Monatshefte für Chemie 137, 55–68 (2006)
DOI 10.1007/s00706-005-0404-x

Monatshefte für Chemie
Chemical Monthly
Printed in Austria

Ab Initio Studies on the Molecular Conformation of Lignin Model Compounds I. Conformational Preferences of the Phenolic Hydroxyl and Methoxy Groups in Guaiacol

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Received February 15, 2005; accepted (revised) April 25, 2005

Summary. The conformational preferences of the lignin guaiacyl structural unit were studied at the *MP*2/6-311G(d,p) level of theory using guaiacol (2-methoxyphenol) as model compound. The potential energy surface of guaiacol was investigated by the *ab initio* method with full geometry optimization by varying the torsion angles of the guaiacol functional groups (hydroxyl and methoxy). An overall of nine stationary points were located, four of which were found to be minima and the other five transition structures between them. The energy minima of guaiacol can adopt one *cisoid* and three *transoid* conformations for the hydroxyl and methoxy groups. The *transoid* structures differ by the orientation of the methoxy group inside and outside of the aromatic plane. The most stable *cisoid* conformer has an intramolecular hydrogen bond between phenolic hydrogen and methoxy oxygen with a binding energy of 18.09–18.51 kJ/mol as calculated with the second-order (*MP*2) and fourth-order (*MP*4SDQ) *Møller-Plesset* methods and with larger polarized basis sets including diffuse functions. When comparing the geometrical parameters of the global energy structure with relevant experimental data from crystallographic structures good agreement between the data was found. The saddle points, the effect of calculation level on the energy relative stability, the rotational barrier heights, and the relative concentrations of the conformers are also discussed.

Keywords. Guaiacol; Conformers; Transition states; *Ab initio* calculations; Energy stability.

Introduction

After cellulose lignin is the most abundant natural polymer being the main aromatic chemical compound of vegetal tissues [1, 2]. Lignin is a complex aromatic

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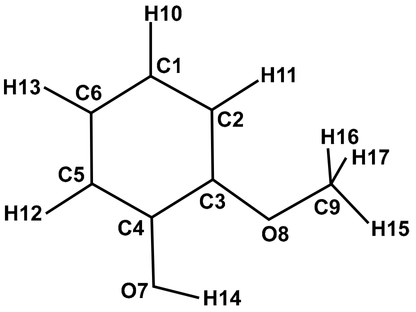

Scheme 1

heteropolymer, mainly deriving from the three hydroxycinnamyl alcohol monomers, which differ by their methoxylation degree: *p*-coumaryl, coniferyl, and sinapyl alcohols [3]. These monolignols produce *p*-hydroxyphenyl (*H*), guaiacyl (*G*), and syringyl (*S*) phenylpropanoid units when incorporated into the lignin polymer [4]. From these three types of structural elements in lignin, guaiacylpropane units are found in all lignins in various proportions [5]. Thus, guaiacylpropane units predominate in softwood lignins (*e.g.*, spruce *G*:*S*:*H* = 94:1:5 [6], loblolly pine *G*:*S*:*H* = 91:4:5 [5]), while hardwood lignins are composed of nearly equal amounts of guaiacylpropane and syringylpropane units (*e.g.*, beech *G*:*S*:*H* = 56:40:4 [7]). The guaiacyl structural units are characterized by the presence of hydroxyl and methoxy groups. The conformational analysis of these functional groups was done using guaiacol (2-methoxyphenol, **1**) as a model compound (Scheme 1).

Although many studies regarding the properties of **1** and its derivatives, in particular the strength of the intramolecular hydrogen bond have been published [8], there are few data on its molecular structure. A search regarding determination of the structure of **1** by X-ray or electron diffraction measurements has led to no result. Still, there is a crystallographic study on a guaiacol derivative, acetovanillone (4-hydroxy-3-methoxyacetophenone) [9], which could be used as comparison model. Theoretical studies of **1** were mainly focused on intramolecular [10–13] and intermolecular hydrogen bonds with a series of proton acceptors [14] using the CNDO/2 and PCILO methods, without offering any data on its molecular structure. Summary information on the molecular geometry of *cisoid* **1** based on the minimal basis set (STO-3G) has been reported [15]. On the conformation of the hydroxyl and methoxy groups of **1** calculations have been done with the MM molecular mechanics method [16].

In the present work, we investigated the preferential conformation of phenolic hydroxyl and methoxy groups in **1** using high level *ab initio* methods. We explored the potential energy surface of **1** locating the energy minima and transition state structures for interconversion. The theoretical models are compared with the available literature data for different compounds with an *o*-methoxyphenolic moiety.

