sup>9</sup> The existence of an equilibrium mixture of conformers with different amide group orientations has been cited as a possible reason. Our calculations show a ratio of conformers  $3_Z:3_E=7:1$  for isomer **3** and a ratio of conformers  $2_Z:2_E=3:1$  for isomer **2**. The experimental  $^1H$  NMR spectra also show the presence of two conformers in a ratio  $Z:E=3:1$  for both compounds. These



**Scheme 3.**

results are consistent with  $^3J$  coupling of formyl protons<sup>22,23</sup> (Scheme 3). Vicinal constants for protons on adjacent stereogenic centers typically fall in the range  $J_{anti(E)} > J_{syn(Z)}$ .<sup>24</sup>

Stereoisomeric pairs of 13-*R*-tricyclo[7.3.1.0<sup>2,7</sup>]tridec-2(7)-ene, 9-*R*-bicyclo[3.3.1]non-2-ene, 12-*R*-tricyclo[7.2.1.0<sup>2,7</sup>]dodec-2(7)-ene and 8-*R*-bicyclo[3.2.1]oct-2-ene systems show some distinctions in the chemical shifts of the respective carbons. In particular, the carbon chemical shift difference of the double bond ( $\Delta\delta_{C=C}$ ) is specific for each isomer, without dependence on a substituent (Table 4). The reason for this specificity is the influence of the  $\gamma$ -*gauche* effect on the  $^{13}C$  chemical shift of the C(2) atom.<sup>25,26</sup> In

**Table 4.**  $^{13}C$  NMR chemical shift differences (ppm) of the double bond for various cyclic systems

Compounds	$\Delta\delta_{C=C}$ anti-isomer	$\Delta\delta_{C=C}$ syn-isomer
<i>13-R-tricyclo[7.3.1.0<sup>2,7</sup>]tridec-2(7)-ene</i>		
Hydrocarbon		0.8
Formylamines <sup>a</sup>	0.83	3.66
Amines	0.24	2.46
Shiff bases	0.79	3.78
Alcohols	1.29	4.15
<i>9-R-bicyclo[3.3.1]non-2-ene</i>		
Hydrocarbon		1.1
Alcohols	1.06	4.33
<i>12-R-tricyclo[7.2.1.0<sup>2,7</sup>]dodec-2(7)-en</i>		
Hydrocarbon		11.51 <sup>b</sup>
Amines	—	6.4
	11.28 <sup>b</sup>	7.18 <sup>b</sup>
Alcohols	—	4.4
	9.82 <sup>b</sup>	4.87 <sup>b</sup>
<i>8-R-bicyclo[3.2.1]oct-2-ene</i>		
Hydrocarbon		10.9
Alcohols	8.4	3.3
<i>7-R-bicyclo[3.1.1]hept-2-ene</i>		
Hydrocarbon		15.57 <sup>b</sup>
<i>10-R-bicyclo[4.3.1]dec-7-ene</i>		
Hydrocarbon		5.77 <sup>b</sup>

<sup>a</sup> Conformers **2<sub>Z</sub>** and **3<sub>Z</sub>**; paper<sup>8</sup> contains incorrect  $\Delta\delta_{C=C}$  values.

<sup>b</sup> Based on theoretical spectra.

