

Structural, Spectroscopic (FT-IR, Raman, NMR and UV-Vis.) and Theoretical Investigations of Cyclopentolate

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Abstract

In this study, the structural and spectroscopic characterizations (FT-IR, Laser-Raman, ¹H and ¹³C NMR and UV-vis spectra) of cyclopentolate were performed using experimental and theoretical methods. Four conformational structures and optimized molecular geometries of the molecule were examined. The vibrational wavenumbers, proton and carbon-13 NMR chemical shifts, UV-Vis. parameters were theoretically obtained for the most stable form of the molecule and the HOMO-LUMO analyses were performed with DFT/B3LYP method at aug-cc-pVDZ basis set. The weak intra-molecular hydrogen bond interaction in O45-H46...N23 group was determined. The ¹H and ¹³C NMR chemical shifts were experimentally and theoretically investigated. The assignments of theoretical vibrational modes were obtained using VEDA 4 software in terms of potential energy distribution (PED). The theoretically and experimentally obtained data were found to be consistent with each other.

Keywords: Cyclopentolate, Vibrational spectroscopy, UV-Vis. spectral parameters, HOMO-LUMO analyses, NMR chemical shifts

Siklopentolat Molekülünün Yapısal, Spektroskopik (FT-IR, Raman, NMR ve UV-Vis.) ve Teorik Olarak İncelenmesi

Özet

Bu çalışmada siklopentolat molekülünün yapısal ve spektroskopik karakterizasyonları (FT-IR, Laser-Raman, ¹H ve ¹³C NMR ve görünür UV spektrumları) deneysel ve teorik yöntemler kullanılarak incelendi. Molekülün dört adet konformasyon yapısı ve optimize edilmiş moleküler geometrileri incelendi. En kararlı form için molekülün titreşimsel dalga-boyları, ¹H ve ¹³C NMR kimyasal kaymaları, görünür UV (UV-Vis) parametreleri teorik olarak elde edildi ve HOMO-LUMO analizleri DFT/B3LYP yöntemi ile aug-cc-pVDZ temel seti kullanılarak gerçekleştirildi. O45-H46...N23 grubundaki zayıf molekül-içi hidrojen bağ etkileşimi belirlendi. Teorik titreşim mod atamaları VEDA 4 yazılımı kullanılarak potansiyel enerji dağılımı (PED) cinsinden elde edildi. Teorik ve deneysel yöntemlerle elde edilen verilerin birbirleri ile tutarlı oldukları belirlendi.

Anahtar Kelimeler: Siklopentolat, Titreşim spektroskopisi, Görünür UV. Spektrum parametreleri, HOMO-LUMO analizleri, NMR kimyasal kaymaları

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1. Introduction

Cycloplegia is the temporary paralysis of siliceous muscles that provide accommodation with the aid of various drops. Cycloplegia agents include atropine, homatropine, cyclopentolate, scopolamine and tropicamide (Özer, 2005). Cycloplegic drugs, also referred to as anticholinergics, block the muscarinic action of acetylcholine. This action inhibits cholinergic stimulation of the iris sphincter and ciliary muscle, which results in mydriasis and cycloplegia (Mindel, 1994). Drugs acting like acetylcholine at the receptor such as pilocarpine are called muscarinic agonists; and drugs blocking the action of acetylcholine at the receptor such as atropine, homatropine and cyclopentolate are called muscarinic antagonists (Vale and Cox, 1979). Cyclopentolate hydrochloride is a cycloplegic and mydriatic agent and an ester of a substituted benzeneacetic acid, having, N, N-dimethylaminoethanol as the alcohol moiety (Roy and Guillory, 1995). Cyclopentolate hydrochloride's (CPH) IUPAC name is 2-(dimethylamino)-ethyl-1-hydroxy- α -phenylcyclopentaneacetate hydrochloride, molecular weight is 327.85 g/mol and molecular formula is $C_{17}H_{25}NO_3.HCl$ (Frag et al, 2011). 5 Cycloplegic drops have been applied to observe the effects of the drugs in various studies. Hung et al, evaluated the changes of intraocular pressure and refractive status among children (Hung et al, 2015). Farhood assessed the cycloplegic refraction among children. Their study aimed to evaluate the safety and efficacy of two cycloplegic regimens among hyperopic children (Farhood, 2012). Atropine 1% (regimen I) and cyclopentolate 1% (regimen II) eye drops were evaluated on fifty children. Li et al. investigated the effects of intravitreal injection of cyclopentolate on form deprivation myopia in guinea pigs (Zhou et al,

2015). Enantiomers, also known as optical isomers, represent each of the two molecules that are mirror images of each other. Different analytical techniques have been suggested in the literature to separate enantiomers and perform enantioselective analyses of chiral compounds (Izake, 2007; Mericko et al, 2007).