Results and Discussion

The Potential Energy Surface

The potential energy surface of **1** calculated for the rotation of the dihedral angles specific for the hydroxyl and methoxy groups, C3–C4–O7–H14 and C2–C3–O8–C9,

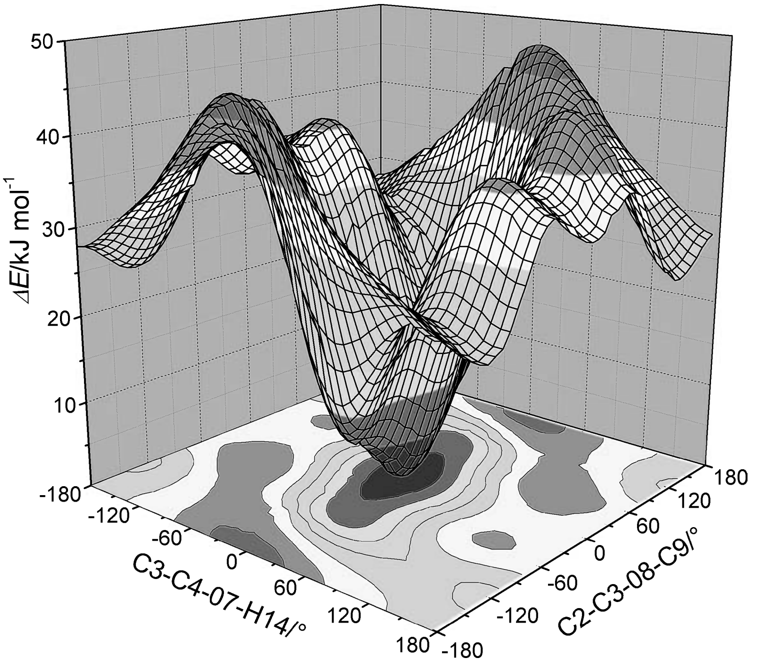

Fig. 1. The conformational energy surface (kJ/mol) of **1** as a function of C3–C4–O7–H14 (hydroxyl) and C2–C3–O8–C9 (methoxy) torsion angles calculated with the 6-31G basis set

is displayed in Fig. 1. From this plot it can be deduced that the global energy minimum corresponds to a conformation characterized by the C3–C4–O7–H14 and C2–C3–O8–C9 angles of almost 0° (**C1**). Thus, the functional groups have a *cisoid* arrangement. In this case, the spatial conformation of the functional groups favors the formation of an intramolecular hydrogen bond between the phenolic hydrogen and the methoxy oxygen, thus explaining the high stability of this conformer. A second energy minimum (**C2**) corresponds to a *transoid* arrangement for which the C3–C4–O7–H14 angle is 180°.

Based on the two lowest energy structures the potential energy curves were computed using the 6-31G(d) basis set maintaining a constant torsion angle and the variation of the second one. Figure 2a presents the variation of the potential energy as a function of the basis set for the rotation of the hydroxyl group, while the methoxy torsion angle is maintained constant at 0°. From this curve **1** can have only two conformations corresponding to the lowest energy structures found previously **C1** (0°) and **C2** (180°). The interconversion of these conformers is achieved via two symmetrical transition states **TS1** and **TS2**.

In Fig. 2b the hydroxyl torsion angle was maintained constant at 0° while the C2–C3–O8–C9 angle was varied. From the plot displayed in Fig. 2b it can be observed that for the 6-31G and 6-31G(d) level of theory there is no significant difference in the variation of the potential energy. In this case, the existence of a single equilibrium structure corresponding to the global energy minimum (**C1**) can be observed. Although from the graph results that the complete rotation of the methoxy group necessitates an energy of approximate 47.18 kJ/mol, for a value of the C2–C3–O8–C9 angle of approximate 180° no transition structure