**Table 5.**  $\gamma$ -Substituent effects<sup>a</sup> on the skeletal carbon shieldings of various cyclic systems

Compound	$\gamma$ -anti	$\gamma$ -gauche
<i>13-R-tricyclo[7.3.1.0<sup>2,7</sup>]tridec-2(7)-ene</i>		
<b>2<sub>Z</sub></b>	-0.92 C(2) 0.55 C(8)	-5.70 C(10) -6.67 C(12)
<b>3<sub>Z</sub></b>	-1.27 C(10) 0.24 C(12)	-3.61 C(2) -4.53 C(8)
<b>4</b>	-0.92 C(2) 1.33 C(8)	-7.50 C(10) -7.69 C(12)
<b>5</b>	-0.34 C(10) 0.67 C(12)	-3.86 C(2) -4.84 C(8)
<b>6</b>	-0.70 C(2) 0.66 C(8)	-5.61 C(10) -6.18 C(12)
<b>7</b>	-1.10 C(10) -1.01 C(12)	-4.16 C(2) -3.57 C(8)
<b>8</b>	-0.97 C(2) 0.77 C(8)	-7.19 C(10) -7.26 C(12)
<b>9</b>	-1.37 C(10) -0.60 C(12)	-4.35 C(2) -4.77 C(8)
<i>9-R-bicyclo[3.3.1]non-2-ene</i>		
<b>11</b>	-2.49 C(2) 1.21 C(4)	-7.17 C(6) -7.00 C(8)
<b>12</b>	-1.29 C(6) -0.22 C(8)	-4.53 C(2) -4.26 C(4)
<i>12-R-tricyclo[7.2.1.0<sup>2,7</sup>]dodec-2(7)-en<sup>b</sup></i>		
<b>14</b>	-0.26 C(2) 0.14 C(8)	-1.48 C(10) -2.29 C(11)
<b>15</b>	-1.19 C(10) -2.33 C(11)	-3.91 C(2) -4.51 C(8)
<b>16</b>	-1.41 C(2) -0.26 C(8)	-1.77 C(10) -2.44 C(11)
<b>17</b>	-2.51 C(10) -4.02 C(11)	-4.81 C(2) -4.88 C(8)
<i>8-R-bicyclo[3.2.1]oct-2-ene</i>		
<b>19</b>	-2.1 C(2) 0 C(4)	-2.3 C(6) -2.9 C(7)
<b>20</b>	-2.2 C(6) -3.3 C(7)	-4.8 C(2) -6.0 C(4)

<sup>a</sup>  $\Delta\delta^X = \delta_C^{R-X} - \delta_C^{R-H}$  where R-H=unsaturated hydrocarbon (in ppm); negative values indicate upfield shifts.

<sup>b</sup> Based on theoretical spectra.

*anti*-forms the C(2) atom is under the influence of a small  $\gamma$ -*anti* effect, while in *syn*-forms the same atom experiences a large upfield shift as a result of the  $\gamma$ -*gauche* effect (Table 5). The  $\gamma$  effect influences the corresponding aliphatic carbons too, but the application of their signals as a diagnostic sign is inconvenient because the assignment by visual inspection of the experimental spectra is not straightforward.

The relative configuration of tricyclo[7.3.1.0<sup>2,7</sup>]tridec-2(7)-enes **2–9** is established.<sup>8,9</sup> For these compounds a smaller  $\Delta\delta_{(C=C)}$  value corresponds to the *anti*-forms, while the *syn*-forms have a larger one (Table 4). The  $\Delta\delta_{(C=C)}$  for hydrocarbon **1** is relatively close to the same value for the *anti*-forms (compounds **2, 4, 6, 8**) and significantly farther apart from it for the *syn*-forms (compounds **3, 5, 7, 9**). This finding is a characteristic feature. It is referred that a 2:3 mixture of isomeric bicyclo[3.3.1]non-2-en-9-ols has been received.<sup>17</sup> An assignment of <sup>13</sup>C NMR spectra was made, but a relative configuration of these products was not specified. Our finding allows us to assign the major isomer to the *anti*-form **11** and the minor to the *syn*-form **12** (Table 1).

The relative configuration of *syn*-amine **15** is established,<sup>10</sup> but the *anti*-isomer was not isolated. Mathematically, the  $\gamma$ -substituent effect defined as a difference  $\delta_C^{R-X} - \delta_C^{R-H}$ , but the experimental spectrum for hydrocarbon **13** is absent, so a theoretical spectrum was calculated. Also we carried out calculations of spectra for compounds **14–17**. The  $\gamma$  effect values based on the theoretical spectra are presented in Table 5. A larger  $\Delta\delta_{(C=C)}$  value corresponds to the *anti*-forms (compounds **14, 16**) and only slightly different from it for hydrocarbon **13**, while a smaller value corresponds to the *syn*-forms (compound **15**). It is noteworthy that the difference between the theoretical and experimental  $\Delta\delta_{(C=C)}$  values for 12-*R*-tricyclo[7.2.1.0<sup>2,7</sup>]dodec-2(7)-ene system does not exceed 0.8 ppm. Thus, obtained compound **17** we have assigned to the *syn*-form. This rule applies also to alcohols **19** and **20**.

