Structural and vibrational studies of equilenin, equilin and estrone steroids

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ABSTRACT

Three species associated with estrogens have been studied in this work, equilenin, equilin and estrone. Their molecular structures have been theoretically studied in gas phase with the hybrid B3LYP/6-31G* method. NBO, AIM and frontier orbital calculations were computed for the three species at the same level of theory. Higher dipole moment and volume were observed for estrone while equilenin presents higher volume than equilenin but lower dipole moment value. Probably, the unsaturated C=C in the B ring of equilin could explain those differences. The differences observed in the properties could be clearly explained by differences in the dihedral angles. The analyses of MK and Mulliken charges evidence the higher variations on the C atoms common to the B, C and D rings in the three species. The mapped MEP surfaces show that both A and B rings of equilenin are different from the other ones because they have aromatic naphthalene core, as was evidenced experimentally. The NBO studies support the higher stability of equilin, in relation to equilenin and estrone while the AIM analyses reveal the higher stability for estrone. The gap values suggest that equilenin is the most reactive species due to its higher global electrophilicity value, in agreement with the higher stability observed for this species while the higher global nucleophilicity values are observed for equilin and estrone. Here, the harmonic force fields, scaled force constants and the complete assignments of 108, 114 and 120 vibration modes for equilenin, equilin and estrone, respectively are reported for the first time.  

Keywords: Steroids; Force fields; Vibrational analysis; DFT calculations; Molecular structure.

1. INTRODUCTION

Steroid hormones are important compounds found in the human body that are derived from cholesterol and have characteristics lipid-soluble and normally are grouped into two classes: corticosteroids and sex steroids differentiated by bonding receptors and biological functions [1-17]. Hence, different factors (solubilization, motility, transport, metabolism, and complementarity of fit between hormone and receptor) have influence on the activity of steroid hormones. Thus, according to the receptors to which they bind there are five types: glucocorticoids, mineralo-corticoids, androgens, estrogens, and progesterone. Steroid hormones have multiple functions in the human body being among others, control metabolism, immune functions, inflammation, salt and water balance, development of sexual characteristics, and the ability to resist illness and hurt [18-22]. For instance, estrone, estradiol, estriol, equilin, equilin and their derivatives are some of species associated with estrogens and, obviously, to steroid hormones [1-9,11,13]. Structural studies on these hormones and their quick identifications are very important from medicinal, chemistry, human health, environmental and pharmacological points of view because when these hormones are discharged toward the environmental can affect the systems of all living beings [14,15]. On the other hand, from long time the vibrational spectroscopy was a very useful technique used widely to detect the species related to steroid hormones, as evidenced in the numerous research papers published in the literature [10,12,14,17]. Hence, the knowledge of their structures is necessary to perform the complete and reliable vibrational assignments of these species. So far, previous vibrational works on those steroids were carried out without considering the corresponding force fields necessary to produce a correct assignment of all the bands observed in the infrared and Raman spectra [10,12,14,17]. These potential energy contributions are necessary to perform the vibrational assignments because, specifically, in the region of smaller wavenumbers region the vibration modes are strongly coupled with each other. In this study, the experimental available infrared and Raman spectra of equilenin, equilin and estrone steroids were completely assigned taking into account their corresponding harmonic SQM force fields by using the SQMFF methodology, the normal internal coordinates and the Molvib program [23-25]. A scheme of three structures studied in this work can be seen in Scheme 1 together with the definitions of four rings.

Hence, the harmonic force fields of equilenin, equilin and estrone steroids species in gas phase were obtained first optimizing the three structures with the hybrid B3LYP/6-31G* method [26,27] and, then, their corresponding vibrational spectra were predicted in order to compare with the experimental ones. In additional form, the harmonic force constant for the three species was also reported together with the studies of frontier orbitals because the...
predictions of the reactivities and behaviours of three species are of interest taking into account their important biological functions.

2. MATERIALS AND METHODS

The initial theoretical structure of equilenin was that experimental determined by X-ray diffraction to 100 K by Frampton and MacNicol [13] and, later with this structure were modelled the structures corresponding to equilin and estrone by using the GaussView program [28]. The optimizations of three structures in gas phase were carried out with the Revision A.02 of Gaussian program [29] and by using the hybrid B3LYP/6-31G* method [26,27]. In Figure 1 are presented the three structures with the atoms labeling and the definitions of four rings, as in scheme 1. The predicted energies values for the three species in gas phase were corrected by zero point vibrational energy (ZPVE) and the volumes in gas phase were computed at the same level of theory with the Moldraw program [30]. The scaled quantum mechanical force field (SQMFF) methodology together with the Molvib program was employed to obtain the harmonic force fields and the potential energy distribution (PED) contributions [23-25]. Here, the assignments oh three species were performed considering the corresponding normal internal coordinates, transferable scaling factors and only contributions ≥ 10%. In addition, the frontier orbitals and some remarkable descriptors were used to predict reactivities and behaviours of three species [31-41].

3. RESULTS

Optimized Structures of all species in gas phase.

Structurally, equilenin [13] is different from equilin and estrogen in the B ring, as can be seen in Figure 2.

Thus, in equilenin both A and B rings are practically coplanar forming a full aromatic naphthalene core, as mentioned by Frampton and MacNicol [13], with two aromatic C-H bonds in B. In equilin, due to the presence of a C=C in B only an aromatic C-H bond it is observed in this ring. On the contrary, in estrone there are two CH₂ groups in B, for which, the total number of atoms increase from 38 in equilenin to 42 in estrone while in equilin the total number of atoms is 40. Calculated total energies (E) and by zero point vibrational energy (ZPVE), dipole moments (µ) and volumes (V) of equilenin, equilin and estrone in gas phase by using the B3LYP/6-31G* method are presented in Table 1.

Table 1. Calculated total energies (E) and by zero point vibrational energy (ZPVE), dipole moments (µ) and volumes (V) of equilenin, equilin and estrone in gas phase by using the B3LYP/6-31G* method.

| Species   | B3LYP/6-31G* Method | E (Hartrees) | ZPVE (Hartrees) | µ (D) | V (Å³) |
|-----------|---------------------|-------------|-----------------|-------|--------|
| Equilenin |                     | -847.2153   | -846.8965       | 3.34  | 291.3  |
| Equilin   |                     | -848.3997   | -848.0583       | 2.18  | 296.2  |
| Estrone   |                     | -849.6227   | -849.2569       | 3.80  | 304.0  |

However, despite equilin presents higher volume than equilenin its dipole moment value is lower (2.18 D). This difference between equilenin and equilin probably could be explained by the presence...
of the unsaturated C=C in B which rotates the C and D rings of the steroid generating the translation of the O1 atom belonging to C11=O1 group, as was experimentally observed for equilin by Sawicki et al [7]. This translation of the O1 atom was attributed by Sawicki et al [7] to the increased anti-human estrogenic 17β-hydroxysteroid dehydrogenase inhibitory behavior of equilin in relation to estrone. Furthermore, the methyl group in equilenin and equilin is also translated by 0.79 and 1.40 Å, respectively in relation to estrone increasing the estrogenic activity of equilenin than equilin [7].