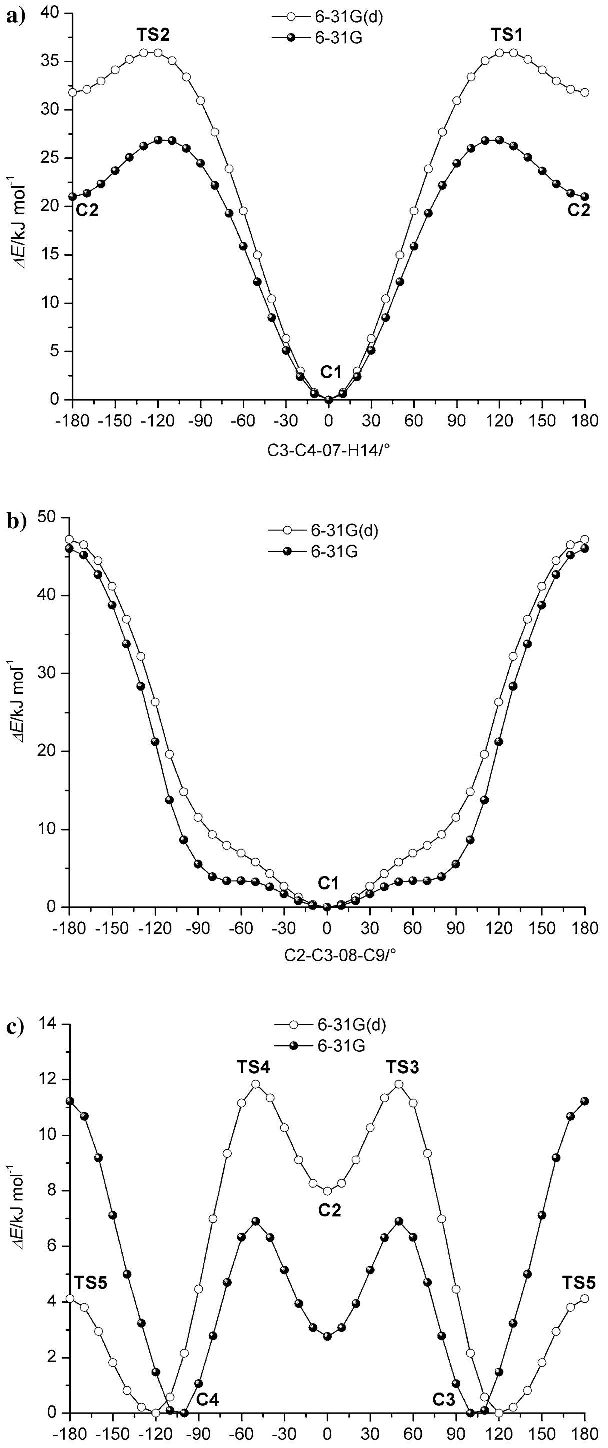

Fig. 2. The potential energy curves calculated with the 6-31G(d) and 6-31G basis sets by variation of the C3–C4–O7–H14 angle at 0° fixed C2–C3–O8–C9 angle (a), and by variation of the C2–C3–O8–C9 angle for fixed C3–C4–O7–H14 angle at 0° (b) and 180° (c)

was found due to the strong steric interactions between the hydroxyl and methoxy groups.

For the *transoid* conformer (C3–C4–O7–H14 180°) a more pronounced relaxation of the molecule appears making the methoxy group to adopt three different spatial orientations (Fig. 2c). A first arrangement corresponds to the **C2** conformer, while the other two conformations are arranged symmetrically on the potential energy curve for values of the C2–C3–O8–C9 angle of about 110 (**C3**) and −110° (**C4**). These conformers correspond to a nonplanar arrangement of the methoxy group. The interconversion from the planar conformation **C2** into the nonplanar conformations **C3** and **C4** is achieved *via* two transition states **TS3** (50°) and **TS4** (−50°). The interconversion of the nonplanar conformers

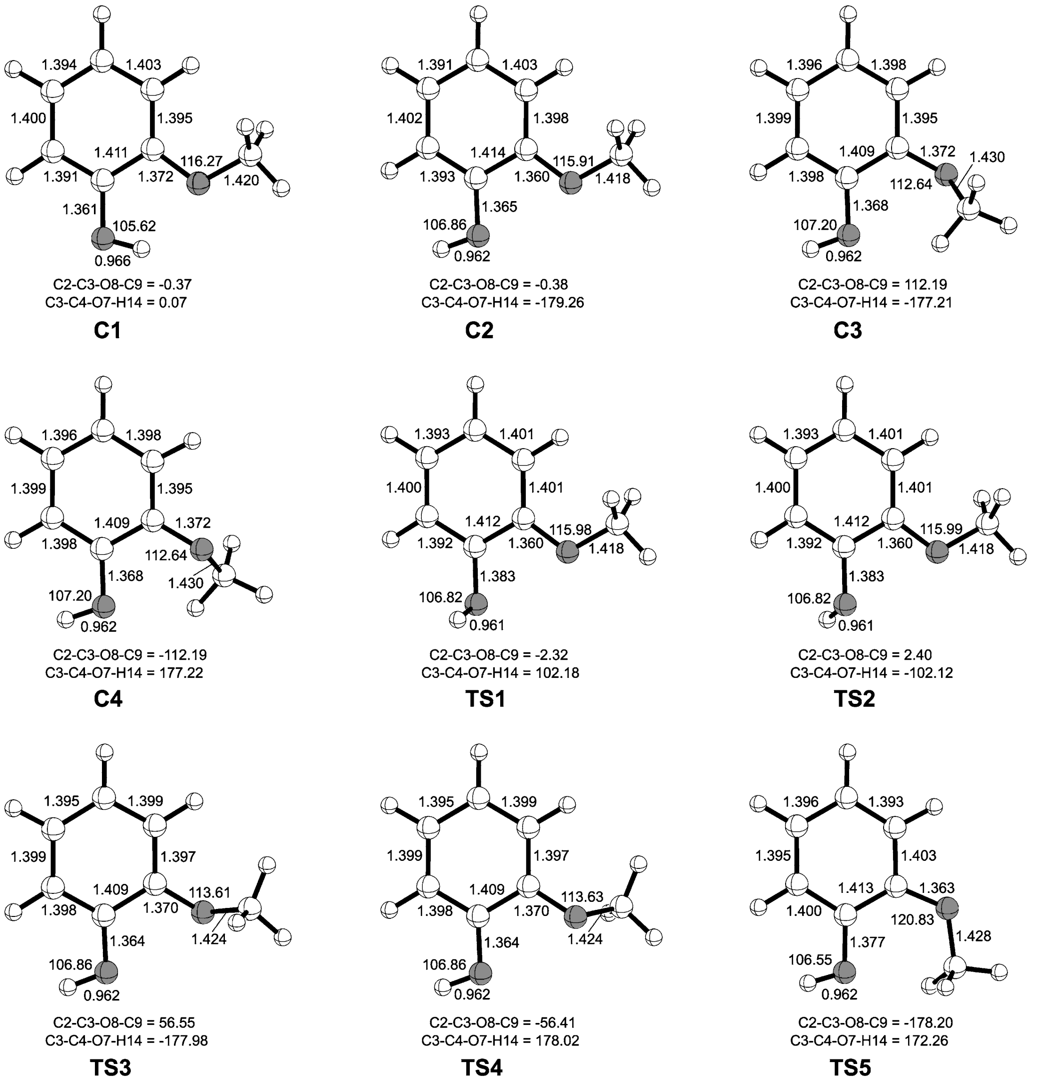

Fig. 3. The *MP*2/6-311G(d,p) fully optimized minimum energy structures (**C1–C4**) and transition states (**TS1–TS5**) located on the PES for **1**; distances in Å, angles in degree; black balls denote the positions of O atoms, large white balls those of C atoms, and small white balls those of H atoms

(**C3** ↔ **C4**) runs through the saddle point **TS5**, for which the hydroxyl and methoxy torsion angles have values of approximate 180°.