The aim of this study is to investigate the structural and spectroscopic analyses of cyclopentolate molecule used in eye treatments. Conformational analysis was performed, and four conformation energy values were calculated. The four conformational structures of the cyclopentolate molecule involve in-plane, out-of-plane OH bonds, and inward and outward oriented C=O bonds (Figure 1). The results of all spectroscopic analyses are given for conformation I in the study. The vibrational wavenumbers (FT-IR and Laser-Raman), UV analysis and 1H and ^{13}C NMR chemical shifts of cyclopentolate were experimentally and theoretically studied. The recorded experimental data (FT-IR, Laser-Raman, UV, NMR chemical shifts) were supported with parameters computed using theoretical methods with the DFT/B3LYP/aug-cc-pVDZ level.

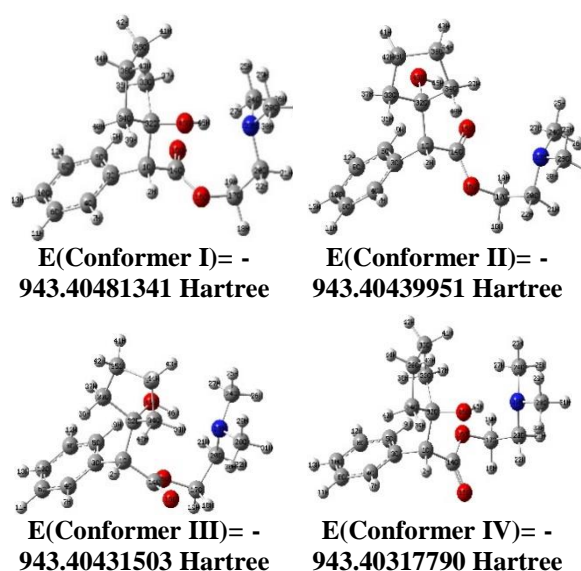


Figure 1. The optimized four molecular conformational forms in the lowest energy for cyclopentolate

2. Experimental Analyses

Cyclopentolate was purchased from Sigma-Aldrich Corporation. The FT-IR spectrum of cyclopentolate was collected in the region of 400-4000 cm^{-1} at room temperature on a Perkin-Elmer Spectrum Two FT-IR Spectrometer with standard resolution of 0.5 cm^{-1} in the transmission mode in the solid phase of the sample. The samples were compressed into self-supporting pellets and introduced into an IR cell equipped with KBr window.

The Laser-Raman spectrum was recorded on a Renishaw Invia Raman Microscope Spectrophotometer in 100-4000 cm^{-1} region in the solid phase of the sample. The excitation line width, scan number and resolution of the diode laser were 785 nm, 100 and 1 cm^{-1} , respectively.

The ^1H and ^{13}C NMR chemical shifts of the sample dissolved in DMSO- d_6 were obtained by Bruker Biospin-Avance III 400 MHz NMR spectrometer at the temperature of 295 K. The chemical shifts were reported at a frequency

of 400 MHz at ppm level relative to tetramethylsilane (TMS).

The ultraviolet visible spectrum of cyclopentolate dissolved in methanol was recorded using a UV-6100 Double Beam Spectrophotometer in the 200-400 nm region at room temperature. The spectral bandwidth is 2 nm.

3. Computational Procedures

The optimized molecular geometries, vibrational wavenumbers, proton and carbon-13 NMR chemical shifts, UV-Vis. electronic absorption parameters and HOMO-LUMO analyses of the title molecule were computed using B3LYP (Becke's three parameter exact exchange-functional (B3) combined with gradient-corrected correlational functional of Lee, Yang, Parr (LYP)) functional in density functional theory (DFT) with aug-cc-pVDZ basis set (Becke, 1993; Lee et al, 1988). The molecular geometric parameters, spectral properties and other molecular properties were performed using Gaussian 09W program package on a computing system (Frisch et al, 2009). GaussView5 program was used for visualization of the computed structural, spectroscopic and electronic properties (Dennington et al, 2019).