**Geometrical parameters in both media.**

Here, the calculated geometrical parameters for equilenin, equilin and estrone steroids in gas phase by using the B3LYP/6-31G* method were compared with the experimental values determined for equilenin by Frampton and MacNicol [13]. The root-mean-square deviation (RMSD) values were employed to compare the experimental values with the corresponding theoretical ones. Hence, in Table 2 are summarized those parameters together with the RMSD values for the three species. The results show very good correlations in the bond lengths and angles (0.008 Å and 0.5º) for equilenin, as expected because its structure is in agreement with the compared one while the RMSD values increase for equilin and estrone to values between 0.054-0.065 Å for bond lengths and to 2.7-1.6 º for bond angles.

**Table 2.** Calculated geometrical parameters of equilenin, equilin and estrone in gas phase by using the B3LYP/6-31G* method compared with the corresponding experimental values for equilenin taken from Ref [13].

| Parameters | B3LYP/6-31G* Methoda | Experimentalb |
|------------|-----------------------|---------------|
| Bond lengths (Å) | | |
| C20-O2     | 1.367                 | 1.369         | 1.369 | 1.3714(17) |
| C11=O1     | 1.211                 | 1.211         | 1.212 | 1.220(2)  |
| C17-C19    | 1.374                 | 1.391         | 1.389 | 1.369(2)  |
| C17-C14    | 1.425                 | 1.402         | 1.405 | 1.423(2)  |
| C19-C20    | 1.416                 | 1.398         | 1.397 | 1.411(2)  |
| C20-C18    | 1.378                 | 1.393         | 1.393 | 1.369(2)  |
| C18-C16    | 1.419                 | 1.399         | 1.401 | 1.4243(19)|
| C16-C15    | 1.418                 | 1.515         | 1.519 | 1.413(2)  |
| C14-C16    | 1.434                 | 1.405         | 1.408 | 1.429(2)  |
| C15-C10    | 1.373                 | 1.501         | 1.531 | 1.369(2)  |
| C5-C10     | 1.418                 | 1.335         | 1.532 | 1.414(2)  |
| C7-C9      | 1.549                 | 1.543         | 1.544 | 1.5433(19)|
| C7-C4      | 1.526                 | 1.533         | 1.532 | 1.520(2)  |
| C4-C11     | 1.531                 | 1.531         | 1.532 | 1.5118(19)|
| C4-C3      | 1.544                 | 1.557         | 1.549 | 1.537(2)  |
| C4-C13     | 1.550                 | 1.550         | 1.552 | 1.544(2)  |
| C3-C8      | 1.543                 | 1.539         | 1.543 | 1.535(2)  |
| C8-C12     | 1.547                 | 1.547         | 1.547 | 1.547(2)  |
| C11-C12    | 1.543                 | 1.543         | 1.542 | 1.523(2)  |
| C5-C6      | 1.392                 | 1.521         | 1.554 | 1.381(2)  |
| C5-C3      | 1.511                 | 1.503         | 1.529 | 1.5103(19)|
| C6-C14     | 1.434                 | 1.520         | 1.531 | 1.4309(19)|
| C6-C9      | 1.528                 | 1.561         | 1.549 | 1.5234(19)|
| **RMSD**   | **0.008**             | **0.054**     | **0.065** |
| Bond angles (º) | | |
| C19-C17-C14 | 121.92               | 122.04        | 122.54 | 121.43(14) |
| C17-C19-C20 | 120.14               | 119.27        | 119.24 | 120.34(14) |
| C18-C20-O2  | 123.66               | 117.67        | 122.88 | 124.14(14) |
| C18-C20-C19 | 119.97               | 119.52        | 119.34 | 120.39(13) |
| O2-C20-C19  | 116.36               | 122.80        | 117.76 | 115.46(14) |
| C20-C18-C16 | 120.78               | 121.02        | 121.36 | 120.47(14) |
| C15-C16-C18 | 121.33               | 118.32        | 118.07 | 121.68(14) |
| C15-C16-C14 | 118.80               | 121.69        | 122.03 | 118.77(13) |
Atomic MK and Mulliken charges and Molecular electrostatic potentials (MEP).
The studies of atomic charges in the three species associated to estrogens are of great interest to explain the structural differences among the B rings where, for instance, equilenin is different from equilin by the unsaturated C5=C10 in B which rotates the C and D rings of the steroid generating the translation of the O1 atom belonging to C11=O1 group, as was experimentally observed for equilenin by Sawicki et al [7]. Therefore, the atomic Merz-Kollman (MK) and Mulliken charges on all atoms of three species were calculated in gas phase by using the B3LYP/6-31G* method [44]. Hence, both charges are given in Table 3 while in Figure 4 can be seen the behaviours of two charges in the three species. In Fig. 4 are presented the atoms numbering according to Table 3. Both charges on the O1, O2 and C3 atoms that belong to D rings present practically the same behaviours while the higher variations in the charges are observed on the atoms from the C4 to C16 because these atoms are common to the B, C and D rings. Hence, the charges on the C17, C18, C19 and C20 atoms of A rings in the three species basically do not change. Note that the two charges on the C15 atoms are different in equilenin than equilin and estrone because that C atom in equilenin has hybridization sp² and one H atom while in the other two species that C15 atoms present sp³ hybridization containing CH₂ groups. Another important observation is that the two charges on the C11, C12 and C13 in equilenin and estrone have approximately the same values while in equilin the MK charges present lower values. The charges on all H atoms present practically the same positive values in the three species with exception of those atoms linked to O2 atoms where are observed the higher values.
The molecular electrostatic potentials (MEP) values are very interesting parameters to describe the distributions of charges on species containing different rings and OH and C=O groups as, equilin, equilin and estrone and, in particular, their mapped surfaces are useful to find the nucleophilic and electrophilic sites where the reactions with potential biological electrophils and nucleophils reactive take place. Here, the MEP values were calculated from the MK charges for the three species but