Molecular Geometry

From the potential energy curves it can be observed that for **1** there are four energy minima characterized by different spatial arrangements of the hydroxyl and methoxy groups. The interconversion of these structures crosses five saddle points. All lowest energy structures and transition states were fully optimized without any molecular constraint at the $MP2/6\text{-}311G(d,p)$ level of theory. In Fig. 3 the molecular geometry of all stationary points located on the potential energy surface are displayed.

Minimum Structures

Between the four energy minima found on the potential energy curves, the **C1** and **C2** conformers are characterized by the disposition in the aromatic ring plane of the hydroxyl and methoxy groups, whereas the **C3** and **C4** conformers correspond to a nonplanar arrangement of the methoxy group. Depending on the value of the hydroxyl torsion angle (C3–C4–O7–H14) a *cisoid* conformer (**C1**) and three *transoid* conformers (**C2**, **C3**, and **C4**) can be distinguished. For **1** the global energy minimum corresponds to the **C1** conformer for which the hydroxyl and methoxy torsion angles are approximate 0°.

From the calculations it can be derived that between the four energy minima there are no significant differences of the geometrical parameters, with the exception of the torsion angles specific for the functional groups. For **C2** the length of the bond between the aromatic carbon and the methoxy oxygen (C3–O8) is 1.360 Å, whereas for the other conformers the calculated values are 1.372 Å. The smallest C3–O8 bond length for this structure is due to the particular structure of this conformer inside which the steric interactions between the hydroxyl and methoxy groups are minimal. For the planar conformers **C1** and **C2** the phenolic oxygen atom together with the methoxy oxygen and carbon atoms are located in the plane defined by the aromatic carbon atoms. In this case the deviation from the planarity is very small (0.00016 Å (O7), 0.00062 Å (O8) and −0.00676 Å (C9) for **C1** and −0.00819 Å (O7), 0.00903 Å (O8) and 0.00387 Å (C9) for **C2**). For the **C3** and **C4** conformers phenolic and methoxy oxygen atoms are in the aromatic plane (±0.03219 Å for O7 and ±0.05283 Å for O8, while the methoxy carbon is ±1.15608 Å out of the respective plane).

The geometrical parameters calculated for the lowest energy conformer **C1** at the $MP2/6\text{-}311G(d,p)$ level of theory were compared with the experimental values obtained for structures similar to **1**, *i.e.* 4-hydroxy-3-methoxyacetophenone [9], phenol [17], and also with various compounds with an *o*-methoxyphenolic moiety [18–23]. For the aromatic carbon atoms a better correspondence between the calculated and experimental results can be observed. Thus, the medium value of the length of the bonds between the aromatic carbon atoms is 1.399 Å, the maximum difference compared to acetovanillone being of 0.015 Å, and 0.020 Å compared to phenol. For the aromatic bond angle the medium calculated value is 120.00°, the difference compared to the experimental data being 0.10–0.97° (acetovanillone) and 0.60–1.15° (phenol).

For the methoxy group the length of the $C_{aromatic}$–O bond is 1.372 Å, a value equal to the value obtained for acetovanillone, while the length of the O–$C_{aliphatic}$ bond is by 0.011 Å shorter compared to the experimental value of 1.431 Å. The values reported in literature for various compounds with a guaiacyl nucleus vary in the 1.354–1.373 Å range for the $C_{aromatic}$–O bond and 1.409–1.431 Å for the O–$C_{aliphatic}$ bond, the medium values being 1.368 and 1.421 Å. The calculated values of the ether bonds are 1.372 and 1.420 Å, which are equal to the medium of the experimental values. A good correspondence between the calculated values and experimental data exists also for the C2–C3–O8 and C3–O8–C9 bond angles, the difference compared to acetovanillone being of 0.38 and −0.53°. The theoretical values calculated for these bond angles are 126.28 and 116.27°, which are also close to the medium value for various guaiacyl model compounds (125.90 and 117.69°). The experimental value for the methoxy torsion angle (C2–C3–O8–C9) is −0.76° for acetovanillone while the calculated value is −0.37°. For the other *o*-methoxyphenolic compounds the data reported in literature for the C2–C3–O8–C9 torsion angle vary inside a larger domain of 0.67–9.02°.

For the methoxy group the calculated values are close to those of crystallographic studies. For the hydroxyl group the differences to literature data are in general larger. Thus, the length of the C–O bond is 1.361 Å (*MP*2/6-311G(d,p)), 1.375 Å (phenol), and 1.353 Å (acetovanillone). If the calculated C–O bond length is compared with the values obtained for various model compounds with guaiacyl nucleus (except acetovanillone) the theoretical value is close to the values reported in literature with the length of the C–O bonds varying inside the 1.360–1.369 Å domain.