The dispersion of  $\Delta\delta_{(C=C)}$  values for the *anti*-forms of 13-*R*-tricyclo[7.3.1.0<sup>2,7</sup>]tridec-2(7)-ene/9-*R*-bicyclo[3.3.1]non-2-ene systems is 0.24–1.29 ppm and for the *syn*-forms-2.46–4.33 ppm. In the case of 12-*R*-tricyclo[7.2.1.0<sup>2,7</sup>]dodec-2(7)-ene/8-*R*-bicyclo[3.2.1]oct-2-ene systems, dispersion of these values for the *anti*-forms is 8.4–11.3 ppm and for the *syn*-forms-3.3–6.4 ppm. Formally, the relative  $\Delta\delta_{(C=C)}$  values for isomeric forms of mentioned systems are inverted. This is due to the distinction between  $\Delta\delta_{(C=C)}$  values for corresponding unsaturated hydrocarbons. The  $\Delta\delta_{(C=C)}$  value for hydrocarbons **1** and **10** does not exceed 1.1 ppm and a large upfield  $\gamma$ -*gauche* effect for the C(2) atom of *syn*-isomers **3, 5, 7, 9, 12** leads to an increase of that quantity. In the case of *syn*-isomers **15, 17** and **20**, the same effect leads to a decrease of initially large  $\Delta\delta_{(C=C)}$  value (ca. 11 ppm) for hydrocarbons **13** and **18**. In contrast, the *anti*-isomers for all systems showing  $\Delta\delta_{(C=C)}$  close to these values for corresponding hydrocarbons.

This finding can be extended to bicyclic systems **21** and **23**. For compound **23**, the two most stable twist-chair conformations of the seven-membered ring were taken into account. Theoretical  $\Delta\delta_{(C=C)}$  values for unsaturated hydrocarbons **21** and **23** are 15.57 and 5.77 ppm, respectively. For the *anti*-forms of 7-*R*-bicyclo[3.1.1]hept-2-ene and 10-*R*-bicyclo[4.3.1]dec-7-ene systems, estimated  $\Delta\delta_{(C=C)}$  should be near the value of corresponding hydrocarbon, while for the *syn*-forms it should be considerably smaller due to the influence of the  $\gamma$ -*gauche* effect. Compounds **21**<sup>27</sup> and **22**<sup>28</sup> are known, but experimental <sup>13</sup>C NMR data were omitted.

#### 4. Conclusions

The comparison of  $\Delta\delta_{(C=C)}$  values for some stereoisomer and respective hydrocarbon allows the *syn*-/*anti*-isomers to be distinguished without recourse to the calculations. For the *anti*-isomers of studied systems  $\Delta\delta_{(C=C)}$  should be near the value of respective hydrocarbon, and for the *syn*-isomers it should be considerably different. Moreover, the relative order of  $\Delta\delta_{(C=C)}$  values is transferable within the same bicyclic carbon framework, without dependence on a substituent. The specificity of  $\Delta\delta_{(C=C)}$  values for the two stereoisomers with known relative configurations permit an assignment of relative configuration for the stereoisomers

with another substituent at the bridged carbon, without experimental spectra for corresponding hydrocarbon, even if only one of the unknown isomers is available. Also it is possible to suggest that this rule will be kept for any alkyl substituents on the carbon–carbon double bond.

## 5. Experimental

The NMR spectra were obtained in the pulse Fourier transform mode using Bruker WM 250 spectrometer operating at 62.9 MHz ( $^{13}\text{C}$ ) and 250.1 MHz ( $^1\text{H}$ ). The spectral data were recorded in a  $\text{CDCl}_3$  solution with solvent or tetramethylsilane as an internal standard. For the preparation of **4**, **5**, **8** and **9** see the literature.<sup>8,9</sup> Alcohol **17** was obtained by  $\text{LiAlH}_4$  reduction of the appropriate ketone on the analogy with synthesis of **9**.<sup>8</sup>

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