| C7-C9-C6     | 116.37 | 113.26 | 113.33 | 116.13(13) |
| C7-C4-C11    | 117.04 | 116.71 | 116.52 | 116.95(12) |
| C3-C4-C13    | 113.61 | 112.83 | 114.11 | 112.60(12) |
| C5-C3-C8     | 121.7  | 123.06 | 121.58 | 121.14(13) |
| C8-C3-C4     | 104.46 | 104.36 | 104.3  | 103.87(12) |
| C3-C8-C12    | 102.41 | 102.54 | 102.67 | 101.83(12) |
| C8-C12-C11   | 105.91 | 105.94 | 105.85 | 105.59(13) |
| C4-C11-O1    | 126.55 | 126.48 | 126.49 | 125.78(15) |
| C12-C11-O1   | 125.53 | 125.43 | 125.46 | 125.78(15) |
| C4-C11-C12   | 107.90 | 108.08 | 108.04 | 108.43(13) |
| RMSD          | 0.5    | 2.7    | 1.6    |            |

| Dihedral angles (°) |
|---------------------|
| C17-C19-C20-O2      | -179.87° | 179.83° | -179.93° | 179.27(14) |
| O2-C20-C18-C16      | 179.95   | -179.9  | 179.99   | 179.87(14) |
| C14-C6-C9-C7        | -177.95  | 179.12  | 179.79   | -175.62(14) |
| C9-C7-C4-C11        | 172.93   | 169.20  | 168.68   | 173.40(14) |
| C3-C5-C6-C14        | 177.80   | 178.02  | 176.62   | 175.63(14) |
| C9-C6-C14-C17       | 1.38     | 59.88   | 33.50    | 1.3(2)      |
| C5-C6-C9-C7         | 4.08     | 51.12   | 51.99    | 4.1(2)      |
| C6-C5-C3-C8         | 157.69   | -175.30 | -175.53  | 155.31(15) |
| C10-C5-C3-C8        | -24.82   | 7.35    | -53.49   | -28.7(2)    |
| C6-C5-C3-C4         | 33.05    | 7.35    | 59.97    | 32.65(19)   |
| C7-C4-C3-C5         | -61.07   | -60.41  | -61.28   | -61.31(16)  |
| C7-C4-C3-C8         | 165.20   | 165.25  | 165.16   | 166.61(13)  |
| C5-C3-C8-C12        | -168.24  | -167.32 | -168.01  | -167.57(14) |
| C3-C8-C12-C11       | 22.20    | 22.53   | 21.82    | 22.97(18)   |
| C13-C4-C11-O1       | -88.90   | -90.05  | -89.14   | -91.6(2)    |
| C13-C4-C11-C12      | 91.11    | 90.29   | 90.95    | 88.83(16)   |
| RMSD                 | 89.8     | 152.5   | 152.0    |            |
| RMSD¹                | 1.8      | 157.5   | 126.6    |            |

*This work, ¹From Ref [13], ²Removed value, Letter Bold: RMSD values
significant differences in the values were not found and, for this reason, these values are not presented here [44].

![Figure 4](image-url) **Figure 4.** Variations and behaviours of atomic Merz-Kollman (MK) and Mulliken charges on all atoms of equilenin, equilin and estrone steroids in gas phase by using the B3LYP/6-31G* method.

Obviously, the higher negatives values are observed on the O atoms, showing the higher values in the three species the O1 atoms (-22.333—22.331 a.u.) than the O2 ones (-22.284—22.278 a.u.).

![Figure 5](image-url) **Figure 5.** Calculated electrostatic potential surfaces on the molecular surfaces of equilenin, equilin and estrone. Color ranges are indicated in units a.u. B3LYP functional and 6-31G* basis set. Isodensity value of 0.005.

The MEP values on the C atoms have evidenced different values, for instance, from 14.749 to 14.665 a.u. while the H atoms present the less negative values, as expected, showing the lower values on the H atoms linked to the O2 atoms in the three species because these atoms are the most labile. When the mapped surface from

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Table 3. Atomic MK and Mulliken charges of equilenin, equilin and estrone in gas phase and aqueous solution by using the B3LYP/6-31G* method.

| Atoms | Equilenin | Equilin | Estrone | Equilenin | Equilin | Estrone |
|-------|-----------|---------|---------|-----------|---------|---------|
| O     | -0.473    | -0.479  | -0.495  | -0.458    | -0.457  | -0.459  |

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**NBO studies.** The analyses of stabilization energies in equilenin, equilin and estrone are important factors taking into account that three of four rings present in their structures are different in the three species showing, in particular the A and B rings of equilenin, aromatic naphthalene core, as reported for this species by Frampton and MacNicol [13]. Hence, in Table 4 are presented the main delocalization energies for equilenin, equilin and estrone in gas phase by using B3LYP/6-31G* calculations. The careful analysis of results show for the three species four different \( \Delta E_{\pi-\pi^*} \), \( \Delta E_{\sigma-\sigma^*} \) and \( \Delta E_{\pi-\pi^*} \) interactions where the first and the latter transitions present clearly the higher values in the three species showing the only equilin the higher value in the \( \Delta E_{\pi-\pi^*} \) interaction. In addition, due to the presence of two aromatic rings in equilenin the \( \pi^*C14-C16 \rightarrow \pi^*C5-C6 \) interaction only for this species is observed. On the other hand, the \( \pi^*C17-C19 \rightarrow \pi^*C14-C16 \) interaction is observed only for equilin. Here, a very important resulted is the presence of six \( \Delta E_{\pi-\pi^*} \) interactions observed only in equilenin due to the presence of two aromatic A and B rings and different from the other ones. Note that in the three species the \( \Delta E_{\sigma-\sigma^*} \) and \( \Delta E_{\pi-\pi^*} \) interactions show low values, as compared with the other ones. When the total energy values are evaluated for the three species it is observed the higher value for equilin, then equilenin and, finally estrone. Hence, equilin is the most stable species, compared with equilenin and estrone. Probably, the high value evidenced for equilin and its high stability and the lower value observed for estrone could justify the increase in the anti-human estrogenic 17β-hydroxysteroid dehydrogenase inhibitory behavior of equilin in relation to estrone, as suggested by Sawicki et al [7].

**AIM analyses.** The above NBO studies have revealed the high stability of equilenin, as compared with equilenin and estrone showing only this species a high value in the \( \pi^*C17-C19 \rightarrow \pi^*C14-C16 \) transition. Another form different of analyzing the stabilities of these species is through of the Bader’s theory of atoms in molecules (AIM) where is possible to examine possible H bonds and/or intra-molecular interactions by using the topological properties with the AIM2000 program [46,47].
This work, Atomic units (a.u.)