Regarding the length of the O–H bond of compounds with the guaiacyl nucleus, literature data are contradictory, with the reported values varying in a very large domain of 0.819–0.985 Å [18–23]. The value of the O–H bond length obtained by calculation using the *MP*2/6-311G(d,p) method is 0.966 Å. For the two compounds taken as reference, the values are 0.819 Å (acetovanillone) and 0.957 Å (phenol). From the experimental data two categories of O–H bond lengths can be found in compounds with *o*-methoxyphenolic nucleus. Thus, for the lignin model compounds, the values reported in the literature vary inside the 0.819–0.841 Å domain [18–21], while for other categories of compounds with guaiacyl nucleus the reported values are inside the 0.910–0.985 Å domain [22, 23].

These differences between the experimental values and those calculated theoretically are also kept for the C–O–H bond angle. Thus, the value calculated for the C–O–H bond angle is 105.62°. The reported values are 113.53° for acetovanillone, 108.77° for phenol, 109.44–109.50° for lignin model compounds, and 109.62–120.52° for other compounds with the guaiacyl nucleus. The theoretical value for the C3–C4–O bond angle is 120.13°, whereas for acetovanillone the bond angle has the value of 122.00°, for phenol 117.01°, and the medium value for all the guaiacyl compounds being 121.18°. If for the theoretical model the hydroxyl group is found in the same plane of the aromatic ring (C3–C4–O7–H14 0.07°), for acetovanillone a deviation from planarity of 1.99° can be observed.

The values reported in literature for the hydroxyl torsion angle of various compounds with an *o*-methoxyphenolic ring is situated in a large domain between 0.63 and 10.17°.

Transition States

If the C2–C3–O8–C9 torsion angle is maintained constant at 0°, the rotation of the hydroxyl group leads to two energy minima **C1** and **C2**. The conversion from one conformer into another is achieved through two saddle points **TS1** and **TS2** (Figs. 2a and 3). For these structures the value of C3–C4–O7–H14 is 102.18° for **TS1** and $-102.12°$ for **TS2**. The two transition states have only one imaginary frequency corresponding to the rotation around the O–H bond. For **TS1** the imaginary frequency is $405.27i\,cm^{-1}$ whereas for the second transition structure it is $400.73i\,cm^{-1}$. Comparing the saddle points to the energy minima it can be derived that the methoxy group slightly deviates from coplanarity with the aromatic ring. Thus, for the **TS1** and **TS2** structures the deviation from the aromatic ring plane is an average of 2.36°, whereas for the minima structures the torsion angle of the methoxy group has the value of $-0.38°$. Other differences between the energy minima and the corresponding transition states can be noted regarding the length of the hydroxyl group bonds and the distance between the aromatic carbon and methoxy oxygen (C3–O8), the other geometrical parameters being identical. For transition states due to perpendicular orientation of the hydroxyl group on the aromatic ring plane, the C4–O7 bond is 0.022 Å longer compared to **C1**, while the O–H bond is by 0.005 Å shorter. For **TS1** and **TS2** the length of the C3–O8 bond is equal to the value obtained for **C2** (1.360 Å).

For the *transoid* conformers a more pronounced relaxation of the molecule appears due to the orientation of the hydroxyl group in the opposite direction towards the methoxy group leading to two spatial orientations of this group, in the aromatic plane (**C2**) and outside (**C3** and **C4**). The conversion of the *transoid* conformers proceeds through three transition states, namely **TS3** and **TS4** (Figs. 2b and 3) for the interconversion of the planar structures into nonplanar structures and **TS5** (Figs. 2c and 3) for interconversion of nonplanar structures. The saddle points **TS3** and **TS4** have only one imaginary frequency corresponding to the rotation around the $C_{aromatic}$–$O_{methoxy}$ bond. For **TS3** the value of the imaginary frequency is $64.05i\,cm^{-1}$ and it is $78.83i\,cm^{-1}$ for **TS4**. For these saddle points the torsion angle of the methoxy group (C2–C3–O8–C9) has the value of 56.55 (**TS3**) and $-56.41°$ (**TS4**), whereas for the nonplanar conformers **C3** and **C4** the calculated value is $\pm 112.19°$.

An interesting structure is **TS5** where the two functional groups are inside the molecular plane in a *cisoid* conformation. The optimization of this structure using a modest basis set leads to values for the two torsion angles of 180°. On the other hand, if using the *MP*2/6-311G(d,p) method a deviation of the functional groups from the planarity of 7.7 (hydroxyl) and 1.8° (methoxy) can be observed. The vibrational calculation done for the *MP*2/6-311G(d,p) transition structure indicates two imaginary frequencies: $306.48i\,cm^{-1}$ corresponding to some deformation vibrations of the aromatic ring and $96.59i\,cm^{-1}$ associated with torsional vibrations of the two functional groups. In contrast, *HF*/6-311G(d,p) vibrational calculation indicates the existence of a single torsional vibration of the methoxy group ($90.58\mathrm{i}\,\mathrm{cm}^{-1}$). The reoptimisation of the molecular geometry of **TS5** led to a structure in which the torsion angles have values of approximate 180° similar to the structures optimized using other basis sets, but the vibrational calculation indicates the existence of three negative frequencies.