The calculated vibrational frequencies were scaled by 0.970 for the B3LYP/aug-cc-pVDZ level (Johnson, 2016). The assignments of vibrational wavenumbers and evaluation of potential energy distribution (PED) were performed using VEDA 4 program (Jamr'oz, 2004). The molecule was optimized in DMSO and methanol using conductor polarizable continuum model (CPCM) (Miertus et al, 1981) at the mentioned computational level to obtain ^1H and ^{13}C NMR isotropic chemical shifts and UV-Vis. parameters of cyclopentolate molecule. Then, ^1H and ^{13}C NMR chemical shifts of the title molecule

were studied using the gauge invariant atomic orbital (GIAO) approach (Ditchfield, 1974; Wolinski et al, 1990, London, 1937). The UV-Vis. spectroscopic analysis for the molecule was theoretically performed using the TD-DFT method (Runge and Gross, 1984). The HOMO and LUMO analyses were simulated at the aforementioned computational level.

4. Results and Discussions

4.1. Geometric Structure

The optimized molecular structures and computed molecular geometric parameters (bond lengths and angles) with the B3LYP/aug-cc-pVDZ level of cyclopentolate molecule are given in Figure 1 and Table 1, respectively. The molecular formula of cyclopentolate is $C_{17}H_{25}NO_3$ and its chemical name is 2-(Dimethylamino)ethyl(2*R*)-(1-hydroxycyclopentyl)(phenyl)acetate.