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
| 2 O | -0.575 | -0.547 | -0.575 | -0.646 | -0.647 | -0.648 |
| 3 C | 0.139 | 0.058 | -0.006 | -0.195 | -0.184 | -0.106 |
| 4 C | 0.298 | 0.175 | 0.190 | 0.009 | 0.018 | 0.018 |
| 5 C | -0.098 | -0.258 | -0.056 | 0.100 | 0.205 | -0.100 |
| 6 C | -0.012 | 0.355 | 0.276 | 0.062 | -0.256 | -0.164 |
| 7 C | -0.240 | -0.166 | -0.125 | -0.269 | -0.269 | -0.268 |
| 8 C | -0.101 | -0.075 | 0.010 | -0.295 | -0.291 | -0.297 |
| 9 C | 0.040 | -0.047 | -0.126 | -0.367 | -0.269 | -0.289 |
| 10 C | -0.145 | -0.120 | -0.058 | -0.191 | -0.212 | -0.274 |
| 11 C | 0.434 | 0.495 | 0.537 | 0.439 | 0.439 | 0.437 |
| 12 C | -0.300 | -0.317 | -0.381 | -0.362 | -0.362 | -0.361 |
| 13 C | -0.395 | -0.466 | -0.476 | -0.473 | -0.473 | -0.479 |
| 14 C | -0.040 | -0.200 | -0.253 | 0.068 | 0.133 | 0.116 |
| 15 C | -0.265 | 0.025 | -0.079 | -0.207 | -0.385 | -0.349 |
| 16 C | 0.285 | 0.108 | 0.202 | 0.152 | 0.115 | 0.114 |
| 17 C | -0.136 | -0.095 | -0.104 | -0.205 | -0.198 | -0.201 |
| 18 C | -0.496 | -0.314 | -0.451 | -0.282 | -0.230 | -0.266 |
| 19 C | -0.263 | -0.354 | -0.292 | -0.157 | -0.198 | -0.165 |
| 20 C | 0.439 | 0.389 | 0.438 | 0.358 | 0.357 | 0.364 |
| 21 H | -0.005 | 0.031 | -0.005 | 0.145 | 0.129 | 0.118 |
| 22 H | 0.049 | -0.024 | 0.034 | 0.141 | 0.139 | 0.121 |
| 23 H | 0.055 | 0.027 | -0.006 | 0.150 | 0.134 | 0.132 |
| 24 H | 0.052 | 0.062 | 0.019 | 0.144 | 0.148 | 0.135 |
| 25 H | 0.039 | 0.051 | 0.048 | 0.149 | 0.147 | 0.146 |
| 26 H | 0.036 | 0.052 | 0.030 | 0.157 | 0.147 | 0.144 |
| 27 H | 0.038 | 0.030 | 0.021 | 0.157 | 0.144 | 0.141 |
| 28 H | 0.113 | 0.015 | 0.040 | 0.124 | 0.138 | 0.140 |
| 29 H | 0.104 | 0.077 | 0.050 | 0.174 | 0.118 | 0.142 |
| 30 H | 0.112 | 0.108 | 0.013 | 0.172 | 0.174 | 0.135 |
| 31 H | 0.093 | 0.112 | 0.027 | 0.168 | 0.171 | 0.135 |
| 32 H | 0.097 | 0.130 | 0.119 | 0.149 | 0.165 | 0.173 |
| 33 H | 0.104 | 0.122 | 0.120 | 0.163 | 0.147 | 0.171 |
| 34 H | 0.149 | 0.129 | 0.123 | 0.124 | 0.162 | 0.161 |
| 35 H | 0.111 | 0.033 | 0.119 | 0.134 | 0.161 | 0.148 |
| 36 H | 0.162 | 0.036 | 0.128 | 0.116 | 0.160 | 0.166 |
| 37 H | 0.174 | 0.125 | 0.044 | 0.142 | 0.125 | 0.151 |
| 38 H | 0.423 | 0.158 | 0.047 | 0.408 | 0.130 | 0.145 |
| 39 H | 0.157 | 0.115 | 0.116 | 0.116 | 0.126 |
| 40 H | 0.403 | 0.145 | 0.406 | 0.106 |
| 41 H | 0.175 | 0.136 |
| 42 H | 0.418 | 0.406 |
highest value. Also, for estrone is observed an only H bonds interaction (H39—H29) with low density and Laplacian values because the distances between both involved H atoms is 2.058 Å. In addition, the new RCPN has also low values in its properties. These studies clearly evidence the higher stability of estrone in gas phase due to the new H—H interaction which confers to its structure higher stability.

**Frontier orbitals and quantum global descriptors studies.**

The frontier orbitals are parameters frequently used in the determination of gap values, as suggested by Parr and Pearson [31], because from their differences can be predict the reactivities and, also, with the gap values it is possible to calculate some descriptors of great interest to predict the behaviours of species in different media [32-41]. Hence, the frontier molecular HOMO and LUMO orbitals, gap values and the chemical potential (µ), electronegativity (χ), global hardness (η), global softness (S), global electrophilicity index (ω) and global nucleophilicity index (E) descriptors of equilenin, equilin and estrone in gas phase by using the B3LYP/6-31G* method are summarized in Table 6. If the gap values are analyzed it is possible to observe the lower value in equilenin and the higher values for equilin and estrone, where equilin clearly has the highest value and, for this reason, it is the less reactive species in agreement with the higher stability observed by NBO studies. Evidently, the presence of the unsaturated C5=C10 in the B ring of equilin, which rotates the C and D rings of this steroid generating the translation of the O1 atom belonging to C11=O1 group, as was experimentally by Sawicki et al [7], produces a decreasing in its reactivity. On the other hand, equilin is the most reactive species due to its low gap value. If now the descriptors are analyzed, equilin has a higher global electrophilicity value while the higher global nucleophility values are observed for equilin and estrone. Apparently, the higher global electrophilicity value evidenced by equilin is related to its higher reactivity and with the less negative nucleophilicity value. The comparisons of these gap values of three steroids species with other such as the free base, cationic and hydrochloride species of alkaloids or antihistaminic agents [48-57] are interesting to know how the different groups and rings present in their structures have influence on their reactivities and behaviours in the different media. Thus, the gap value of 4.5008 eV for equilenin is similar to those observed for the hydrochloride species of morphine (4.5840 eV) and of the R(+) form of promethazine (4.4926 eV) while the values of 5.4695 and 5.4342 eV observed for equilenin and estrone, respectively are similar to value predicted for the cationic species of cocaine (5.4468 eV). All these compared species have different fused rings and, also, other groups.