Relative Stabilities, Rotational Barrier Heights

The total energies relative to the lowest energy stable conformer (**C1**) are reported in Table 1. The values obtained for the molecules optimized for a given basis set, together with the relative energies obtained from the single point calculations with several larger basis sets which include the *d*, *p*, and *f* polarization functions, and *s* and *sp* diffusion functions, both for the *Hartree-Fock* method (*HF*) and for second-order (*MP*2) and fourth-order (*MP*4SDQ) *Møller-Plesset* corrections. These last calculations were done using the molecular geometry optimized at the *MP*2/6-311G(d,p) level of theory.

From Table 1 it can be observed that the increase of the calculation level complexity leads to a reduction of the total relative energies. Thus, for the 6-31G basis set, the inclusion of the *d* polarization function for heavy atoms led to a decrease of the total relative energy with 10.77 kJ/mol (*HF*) and with 5.50 kJ/mol (*MP*2) for **C2**, and with 6.19 kJ/mol (*HF*) and 0.77 kJ/mol (*MP*2) for the nonplanar conformers **C3** and **C4**. The optimization of the molecular geometry using the 6-311G(d,p) basis set has a less pronounced effect on the relative energy compared to the values obtained for the 6-31G(d) basis set. Thus, the

Table 1. *Ab initio* (*HF*, *MP*2, *MP*4) energy differences ($\Delta E/\mathrm{kJ\,mol^{-1}}$) in relation to lowest energy conformer for **1**

	Structure								
	C1	**C2**	**C3**	**C4**	**TS1**	**TS2**	**TS3**	**TS4**	**TS5**
6-31G	0.00	31.78	23.60	23.60	35.87	35.87	35.60	35.60	27.93
6-31G(d)	0.00	21.01	18.10	18.10	26.89	26.89	25.13	25.13	29.47
6-311G(d,p)	0.00	20.92	17.53	17.53	26.37	26.37	25.03	25.03	29.45
*MP*2/6-31G	0.00	27.12	22.74	22.74	35.21	35.21	33.47	33.47	28.39
*MP*2/6-31G(d)	0.00	20.93	21.97	21.97	32.55	32.55	28.56	28.56	30.55
*MP*2/6-311G(d,p)	0.00	19.96	20.85	20.85	30.28	30.28	27.12	27.12	31.32
HF/6-311++G(2d,p)*	0.00	19.29	17.38	17.38	24.25	24.22	22.96	22.97	30.28
HF/6-311++G(2d,2p)*	0.00	19.16	17.51	17.51	23.99	23.96	23.02	23.03	30.37
HF/6-311++G(df,p)*	0.00	21.14	19.27	19.27	26.59	26.56	25.49	25.50	30.75
*MP*2/6-311++G(2d,p)*	0.00	19.05	22.03	22.03	29.67	29.66	27.78	27.77	31.58
*MP*2/6-311++G(2d,2p)*	0.00	18.87	22.46	22.46	29.28	29.26	28.05	28.04	31.73
*MP*2/6-311++G(df,p)*	0.00	18.99	19.93	19.93	29.81	29.82	25.46	25.45	32.54
*MP*4/6-311++G(2d,p)*	0.00	18.74	20.51	20.51	27.40	27.39	26.17	26.17	30.43
*MP*4/6-311++G(2d,2p)*	0.00	18.64	20.97	20.97	27.07	27.06	26.53	26.53	30.64
*MP*4/6-311++G(df,p)*	0.00	18.99	19.13	19.13	27.98	27.98	24.74	24.74	31.53

* Single point calculation using molecular geometry optimized at the *MP*2/6-311G(d,p) level of theory

energy difference for the structures optimized using the 6-31G(d) and 6-311G(d,p) basis sets is 0.09–0.57 kJ/mol (*HF*) and 0.97–1.12 kJ/mol (*MP*2).

The relative stabilities of the *transoid* conformers depend on the method used for the calculation. For the *HF* methods the values obtained indicate a greater stability of the nonplanar conformers compared to the planar structure. In this case the zero point energy's uncorrected energetic difference is 2.91–8.18 kJ/mol. Addition to the calculation of the *MP*2 correlation energy led to a decrease of energy difference between these conformers. Thus, for *MP*2/6-311G(d,p) structures the planar structure is by 0.89 kJ/mol more stable than the nonplanar conformers. In contrast, the inclusion of the relative zero point vibrational energies (ΔZPVE) is followed by the inversion of the relative stability order of the *transoid* conformers: **C2** being richer in energy by 0.31–0.49 kJ/mol compared with **C3** and **C4**. For the polarized 6-311G basis sets including diffuse functions, the values obtained using the *HF* method indicate for all calculations a greater stability of the nonplanar conformers. The energy difference being 1.65–1.91 kJ/mol compared to planar structure. In this case, the inclusion of the *MP*2 and *MP*4SDQ correlation energy leads to an inversion of the relative stabilities of the *transoid* conformers, meaning that **C2** is by 0.94–3.59 kJ/mol (*MP*2) and 0.14–2.33 kJ/mol (*MP*4) more stable than the nonplanar conformers. The addition of ΔZPVE (-1.20–-1.38 kJ/mol) led to the reduction of the energy difference between the *transoid* conformers and for the 6-311++G(df,p) basis set to the inversion of stability order.