| Table 1. The optimized molecular geometric parameters for cyclopentolate. | | | | | | | |
|--|--------------------|-----------------|-----------------|-------------|-----------------|-------------|-------|
| Bond lengths (Å) | Literature | Calc. | Bond angles (°) | Calc. | Bond angles (°) | Calc. | |
| C1-H2 | - | 1.095 | H2-C1-C3 | 107.9 | N23-C24-H25 | 109.2 | |
| C1-C3 | - | 1.523 | H2-C1-C14 | 106.6 | N23-C24-H26 | 112.0 | |
| C1-C14 | - | 1.521 | H2-C1-C32 | 104.3 | N23-C24-H27 | 110.5 | |
| C1-C32 | - | 1.580 | C3-C1-C14 | 113.0 | H25-C24-H26 | 108.2 | |
| C3-C4 | d 1.360-1.410 | 1.405 | C3-C1-C32 | 116.2 | H25-C24-H27 | 107.9 | |
| C3-C5 | | 1.405 | C14-C1-C32 | 108.1 | H26-C24-H27 | 109.1 | |
| C4-C6 | | e 1.3859-1.4151 | 1.397 | C1-C3-C4 | 118.5 | N23-C28-H29 | 109.5 |
| C5-C8 | | | 1.398 | C1-C3-C5 | 123.3 | N23-C28-H30 | 109.7 |
| C6-C10 | | e 1.3920-1.3990 | 1.398 | C4-C3-C5 | 118.2 | N23-C28-H31 | 112.4 |
| C8-C10 | | | 1.398 | C3-C4-C6 | 121.3 | H29-C28-H30 | 108.1 |
| C4-H7 | e 1.0756-1.1015 | 1.091 | C3-C4-H7 | 119.4 | H29-C28-H31 | 108.3 | |
| C5-H9 | | 1.087 | C6-C4-H7 | 119.4 | H30-C28-H31 | 108.7 | |
| C6-H11 | | e 1.0831-1.1010 | 1.091 | C3-C5-C8 | 120.7 | C1-C32-C33 | 116.6 |
| C8-H12 | | | 1.091 | C3-C5-H9 | 119.6 | C1-C32-C34 | 112.6 |
| C10-H13 | | | 1.091 | C8-C5-H9 | 119.7 | C1-C32-O45 | 108.5 |
| C14-O15 | - | 1.215 | C4-C6-C10 | 120.0 | C33-C32-C34 | 102.6 | |
| C14-O16 | - | 1.357 | C4-C6-H11 | 119.8 | C33-C32-O45 | 110.5 | |
| O16-C17 | - | 1.443 | C10-C6-H11 | 120.2 | C34-C32-O45 | 105.4 | |
| C17-H18 | - | 1.096 | C5-C8-C10 | 120.6 | C32-C33-C35 | 104.3 | |
| C17-H19 | - | 1.094 | C5-C8-H12 | 119.4 | C32-C33-H36 | 109.2 | |
| C17-C20 | c 1.5341 | 1.526 | C10-C8-H12 | 120.0 | C32-C33-H37 | 112.1 | |
| C20-H21 | - | 1.111 | C6-C10-C8 | 119.3 | C35-C33-H36 | 110.4 | |
| C20-H22 | - | 1.098 | C6-C10-H13 | 120.3 | C35-C33-H37 | 113.5 | |
| C20-N23 | c 1.4625 | 1.467 | C8-C10-H13 | 120.4 | H36-C33-H37 | 107.4 | |
| N23-C24 | c 1.4629 | 1.465 | C1-C14-O15 | 125.8 | C32-C34-C38 | 104.6 | |
| N23-C28 | c 1.4623 | 1.465 | C1-C14-O16 | 110.7 | C32-C34-H39 | 110.7 | |
| C24-H25 | - | 1.097 | O15-C14-O16 | 123.4 | C32-C34-H40 | 109.4 | |
| C24-H26 | - | 1.109 | C14-O16-C17 | 117.5 | C38-C34-H39 | 113.3 | |
| C24-H27 | - | 1.095 | O16-C17-H18 | 106.2 | C38-C34-H40 | 110.6 | |
| C28-H29 | - | 1.097 | O16-C17-H19 | 109.5 | H39-C34-H40 | 108.2 | |
| C28-H30 | - | 1.097 | O16-C17-C20 | 109.3 | C33-C35-C38 | 105.9 | |
| C28-H31 | - | 1.109 | H18-C17-H19 | 109.1 | C33-C35-H41 | 110.4 | |
| C32-C33 | a 1.522-1.539 | 1.540 | H18-C17-C20 | 109.3 | C33-C35-H42 | 111.2 | |
| C32-C34 | | b 1.510-1.533 | 1.537 | H19-C17-C20 | 113.2 | C38-C35-H41 | 110.2 |
| C33-C35 | | | 1.546 | C17-C20-H21 | 107.8 | C38-C35-H42 | 112.1 |
| C34-C38 | | | 1.546 | C17-C20-H22 | 108.1 | H41-C35-H42 | 107.0 |
| C35-C38 | | | 1.559 | C17-C20-N23 | 114.3 | C34-C38-C35 | 105.7 |
| C32-O45 | a 1.444 b 1.428 | 1.433 | H21-C20-H22 | 107.3 | C34-C38-H43 | 110.4 | |
| C33-H36 | - | 1.097 | H21-C20-N23 | 111.5 | C34-C38-H44 | 111.2 | |
| C33-H37 | - | 1.096 | H22-C20-N23 | 107.6 | C35-C38-H43 | 110.4 | |
| C34-H39 | - | 1.097 | C20-N23-C24 | 112.6 | C35-C38-H44 | 112.0 | |
| C34-H40 | - | 1.097 | C20-N23-C28 | 110.5 | H43-C38-H44 | 107.2 | |
| C35-H41 | - | 1.097 | C24-N23-C28 | 110.7 | C32-O45-H46 | 111.5 | |
| C35-H42 | - | 1.098 | C4-C3-C1-C32 | -100.6 | O45-H46-N23 | 164.1 | |
| C38-H43 | - | 1.096 | C5-C3-C1-C14 | -46.2 | O15-C14-C1-C32 | -74.9 | |
| C38-H44 | - | 1.098 | C14-C16-C17-C20 | 102.3 | O16-C14-C1-C32 | 102.2 | |
| O45-H46 | - | 0.980 | C1-C14-O16-C17 | -164.2 | C14-C1-C32-O45 | -59.1 | |
| H46-N23 | - | 2.027 | C14-C1-C32-C33 | 66.4 | C1-C32-O45-H46 | 66.4 | |
| | | | C17-C20-N23-C24 | -70.1 | C16-C17-C20-N23 | -62.4 | |
| | | | C17-C20-N23-C28 | 165.5 | C32-C34-C38-C35 | 24.0 | |
| | | | C5-C3-C4-C6 | -0.8 | C33-C35-C38-C34 | 0.6 | |
| | | | C3-C1-C32-C33 | -61.9 | O15-C14-O16-C17 | 12.9 | |

a, b, c, d and e Taken from Refs. Hirschler, 1994; Angelova, 1992; Sroczyński, 2017; Trotter, 1960; Palafox, 2000, respectively.