**Table 5. Analysis of the Bond Critical Points (BCPs) and Ring critical points (RCPs) for equilenin, equilin and estrone in gas phase by using the B3LYP/6-31G* method.**

| Parameter | B3LYP/6-31G* Method | Equilin | Estrone | H39-H29 | RCPN |
|-----------|---------------------|---------|---------|---------|------|
| ρ(r) | 0.0193 | 0.0192 | 0.0179 | 0.0367 |
| V^2ρ(r) | 0.1512 | 0.1500 | 0.1176 | 0.2482 |
| ρ(r) | 0.0199 | 0.0169 | 0.0177 | 0.0365 |
| V^2ρ(r) | 0.1581 | 0.1201 | 0.1117 | 0.2466 |
| ρ(r) | 0.0198 | 0.0172 | 0.0176 | 0.0371 |
| V^2ρ(r) | 0.1565 | 0.1152 | 0.1093 | 0.2509 |

**Table 6.** Main delocalization energies (in kJ/mol) for equilenin, equilin and estrone in gas phase by using B3LYP/6-31G* calculations.

| Delocalization | Equilin | Equilin | Estrone |
|----------------|---------|---------|---------|
| πC14-C16→π*C17-C19 | 76.29 | 100.61 | 95.47 |
| πC14-C16→π*C18-C20 | 64.87 | 77.04 | 74.70 |
| πC17-C19→π*C14-C16 | 57.98 | 66.42 | 69.14 |
| πC17-C19→π*C18-C20 | 79.13 | 91.63 | 93.59 |
| πC18-C20→π*C16-C14 | 74.78 | 93.88 | 91.88 |
| πC18-C20→π*C17-C19 | 62.07 | 74.57 | 68.68 |
| ΔE_{ρ-σ^∗} | 835.12 | 504.15 | 493.45 |
| LP(2)/O1→π*C4-C11 | 90.33 | 90.41 | 90.29 |
| LP(2)/O1→π*C11-C12 | 98.36 | 97.94 | 98.06 |
| ΔE_{ρ-σ^∗} | 188.69 | 188.35 | 188.35 |
| LP(2)/O2→π*C18-C20 | 124.56 | 115.12 | 119.92 |
| ΔE_{ρ-σ^∗} | 124.56 | 115.12 | 119.92 |
| π*C14-C16→π*C5-C6 | 936.28 | 759.92 | 837.84 |
| π*C17-C19→π*C14-C16 | 848.21 | 837.84 | 837.84 |
| ΔE_{ρ-σ^∗} | 936.28 | 1808.13 | 1639.56 |
| ΔE_{total} | 2084.65 | 2415.75 | 1639.56 |

**Figure 6.** Molecular graphic of estrone in gas phase showing the geometry of all its bond critical points (BCP) and ring critical points (RCPs) by using the B3LYP/6-31G* method. In blue colours are presented the RCPs of A, B, C and D rings and in red colour the only RCPN new while the arrow show the BCP.
Vibrational study.
The structures of equilenin, equilin and estrone species by using B3LYP/6-31G* calculations were optimized with C1 symmetries. For equilenin are expected 108 vibration modes, for equilin 114 and for estrone 120. All vibration modes present activity in both IR and Raman spectra. In Figures 7 and 8 are compared the experimental available IR and Raman spectra of equilenin in the solid phase taken from Ref [58] with the corresponding predicted by calculations in the gas phase. In Figures 9 and 10 are compared the experimental available IR and Raman spectra of equilin taken from Ref [58] with the corresponding predicted in gas phase by using the hybrid B3LYP/6-31G* method. In Figure 11 can be seen the predicted IR spectrum of estrone in gas phase by using the hybrid B3LYP/6-31G* method while in Figure 12 are compared the experimental available Raman spectrum taken from Ref [17] with the corresponding predicted in gas phase by using the hybrid B3LYP/6-31G* method. All predicted Raman spectra were corrected to intensities by using known equations [42,43].
Here, the expected modes common to the three species are, C=O, C=C, C-O and C-C stretching modes, deformation, wagging, rocking modes of CH₂ groups, OH deformation, deformation and rocking modes of CH₃ groups and C-H rocking modes. A careful detail of the assignments of those modes for the three species can be seen in Table 7 where the most intense bands are assigned to the C=O and C=C stretching modes. Hence, the intense IR and Raman bands between 1751 and 1496 cm⁻¹ can be easily assigned to the C=O and C=C stretching modes corresponding to the three species, as reported for species containing these groups [34-41]. Obviously, those C=O and C-C bonds present double bond characters and, for these reasons, their vibration modes are observed at higher wavenumbers but, the C-C bonds with partial double bond characters are predicted at lower wavenumbers, thus, they can be assigned between 1454 and 1325 cm⁻¹, as observed in Table 7. A very important observation is the differences in the positions of C5-C10 stretching modes because these bonds have different characteristics in the three species. Thus, in equilenin and equilin those bonds present double bond characters (1704-1523 cm⁻¹) and, as a consequence they are observed at higher wavenumbers than the corresponding to estrone while, in estrone, that mode is predicted to 1085 cm⁻¹. The other C-C stretching modes expected in the three species with simple bond characters can be assigned from 1001 up to 553 cm⁻¹. Here, it is notable the difference in the C4-CH₃ stretching modes (C4-C13) because in the three species these modes are predicted coupled with other vibration modes and in different positions. In the three species the C20-O2 stretching modes are predicted in approximately the same regions, hence, they can be assigned to the intense and of media intensities IR and Raman bands between 1293 and 1281 cm⁻¹. In the same way, the OH deformation modes for the three species are predicted in the same regions, therefore, the bands observed between 1171 and 1137 cm⁻¹ are assigned to these vibration modes.

### Table 6. Frontier molecular HOMO and LUMO orbitals, gap values and descriptors (in eV) of equilenin, equilin and estrone in gas phase by using the B3LYP/6-31G* method.

| Orbitals | Equilenin | Equilin | Estrone |
|----------|-----------|---------|---------|
| HOMO     | -5.5321   | -5.7933 | -5.7607 |
| LUMO     | -1.0313   | -0.3238 | -0.3265 |
| \[\text{GAP}\] | 4.5008    | 5.4695  | 5.4342  |

\[\chi = - \frac{\text{E(LUMO)} - \text{E(HOMO)}}{2}; \mu = \frac{\text{E(LUMO)} + \text{E(HOMO)}}{2}; \eta = \frac{s}{\sqrt{3}}; \omega = \mu/2\eta; E = \mu*\eta\]

The complete vibrational assignments for the three species were performed with the SQMFF methodology computing their harmonic force fields in gas phase [23]. Hence, the normal internal coordinates were employed and transferable scale factors together with the Molvib program [24,25]. Here, only potential energy contributions ≥ 10% were considered. In Table 7 are summarized the observed and calculated wavenumbers and assignments for equilenin, equilin and estrone. For equilenin and equilin, the observed bands correspond to the experimental available IR spectra [58] while for estrone corresponds to experimental available Raman spectrum [17]. Then, some assignments for the more important groups are discussed at continuation.