From the data of Table 1 results that independent of the calculation level the global energy minimum corresponds to **C1** in which the functional groups adopt a *cisoid* arrangement. The *transoid* structures are by 17.38–31.78 kJ/mol more unstable depending on the basis set. Also, based on the small values of the energy difference between the *transoid* conformers we conclude that these structures are practically indistinguishable from the energetic point of view.

Table 2 reports the *ab initio* total *Gibbs* free energy differences (ΔG^{tot}) in relation to the lowest energy structure at room temperature. As for the total energy

Table 2. *Ab initio* total *Gibbs* free energy difference, $\Delta G^{tot}/\mathrm{kJ\,mol^{-1}}$, calculated with respect to the **C1** conformer and concentration of each conformer, $p/\%$, for true minimum energy structures on PES for **1**

	ΔG^{tot}				p			
	C1	**C2**	**C3**	**C4**	**C1**	**C2**	**C3**	**C4**
HF/6-311G(d,p)	0.00	18.77	13.29	13.28	99.01	0.05	0.47	0.47
*MP*2/6-311G(d,p)	0.00	20.00	16.83	17.83	99.75	0.07	0.11	0.07
*MP*2/6-311++G(df,p)*	0.00	19.03	15.91	16.91	99.64	0.10	0.16	0.11
*MP*3/6-311++G(df,p)*	0.00	19.41	14.59	15.59	99.47	0.09	0.27	0.18
*MP*4D/6-311++G(df,p)*	0.00	19.10	14.46	15.46	99.43	0.10	0.28	0.19
*MP*4DQ/6-311++G(df,p)*	0.00	19.29	14.26	15.26	99.40	0.09	0.30	0.20
*MP*4SDQ/6-311++G(df,p)*	0.00	19.03	15.11	16.11	99.54	0.10	0.22	0.15

* Single point calculation using *MP*2/6-311G(d,p) zero point vibrational energy and total *Gibbs* free energy

Table 3. Calculated rotational barrier heights (ΔE/kJ mol^{-1}) of the conformers of **1** using *Møller-Plesset* perturbation theory

	TS1-C1 **TS2-C1**	**TS1-C2** **TS2-C2**	**TS3-C2** **TS4-C2**	**TS3-C3** **TS4-C4**	**TS5-C3** **TS5-C4**
*MP*2/6-311G(d,p)	30.28	10.33	7.17	6.27	10.46
*MP*2/6-311++G(df,p)	29.81	10.82	6.47	5.53	12.61
*MP*3/6-311++G(df,p)	27.71	8.34	4.88	5.65	13.38
*MP*4D/6-311++G(df,p)	27.80	8.75	5.02	5.60	13.08
*MP*4DQ/6-311++G(df,p)	27.41	8.16	4.84	5.81	13.31
*MP*4SDQ/6-311++G(df,p)	27.98	8.99	5.75	5.61	12.40

stability, ΔG^{tot} predicts a greater stability of the *cisoid* conformer in disfavor of the *transoid* structures. In this case, the energy difference ΔG^{tot} between the two conformer categories optimized at the *MP*2/6-311G(d,p) level is inside the domain 16.83–20.00 kJ/mol. If the *transoid* conformers are compared it can be deduced that indifferent from the calculation level, the greater stability is reached by the nonplanar conformers disfavoring those with a planar structure. The energy difference between these two categories of structures being 3.12–5.48 kJ/mol depending on the basis set. The concentrations of all minima of **1** calculated based on the *ab initio* equilibrium constant ($K_{\mathrm{eq}} = \exp(-\Delta G/RT)$) is displayed in Table 2. According to these data, the highest concentration (99%) is reached by the global energy minimum, which adopts a *cisoid* conformation, while for the other conformers (*transoid*) the concentration is less than 0.50%.

The relative stabilities of the saddle points found on the potential energy curves of **1** in relation to the global energy minimum are presented in Table 1. Based on these values the barrier heights of the interconversion of the guaiacol conformers can be calculated for different calculation levels. Table 3 displays the influence of the correlation energy calculated using the *Møller-Plesset* perturbation theory on the rotational energy barrier. The conversion of **1** from the lowest energy structure **C1**, into the *transoid* conformer **C2** necessitates the highest energy. For *MP*2/6-311G(d,p) the barrier height is estimated 30.28 kJ/mol. The inclusion of the correlation energy using various perturbation theories leads to a reduction of the rotational barrier height of 0.47–2.87 kJ/mol.

For the *transoid* conformers the interconversion is much easier. The rotational energy barriers have in these cases values of 4.84–7.17 kJ/mol. The inclusion of the correlation energy leads to a reduction of the values registered for the ΔE(**TS3-C2**) with 0.70–2.33 kJ/mol. For ΔE(**TS3-C3**) the effect of the correlation energy on the value of the barrier height is much smaller. The interconversion of the nonplanar conformers **C3** ↔ **C4** through the **TS5** transition state is much richer in energy due to the planar orientation of the methoxy group. The direct interconversion of these two conformers through these transition states requires 10.46 kJ/mol (*MP*2/6-311G(d,p)). In this case, the inclusion of the *MP*3, *MP*4 correlation energy leads to an increase of the potential energy value. From an energetic point of view, the interconversion of the nonplanar conformers is much favored by the transition in a first step into the planar conformer, compared to the direct interconversion.