In the literature, two molecular forms as *R*- and *S*- are available for cyclopentolate. These structures are also known as enantiomers or optical isomers. Szwed et al. (2013) used experimental and computational (optimized molecular geometries) methods to determine the absolute configurations of enantiomers of cyclopentolate molecule. They reported optimized molecular structures for the three lowest-energy conformers with the B3LYP/aug-ccpVDZ level of (*R*)-cyclopentolate (Szwed et al, 2013). In this study, considering the molecular geometric forms obtained by Szwed et al. (2013), we determined the four conformational forms for the cyclopentolate molecule. In our study, as shown in Figure 1, the calculated energy values for four lowest-energy conformational forms of cyclopentolate molecule were obtained as -943.40481341 Hartrees (for conformer I), -943.40439951 Hartrees (for conformer II), -943.40431503 Hartrees (for conformer III) and -943.40317790 Hartrees (for conformer IV) with the B3LYP/aug-cc-pVDZ level, respectively. As indicated by these computed energy values, conformer I is the most stable molecular form. Therefore, in this study, detailed structural and spectroscopic analyses were performed for conformer I.

The C-C bond lengths in phenyl ring of the title molecule were calculated at the interval of 1.397-1.405 Å, while they recorded between 1.36-1.41 Å for benzene derivatives in the literature (Trotter, 1960). Additionally, the C-C and C-H bond lengths obtained with some quantum chemical computational levels of the benzene ring were calculated at the intervals of 1.3920-1.3990 Å (1.3920-1.3990 Å (exp.)) and 1.0831-1.1010 Å (1.0831-1.1010 Å (exp.)) by Palafox (2000) respectively. Similarly, the C32-C33, C32-C34, C33-C35, C34-C38, C35-C38 and C32-

O45 bond lengths in 1-hydroxycyclopentyl group were computed as 1.540 Å, 1.537 Å, 1.546 Å, 1.546 Å, 1.559 Å and 1.433 Å, respectively.

Hirschler et al. (1994) reported values at the interval of 1.522-1.539 Å for C-C bond lengths and 1.444 Å for C-O bond length in 1-hydroxycyclopentyl group in (1*R*,3*R*)-2[(2*R*,4*R*,5*R*)-3-(*p*-chlorophenylsulfonyl)-4-methyl-5-phenyl-1,3-oxazolidin-2-yl]-5-{2-(1*R*,2*S*)-[(2*R*,4*R*,5*R*)-3-(*p*-chlorophenylsulfonyl)-4-methyl-5-phenyl-1,3-oxazolidin-2-yl]-1-hydroxycyclopentyl}-1-cyclopentanone (C₄₂H₄₄Cl₂N₂O₈S₂) molecule. Likewise, the C-C and C-O bond lengths in 1-hydroxycyclopentyl group of (±) diethyl ester of (1-hydroxycyclopentyl) (2-methylphenyl)methylphosphonic acid were measured between 1.510-1.533 Å and at 1.428 Å by Angelova et al. (1992) The C1-C3, C1-C14 and C1-C32 bond lengths were theoretically obtained at 1.523 Å, 1.521 Å, and 1.580 Å, respectively. The C-O bond lengths were calculated as 1.215 Å for C14=O15, 1.357 Å for C14-O16 and 1.443 Å for C17-O16. The C24,28-N23, C20-N23 and C17-C20 bond lengths in 2-(dimethylamino)ethyl group in the title molecule were computed at 1.465 Å, 1.467 Å and 1.526 Å. Sroczynski and Malinowski (2017) computed the N-CH₃ bond lengths as 1.4629 Å and 1.4623 Å, the N-C bond length as 1.4625 Å and the CH₂-CH₂ bond length as 1.5341 Å in 2-(dimethylamino)ethyl group of 2-[2-(dimethylamino)ethyl]-6-methoxy-4-(pyridin-2-yl)-1(2*H*)-phthalazinone molecule with the B3LYP/6-311++G(d,p) level (Sroczyński and Malinowski, 2017). The C-H bond lengths in the title molecule were calculated at the interval of 1.087-1.111 Å. Likewise, the O45-H46 bond length was computed as 0.980 Å.