### Band Assignments.

#### 4000-2000 cm⁻¹ region. In this region are expected the antisymmetric and symmetric stretching modes of CH₃ and CH₂ groups, the aromatic and aliphatic C-H and OH stretching modes. In the three species, the OH stretching modes are predicted at higher wavenumbers than the other ones and, for these reasons, these modes are associated with the IR and Raman bands between 3370 and 3307 cm⁻¹. The groups of IR and Raman bands between 3064 and 3013 cm⁻¹ are associated with the aromatic C-H stretching modes while those bands between 2890 and 2822 cm⁻¹ are attributed to aliphatic C-H stretching modes. The antisymmetric CH₃ stretching modes are predicted by calculations at higher wavenumbers than the corresponding symmetric modes and, hence, these modes are assigned to the IR and Raman bands 3027 and 2977 cm⁻¹. On the contrary, the corresponding symmetric modes are assigned to the IR bands at 2920 and 2909 cm⁻¹. The antisymmetric and symmetric CH₂ stretching modes are assigned between 2996 and 2858 cm⁻¹, as predicted by the SQM/B3LYP/6-31G* calculations.

### Table 7. Observed and calculated wavenumbers (cm⁻¹) and assignments of equilenin, equilin and estrone in gas phase by using the B3LYP/6-31G* method.