Hydrogen Bonds

The **C1** conformer of **1**, due to its peculiar structure (the orientation of the hydroxyl towards the methoxy) has an intramolecular hydrogen bond. This bond is formed between the hydroxyl group, which acts as a proton donor and the lone pair electrons of the methoxy oxygen, which act as proton acceptor. The presence of such a hydrogen bond in the structure of the global energy minimum explains its greater stability compared to the other guaiacol conformers. For the structure optimized with *MP*2/6-311G(d,p), the length of the hydrogen bond is shorter compared to the values obtained experimentally for various lignin model compounds [18–21] or for structures with the *o*-methoxyphenolic moiety [22, 23]. Thus, the theoretical value for the length $H \cdots O$ is 2.056 Å, whereas crystallographic studies of various compounds with a guaiacyl nucleus indicate values inside the 2.131–2.312 Å domain. For the other parameters of the hydrogen bond a much better concordance between the experimental and the theoretical results can be observed. Thus, the distance calculated between donor-acceptor centers is 2.639 Å, while the angle of the hydrogen bond is 117.02°. The variation limits of the two geometrical parameters determined for various compounds with an *o*-methoxyphenolic ring are 2.598–2.717 Å for the $O \cdots O$ distance and 98.35–116.15° for the hydrogen bond angle.

The energy of the hydrogen bond, which can be appreciated as the difference between the total energy of the open form (**C2**) and the energy of the chelated structure (**C1**), is equal to the relative total energy calculated for the **C2** conformer (Table 1). The inclusion of the vibrational energy at the zero point does not lead to substantial changes of the bonding energy, *Δ*ZPVE for the structures optimized with the 6-311G(d,p) basis set being −0.986 kJ/mol for the *HF* method and −0.541 kJ/mol for the *MP*2 method. For the structures optimized at the *MP*2/6-311G(d,p) level the value of the corrected hydrogen bond energy is 19.415 kJ/mol. The calculations based on second-order (*MP*2) and fourth-order (*MP*4SDQ) *Møller-Plesset* for the polarized 6-311G basis sets including diffuse functions indicate values for the hydrogen bond energies of 18.09–18.51 kJ/mol.

Conclusions

In this contribution we report a full characterization of the conformational preferences of the phenolic hydroxyl and methoxy groups for lignin guaiacyl structural units, based on **1** using high level *ab initio* method. From the potential energy surface results that hydroxyl and methoxy groups can adopt different spatial orientation. Our calculations indicate the existence of four stable conformers for **1**, which based on orientation of the hydroxyl group, can be classified as *cisoid* and *transoid*. The *transoid* structures are differentiated by the orientation of the methoxy group inside and outside of the aromatic plane. Five saddle points were identified as intermediates of the interconversion between the energy minima. Independent of the basis set or method employed for the optimization of the molecular geometry of the structures located on the potential energy surface, the global energy minimum is represented by the *cisoid* conformer. The geometrical parameters of the global energy structure are compared with the available experimental data for compounds with a similar structure, and a good agreement between experimental and theoretical data was found. The stability of the *cisoid* conformer in relation to the *transoid* conformers is evaluated as 18.09–18.51 kJ/mol based on the second-order (*MP*2) and the fourth-order (*MP*4SDQ) *Møller-Plesset* with complex basis sets. The high stability of the lowest energy structure is the consequence of the intramolecular hydrogen bond between the phenolic hydrogen and the free electron pairs of the methoxy oxygen.

Methods

The geometry optimization of structures and the energy calculations were carried out with the GAMESS program [24]. The potential energy surfaces for the internal rotation of the hydroxyl and methoxy groups in **1** were calculated using the 6-31G [25] and 6-31G(d) [26] basis sets. The selected torsion angles were varied in the −180–+180° domain with a 10° increment. For each rotamer an optimization of all the geometrical parameters was carried out with the exception of the selected torsion angles, which were maintained at constant values. All the stationary points located on the potential surfaces were fully optimized at the *MP*2/6-311G(d,p) level. In addition, equilibrium structures of **1** were optimized with 6-31G, 6-31G(d), and 6-311G(d,p) [27] basis sets. A vibrational analysis was conducted at each stationary point found in order to ascertain whether it corresponds to a minimum or to a transition structure on the potential energy surface and to compute thermodynamic functions. The harmonic frequency was scaled by 0.89 for 6-31G, 0.8953 for 6-31G(d), 0.9051 for 6-311G(d,p), and 0.9496 for *MP*2/6-311G(d,p) [28].

The *MP*2/6-311G(d,p) optimized structures were used to carry out single point calculations using the second-order (*MP*2) and the fourth-order (*MP*4SDQ) *Møller-Plesset* methods with larger polarized basis sets including diffuse functions as well, *i.e.* 6-311++G(2d,2p), 6-311++G(df,p). These particular calculations were done in order to evaluate the basis set and electron correlation effects on the energies and the stability of conformers.

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