| Table 2. The experimental and computed vibrational wavenumbers and their vibrational assignments of cyclopentolate. | | | | | | | |
|---|-------|--|-------------------------|-------|-----------------|--------------------|---|
| Exp. freq. (cm ⁻¹) | | Assignment (PED%) | The computed parameters | | | | |
| IR | Raman | | Mode | Freq. | I _{IR} | S _{Raman} | ^a I _{Raman} (×10 ⁻³⁶) |
| 3230 | - | νOH(100) | ν ₁₃₂ | 3386 | 723.72 | 297.60 | 36.41 |
| 3105 | - | νCH(100) in phenyl | ν ₁₃₁ | 3123 | 1.69 | 75.08 | 11.18 |
| 3090 | - | νCH(91) in phenyl | ν ₁₃₀ | 3099 | 21.50 | 294.58 | 44.67 |
| - | - | νCH(87) in phenyl | ν ₁₂₉ | 3087 | 24.16 | 78.91 | 12.08 |
| - | - | νCH(94) in phenyl | ν ₁₂₈ | 3076 | 1.70 | 106.16 | 16.38 |
| - | 3068 | νCH(95) in phenyl | ν ₁₂₇ | 3069 | 4.45 | 27.06 | 4.20 |
| - | 3051 | ν _{as} CH ₂ (82) | ν ₁₂₆ | 3052 | 6.12 | 44.89 | 7.05 |
| 3039 | 3045 | ν _{as} CH ₃ (81) | ν ₁₂₅ | 3041 | 10.53 | 20.54 | 3.25 |
| - | - | ν _{as} CH ₃ (97) | ν ₁₂₄ | 3029 | 15.49 | 37.24 | 5.95 |
| - | - | ν _{as} CH ₂ (96) in cycl. | ν ₁₂₃ | 3028 | 75.87 | 44.12 | 7.06 |
| 3017 | 3020 | ν _{as} CH ₂ (97) in cycl. | ν ₁₂₂ | 3022 | 13.03 | 52.42 | 8.43 |
| - | - | ν _{as} CH ₂ (86) in cycl. | ν ₁₂₁ | 3009 | 4.09 | 120.98 | 19.63 |
| - | - | νCH(98) | ν ₁₂₀ | 2998 | 5.01 | 25.49 | 4.17 |
| - | - | ν _{as} CH ₃ (55)+ν _s CH ₂ (24) | ν ₁₁₉ | 2994 | 0.44 | 213.06 | 34.98 |
| - | - | ν _{as} CH ₂ (82) in cycl. | ν ₁₁₈ | 2993 | 4.51 | 30.09 | 4.95 |
| 2990 | 2990 | ν _s CH ₂ (68)+ν _{as} CH ₃ (17) | ν ₁₁₇ | 2992 | 50.38 | 46.02 | 7.57 |
| - | - | ν _s CH ₂ (72)+ν _{as} CH ₃ (21) | ν ₁₁₆ | 2988 | 22.68 | 67.99 | 11.21 |
| - | - | ν _{as} CH ₃ (82) | ν ₁₁₅ | 2986 | 13.18 | 28.76 | 4.75 |
| - | - | ν _s CH ₂ (95) in cycl. | ν ₁₁₄ | 2980 | 24.42 | 399.70 | 66.36 |
| 2964 | 2962 | ν _s CH ₂ (81) in cycl. | ν ₁₁₃ | 2972 | 39.52 | 13.57 | 2.27 |
| 2953 | 2943 | ν _s CH ₂ (98) in cycl. | ν ₁₁₂ | 2969 | 61.32 | 32.25 | 5.40 |
| 2927 | 2915 | ν _s CH ₂ (96) in cycl. | ν ₁₁₁ | 2962 | 14.83 | 50.40 | 8.48 |
| 2885 | - | ν _s CH ₃ (87) | ν ₁₁₀ | 2862 | 229.75 | 424.61 | 77.16 |
| 2880 | 2872 | ν _s CH ₃ (92) | ν ₁₀₉ | 2854 | 35.41 | 46.67 | 8.53 |
| - | - | ν _s CH ₂ (91) | ν ₁₀₈ | 2837 | 66.88 | 121.78 | 22.55 |
| 1735 | 1734 | νC=O(87) | ν ₁₀₇ | 1710 | 138.02 | 5.29 | 2.54 |
| 1605 | 1604 | [νCC(52)+δHCC(16)] in phenyl | ν ₁₀₆ | 1595 | 7.87 | 50.21 | 27.01 |
| 1584 | 1584 | [νCC(56)+δCCC(23)] in phenyl | ν ₁₀₅ | 1573 | 0.98 | 10.00 | 5.51 |
| 1472 | 1474 | [δHCC(61)+δCCC(11)] in phenyl | ν ₁₀₄ | 1470 | 15.45 | 0.42 | 0.25 |
| - | - | δ _s CH ₂ (77) in cycl. | ν ₁₀₃ | 1463 | 3.79 | 1.82 | 1.12 |
| 1456 | 1454 | δ _s CH ₃ (41)+δ _s CH ₂ (24) | ν ₁₀₂ | 1450 | 14.09 | 1.30 | 0.81 |
| 1452 | 1452 | δ _s CH ₃ (49)+δ _s CH ₂ (12) | ν ₁₀₁ | 1446 | 10.29 | 11.54 | 7.24 |
| - | - | δ _s CH ₃ (24)+δ _s CH ₂ (21) in cycl. and aliphatic | ν ₁₀₀ | 1440 | 4.77 | 3.54 | 2.23 |
| - | - | δ _s CH ₂ (43) in cycl.+δ _s CH ₂ (10) | ν ₉₉ | 1438 | 6.03 | 1.32 | 0.83 |
| - | - | δ _s CH ₂ (54) in cycl. | ν ₉₈ | 1438 | 3.36 | 3.50 | 2.21 |
| - | - | δ _s CH ₃ (31)+δ _s CH ₂ (30) | ν ₉₇ | 1435 | 31.07 | 5.26 | 3.34 |
| - | - | [δHCC(35)+νCC(10)] in phenyl | ν ₉₆ | 1429 | 9.37 | 2.59 | 1.66 |
| - | - | δ _s CH ₂ (47) in cycl. | ν ₉₅ | 1426 | 2.65 | 9.40 | 6.03 |