| Equilenin | Equilin | Estrone |
|-----------|---------|---------|
| IR⁻ | IR⁻ | IR⁻ | SQM⁻ | Assignments⁻ | SQM⁻ | Assignments⁻ | SQM⁻ | Assignments⁻ |
| 3331m | 3307m | 3370w | 3592 | vO₂-HH₃ | 3597 | vO₂-HH₀ | 3594 | vO₂-HH₂ |
| 3093sh | 3092 | vC₁₇-HH₃ | 3062 | vC₁₈-HH₃ | 3086 | vC₁₉-HH₁ |
| 3075w | 3075 | vC₁₉-HH₃ | 3054 | vC₁₇-HH₇ | 3070 | vC₁₇-HH₉ |
| 3064w | 3040w | 3062w | 3066 | vC₁₀-HH₈ | 3034 | vC₁₉-HH₉ | 3017 | vC₁₈-HH₀ |
| 3027w | 3027w | 3046 | vC₁₅-HH₄ | 3033 | vC₁₀-HH₂ | 3010 | vCH₁ |
| 3025w | 3013w | 3005w | 3030 | vC₁₈-HH₆ | 3012 | vCH₁ | 2995 | vCH₁ |
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| 2996w | 2977m | 2993 | v(CH) | 2994 | v(CH) | 2985 | v(CH) (C8) |
|-------|-------|------|--------|------|--------|------|-------------|
| 2953m | 2986 | v(CH) (C8) | 2975 | v(CH) (C12) | 2966 | v(CH) (C9) |
| 2975 | v(CH) (C12) | 2970 | v(CH) (C9) | 2959 | v(CH) (C7) |
| 2964sh | 2957w | 2968 | v(CH) (C7) | 2960 | v(CH) (C7) | 2951 | v(CH) (C10) |
| 2945m | 2942 | v(CH) (C8) | 2945 | v(CH) (C8) | 2940 | v(CH) (C8) |
| 2937sh | 2937 | v(CH) (C9) | 2936 | v(CH) (C12) | 2936 | v(CH) (C12) |
| 2920m | 2936 | v(CH) (C12) | 2934 | v(CH) | 2935 | v(CH) (C15) |
| 2909m | 2932 | v(CH) | 2931 | v(CH) (C9) | 2933 | v(CH) |
| 2873sh | 2918m | 2921 | v(CH) (C7) | 2912 | v(CH) (C7) | 2913 | v(CH) (C7) |
| 2861m | 2901 | v(CH) (C9) | 2905 | v(CH) (C10) |
| 2890w | 2891 | v(CH) (C15) | 2888 | v(CH) (C5-H22) |
| 2866w | 2858w | v(CH) (C15) | 2887 | v(CH) (C15) |
| 2846w | 2845w | v(CH) (C15) | 2840 | v(CH) (C6-H22) | 2840 | v(CH) (C3-H21) |
| 2834m | 2822w | v(CH) (C3-H21) | 2828 | v(CH) (C3-H21) | 2833 | v(CH) (C6-H23) |
| 1711vs | 1714vs | 1751s | 1771 | v(C11-O1) | 1769 | v(C11=O1) | 1769 | v(C11=O1) |
| 1615m | 1622m | 1629 | v(CH) (C17) | 1704 | v(CH) (C5) |
| 1615m | 1591s | 1652s | 1604 | v(CH) (C10-C15) | 1625 | v(CH) (C18-C20), v(CH) (C17-C19) |
| 1580m | 1511s | 1589m | 1572 | v(CH) (C5) |
| 1496s | 1523 | v(CH) (C19-C20), v(CH) (C5-C10) |
| 1496s | 1501s | 1504w | 1484 | βC10-H28 | 1503 | βC17-H37, βC18-H38 | 1504 | βC17-H39, v(CH) (C16-C14) |
| 1470s | 1478w | 1477 | δCH (C8) | 1476 | δCH |
| 1469w | 1470 | 1472 | δCH (C8) | 1472 | δCH |
| 1465 | 1465 | δCH (C7) | 1461 | δCH (C8), δCH |
| 1454w | 1459 | δCH (C7), δCH (C8) | 1458 | δCH |
| 1459m | 1450w | 1447s | 1454 | δCH |
| 1450w | 1450 | δCH (C9) | 1445 | δCH (C7) |
| 1451mw | 1445 | δCH (C9) | 1445 | δCH (C7) | 1443 | δCH (C15) |
| 1434m | 1423w | 1420 | βC18-H36, v(CH) (C17-C19) | 1435 | δCH (C15) | 1439 | δCH (C15), βC19-H41 |
| 1406m | 1414 | 1416 | δCH (C12) | 1417 | δCH (C12) |
| 1394m | 1400m | 1384 | v(CH) (C18-C20) | 1395 | p(CH) (C3-H21) | 1404 | p(CH) (C3-H21), p(CH) (C5-H22) |
| 1374w | 1378 | wagCH (C9) | 1385 | wagCH (C10) |
| 1366sh | 1372 | δCH |
| 1364sh | 1365 | δCH |
| 1356s | 1354w | 1360 | wagCH (C15) | 1361 | wagCH (C15) |
| 1358m | 1355 | v(CH) (C16-C14) | 1356 | wagCH (C7) |
| 1348sh | 1342sh | 1347w | 1351 | wagCH (C7), p(CH) (C3-H21) | 1352 | wagCH (C7) | 1349 | p(CH) (C6-H23), p(CH) (C5-H22), p(CH) (C9) |
| 1333w | 1333 | wagCH (C9), p(CH) (C6-H22) | 1337 | p(CH) (C3-H21) |
| 1322wv | 1325 | v(CH) (C6-C14) | 1326 | βC10-H29 | 1316 | v(CH) (C10) |
| 1318w | 1314w | 1315 | p(CH) (C3-H21) | 1309 | p(CH) (C3-H21) | 1312 | wagCH (C8) |
| 1301 | wagCH (C8) | 1302 | wagCH (C8) | 1308 | p(CH) (C6-H23) |
| 1295sh | 1293m | 1297 | p(CH) (C6-H22) | 1297 | v(CH) (C12) |
| 1284s | 1281s | 1285 | v(CH) (C16-C18), v(CH) (C20-O2) | 1287 | wagCH (C12), p(CH) (C6-H22) | 1290 | v(CH) (C15) |
| 1281s | 1279 | v(CH) (C20-O2) | 1279 | wagCH (C12) |
| 1256sh | 1259 | 1272 | wagCH (C12) | 1270 | wagCH (C12) | 1263 | v(CH) (C7) |
| 1247s | 1259 | v(CH) (C14-C17) | 1256 | βC18-H40 |
| 1259sh | 1249s | 1247 | p(CH) (C7), βC18-H36 | 1250 | p(CH) (C7) | 1248 | v(CH) (C4-C11) |
| 1250s | 1236w | 1246 | v(CH) (C11) | 1246 | βC18-H38 | 1246 | v(CH) (C10) |
| 1223sh | 1233m | 1227w | 1230 | p(CH) (C9), v(CH) (C3-C5) | 1231 | v(CH) (C4-C11) | 1223 | v(CH) (C15) |
| 1213m | 1215w | 1210 | p(CH) (C9), v(CH) (C5-C10) | 1209 | p(CH) (C8) | 1207 | p(CH) (C8), p(CH) (C12) |
| 1207sh | 1199w | 1197w | 1205 | pCH₂(C8) | 1203 | pCH₂(C15) | 1203 | pCH₂(C15), vC6-C14 |
| 1191w | 1193w | 1189 | vC6-C14 |
| 1185w | 1178 | JC15-H34 | 1184 | pCH₂(C9), pCH₂(C12) | 1183 | vC6-C14, vC6-C18 |
| 1167w | 1161s | 1171w | 1175 | JC18-H36, vC15-C16 | 1167 | δO2-H40 | 1162 | JC19-H41 |
| 1153m | 1151s | 1148 | pCH₂(C12) | 1152 | βC19-H39 | 1153 | δO2-H42,pCH₂(C10) |
| 1144w | 1146 | JC19-H37 | 1149 | vC3-C5 | 1149 | δO2-H42 |
| 1137sh | 1137sh | 1140w | 1145 | δO2-H38 | 1142 | vC3-C5,JC18-H38 | 1127 | pCH₂(C12),pCH₂(C7) |
| 1107sh | 1119m | 1120w | 1126 | pCH₂(C7) | 1121 | pCH₂(C7) | 1121 | pCH₂ |
| 1092w | 1101w | 1108 | βR(A1), vC15-C16 | 1090 | vC3-C5, vC3-C8 |
| 1084m | 1086w | 1084 | vC3-C8, vC6-C9 | 1085 | vC5-C10 |
| 1054s | 1067m | 1064w | 1054 | pCH₁ | 1069 | vC3-C8 | 1057 | vC5-C6 |
| 1046sh | 1046w | 1046 | vC11-C12, vC7-C9 | 1037 | pCH₃ | 1038 | vC6-C9 |
| 1008m | 1012m | 1011w | 1010 | pCH₂(C8), vC4-C13 | 1021 | vC10-C15 | 1016 | vC10-C15 |
| 982w | 994w | 990w | 996 | pCH₁ | 990 | vC7-C9 | 994 | βR(A1) |
| 980w | 985 | pCH₃ | 987 | vC4-C13 |
| 960w | 969 | vC7-C9 | 973 | pCH₁ |
| 965w | 954 | γC17-H35 | 963 | vC7-C9 |
| 962w | 950 | γC10-H28, γC15-H34 | 959 | vC7-C9, vC8-C12 |
| 944w | 952w | 950 | vC8-C12 | 950 | vC8-C12 | 947 | vC8-C12 |
| 932m | 938sh | 946 | γC10-H28, γC15-H34 | 933 | vC8-C12, vC4-C13 | 941 | γC17-H39 |
| 930h | 930 | γC10-H29, vCH₂(C15) |
| 918s | 924 | vC7-C9 | 921 | γC17-H37 |
| 915m | 923w | 918 | γC10-C15 | 915 | vC10-C15, vC20-O2 |
| 896m | 904sh | 902w | 908 | τₜCH₂(C7) τₜCH₂(C9) | 890 | βR(A2) | 901 | τₜCH₂(C8) |
| 873s | 881s | 888 | vC4-C13 | 876 | γC18-H38 | 883 | τₜCH₂(C10), τₜCH₂(C9) |
| 855w | 865s | 860sh | 851 | pCH₁ | 871 | γC18-H38 | 867 | vC4-C13 |
| 849sh | 849w | 843 | γC18-H36 | 840 | γC18-H40 |
| 841w | 830w | 824 | γC19-H37 | 830 | τₜCH₂(C7) | 826 | γC19-H41 |
| 817vs | 827w | 823sh | 811 | βR(A2) | 816 | τₜCH₂(C15), γC10-H29 | 818 | γC19-H41, γC18-H40 |
| 817vs | 815vs | 804 | γC18-H36, γC15-H34 | 800 | τₜCH₂(C7) | 805 | τₜCH₂(C15) |
| 785s | 763w | 791w | 792 | γC15-H34 | 796 | γC19-H39 | 790 | τₜCH₂(C12), vC4-C13 |
| 779sh | 781w | 780 | τₜCH₂(C8), τₜCH₂(C12) vC11=O1 | 781 | τₜCH₂(C8) |
| 775sh | 770 | βR(A2) | 777 | τₜCH₂(C9), vC3-C4 |
| 731w | 727sh | 736m | 755 | τR(A2) | 753 | τR(A1), τₜCH₂(C7) | 763 | τₜCH₂(C7) |
| 717w | 722s | 723 | βR(A1) | 727 | βR(A1), βR(A1), vC15-C16 |
| 708m | 720w | 711 | τR(A1) | 717 | βR(A1) | 704 | τR(A1) |
| 706m | 691 | τR(A1) |
| 670s | 672m | 676w | 684 | vC4-C13, τₜCH₂(C9) | 670 | τₜCH₂(C9), vC4-C13 | 680 | τR(A1), vC4-C13 |
| 646sh | 646w | 647 | τR(A1), τR(A1) | 633 | βR(A4), βR(A2) |
| 628w | 626m | 629w | 617 | βR(A3) | 625 | βR(A2) | 621 | γC20-O2, τR(A1) |
| 582s | 608m | 592 | βR(A4), vC4-C7 | 597 | vC11-C12, vC4-C7 |
| 574sh | 582w | 581w | 585 | γC20-O2 | 584 | βR(A4) | 583 | βR(A4), vC4-C7 |
| 552m | 577sh | 569 | γC20-O2 | 562 | vC11-C12, vC11=O1 |
| 530w | 532m | 556w | 553 | βR(A2), vC11-C12, vC11=O1 | 546 | βR(A3) | 561 | γC20-O2 |
| 529w | 537 | τₜCH₂(C12) | 537 | τₜCH₂(C12), γC11=O1 | 537 | τₜCH₂(C12), γC11=O1 |
| 527m | 527sh | 530 | τR(A2) | 533 | γC11=O1 |
| 515sh | 513m | 513 | βR(A1) βR(A4) | 512 | βR(A1) |
| 515sh | 500w | 502 | τR(A2) ButtC16-C14 | 511 | βR(A1) βR(A4) | 505 | βR(A2) |
| 476w | 474 | βR(A2) | 474 | βR(A2) |