| | | | | | | | |
|------|------|--|------------|------|--------|-------|-------|
| - | 1421 | $\delta_s\text{CH}_3(75)$ | ν_{94} | 1425 | 2.31 | 6.25 | 4.01 |
| 1417 | 1416 | $\delta_s\text{CH}_3(22)+\delta_s\text{CH}_2(20)$ | ν_{93} | 1422 | 3.22 | 4.34 | 2.79 |
| 1399 | - | $\delta_s\text{CH}_3(38)$ (sym. bending)+ $\delta_s\text{CH}_2(13)$ | ν_{92} | 1406 | 1.47 | 4.58 | 3.00 |
| - | - | $\delta\text{HOC}(37)+\delta_s\text{CH}_3(27)$ (sym. bending) | ν_{91} | 1386 | 41.04 | 1.07 | 0.71 |
| 1375 | 1372 | $\delta\text{HOC}(34)+\delta_s\text{CH}_3(11)$ (sym. bending) | ν_{90} | 1379 | 25.58 | 2.71 | 1.83 |
| - | 1361 | $w\text{CH}_2(25)+\delta\text{H}_2\text{C}_1\text{C}_3(13)$ | ν_{89} | 1362 | 10.10 | 0.59 | 0.40 |
| 1354 | - | $w\text{CH}_2(19)$ | ν_{88} | 1350 | 71.97 | 0.99 | 0.69 |
| 1322 | - | $\delta\text{H}_2\text{C}_1\text{C}_3(15)+w\text{CH}_2(15)+\delta\text{HCC}(10)$ in phenyl | ν_{87} | 1328 | 12.25 | 0.63 | 0.45 |
| - | - | $w\text{CH}_2(34)$ in cycl. | ν_{86} | 1316 | 4.89 | 0.40 | 0.29 |
| 1307 | 1299 | $[\delta\text{HCC}(42)+v\text{CC}(40)]$ in phenyl | ν_{85} | 1311 | 2.12 | 1.01 | 0.73 |
| 1289 | - | $w\text{CH}_2(29)$ in cycl. | ν_{84} | 1289 | 6.90 | 1.15 | 0.86 |
| - | - | $w\text{CH}_2(21)$ in cycl. | ν_{83} | 1284 | 31.42 | 2.67 | 2.00 |
| - | - | $w\text{CH}_2(15)$ in cycl.+ $\delta\text{HCC}(15)$ in phenyl | ν_{82} | 1282 | 60.88 | 0.39 | 0.29 |
| - | - | $t\text{CH}_2(21)$ | ν_{81} | 1268 | 12.93 | 5.05 | 3.86 |
| 1265 | 1264 | $w\text{CH}_2(32)$ in cycl. | ν_{80} | 1267 | 3.65 | 1.48 | 1.13 |
| - | - | $t\text{CH}_2(30)+v\text{CN}(14)+p\text{CH}_3(11)$ | ν_{79} | 1260 | 17.23 | 2.86 | 2.20 |
| 1254 | 1258 | $w\text{CH}_2(15)$ in cycl. | ν_{78} | 1250 | 1.30 | 5.49 | 4.29 |
| 1236 | 1234 | $t\text{CH}_2(22)$ | ν_{77} | 1239 | 8.61 | 3.61 | 2.85 |
| - | - | $t\text{CH}_2(67)$ in cycl. | ν_{76} | 1215 | 2.38 | 2.44 | 1.98 |
| 1199 | - | $t\text{CH}_2(14)$ in cycl. | ν_{75} | 1197 | 63.70 | 13.84 | 11.51 |
| 1186 | 1186 | $\nu\text{CN}(15)$ | ν_{74} | 1188 | 12.37 | 9.16 | 7.70 |
| - | - | - | ν_{73} | 1180 | 34.31 | 4.08 | 3.46 |