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| 473w | 448w | 476 | 443 |
|------|------|-----|-----|
| 455s | 448w | 432 | 435 |
| 443s | 439w | 425 | 432 |
| 411w | 416w | 379 | 403 |

The main scaled force constants were calculated using that level of theory. Hence, the main scaled force constants were calculated from scaled quantum mechanics force field, 1From Ref [58], 2From Ref [58], 3From Ref [17].

1000-10 cm⁻¹ region. The main vibration modes expected in this region are, for instance, some C-C stretching modes already analyzed in the previous section, the C-H out-of-plane deformation, CH₂ and CH₃ twisting modes, deformations and torsions of A, B, C and D rings and torsions OH groups. The OH torsions are predicted in the same regions for the three species in gas phase by using that level of theory.

Table 8. Scaled internal force constants for equilenin, equilin and estrone in gas phase by using the B3LYP/6-31G* method.

| Force | Equilenin | Equilin | Estrone |
|-------|-----------|---------|---------|
| f(C=O) | 12.43 | 12.42 | 12.41 |
| f(O-H) | 7.22 | 7.24 | 7.23 |
| f(C-O) | 5.98 | 5.94 | 5.94 |
| f(CH₂) | 4.80 | 4.76 | 4.76 |
| f(C-H) | 5.15 | 4.08 | 5.13 |
| f(C≡C) | 6.35 | 6.86 | 6.48 |
| f(C=CH₂) | 3.67 | 3.67 | 3.61 |
| f(OH) | 0.74 | 0.73 | 0.73 |
| f(βCH₂) | 0.74 | 0.74 | 0.74 |

Units are mdyn Å⁻¹ for stretching and mdyn Å rad⁻² for angle deformations, 4This work

Analysing the results it is observed that some values remain practically constants in the three species, indicating clearly that the involved groups do not present changes in their structures. Hence, the f(C=O), f(O-H), f(C-O), f(CH₂), f(C=CH₂), f(βCH₂) and f(OH) force constants in the three species have the...
same values. On the contrary, the $f(vC-H)_{A,B}$ and $f(vC=C)$ force constants are different in the three species because in equilinien the A and B rings are aromatic and, for these reasons, this species has higher number of CH aromatics while in equilenin the presence of other CH$_2$ group, instead of C-H, in the B ring decrease the number of C-H with aromatic characteristics. Hence, the $f(vC-H)_{A,B}$ force constant has lower value in equilin. Moreover, in equilin the presence of a C=C in the B ring increase the number of C=C increasing the corresponding force constant to 6.86 mdyn Å$^{-1}$. The force constants predicted for the three species present value similar to the observed in other species containing similar groups [32,34,41,48-54].

4. CONCLUSIONS

Here, three species associated with estrogens were studied, equilienin, equilin and estrone. Their molecular structures were theoretically studied in gas phase with the hybrid B3LYP/6-31G* method. NBO, AIM and frontier orbital calculations were computed to study the structural, electronic, topological and vibrational properties of those three species at the same level of theory. Estrone presents higher dipole moment and volume values, as compared with equilienin and equilin, however, equilienin presents higher volume than equilenin but lower dipole moment value. The unsaturated C=C in B ring of equilin, which rotates the C and D rings of the steroid generating the translation of the O1 atom belonging to C11=O1, could probably explain those differences. Differences in the dihedral angles in the three species clearly explain the structural differences in their properties. The analyses of MK and Mulliken charges evidence the higher variations on the C atoms common to the B, C and D rings in the three species. The mapped MEP surfaces show that both A and B rings of equilienin are different from the other ones corresponding to the other two species because they have aromatic naphthalene core, as was evidenced experimentally. The NBO studies support the higher stability of equilienin, in relation to equilenin and estrone while the AIM analyses reveal the higher stability for estrone. The gap values suggest that equilienin is the most reactive species due to its higher global electrophilicity value, in agreement with the higher stability observed for this species while the higher global nucleophilicity values are observed for equilenin and estrone. Here, the harmonic force fields, scaled force constants and the complete assignments of 108, 114 and 120 vibration modes for equilienin, equilenin and estrone, respectively are reported for first time.

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6. ACKNOWLEDGEMENTS

This work was supported with grants from CIUNT Project Nº 26/D608 (Consejo de Investigaciones, Universidad Nacional de Tucumán, Argentina). The author would like to thank Prof. Tom Sundius for his permission to use MOLVIB.

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