| 1177 | - | $t\text{CH}_2(22)$ in cycl. | ν_{72} | 1177 | 4.00 | 19.24 | 16.38 |
| - | 1162 | $t\text{CH}_2(23)$ in cycl.+ $\nu\text{C}_1\text{C}_3(10)$ | ν_{71} | 1168 | 2.83 | 21.48 | 18.49 |
| - | 1158 | $[\delta\text{HCC}(78)+v\text{CC}(17)]$ in phenyl | ν_{70} | 1164 | 1.74 | 4.95 | 4.28 |
| 1149 | - | $p\text{CH}_3(48)$ | ν_{69} | 1143 | 27.54 | 11.69 | 10.39 |
| - | - | $[\delta\text{HCC}(76)+v\text{CC}(14)]$ in phenyl | ν_{68} | 1136 | 0.05 | 3.93 | 3.52 |
| - | - | $\nu\text{C}_{14}\text{O}_{16}(33)+\delta\text{OCO}(12)$ | ν_{67} | 1124 | 312.86 | 3.05 | 2.77 |
| 1101 | 1090 | $\nu\text{CC}(22)$ in cycl. | ν_{66} | 1089 | 32.37 | 8.35 | 7.94 |
| 1080 | - | $p\text{CH}_3(66)$ | ν_{65} | 1078 | 4.79 | 2.12 | 2.05 |
| - | - | $[\delta\text{HCC}(40)+v\text{CC}(36)]$ in phenyl | ν_{64} | 1067 | 10.50 | 1.37 | 1.34 |
| 1061 | 1065 | $\nu\text{CC}(18)$ in cycl. | ν_{63} | 1059 | 15.09 | 8.17 | 8.08 |
| 1049 | 1052 | $p\text{CH}_2(17)+\nu\text{C}_{17}\text{C}_{20}(10)$ | ν_{62} | 1053 | 2.14 | 5.01 | 4.99 |
| 1034 | 1038 | $\nu\text{CN}(29)+p\text{CH}_3(18)$ | ν_{61} | 1044 | 15.89 | 2.32 | 2.34 |
| 1028 | 1031 | $[v\text{CC}(31)+\delta\text{HCC}(14)]$ in phenyl | ν_{60} | 1022 | 1.06 | 19.12 | 19.89 |
| - | - | $\nu\text{CN}(43)+p\text{CH}_3(10)$ | ν_{59} | 1020 | 17.76 | 3.23 | 3.36 |
| 1010 | 1007 | $\nu\text{CC}(28)$ in cycl. | ν_{58} | 1014 | 10.92 | 9.26 | 9.73 |
| - | - | $[\tau\text{CCCC}(26)+\delta\text{CCC}(14)+p\text{CH}_2(11)]$ in cycl. | ν_{57} | 1004 | 2.10 | 2.04 | 2.17 |
| 991 | 990 | $\nu\text{C}_{17}\text{O}_{16}(21)+v\text{CC}(15)$ in cycl. | ν_{56} | 997 | 36.64 | 7.59 | 8.17 |
| - | - | $t\text{CH}_2(19)+\nu\text{C}_{32}\text{O}_{45}(13)$ | ν_{55} | 986 | 14.98 | 15.76 | 17.23 |
| - | 973 | $\delta\text{phenyl}(85)$ | ν_{54} | 980 | 1.69 | 34.95 | 38.53 |
| 967 | - | $[\tau\text{HCCC}(57)+\tau\text{CCCC}(22)]$ in phenyl | ν_{53} | 967 | 0.35 | 1.76 | 1.98 |
| 952 | 953 | $\tau\text{HCCC}(79)$ in phenyl | ν_{52} | 952 | 0.31 | 0.53 | 0.60 |

| | | | | | | | |
|-----|-----|--|-----------------|-----|-------|-------|-------|
| - | 929 | vCC(40) in cycl. | v ₅₁ | 947 | 7.39 | 0.80 | 0.92 |
| 921 | 920 | vCN(35)+pCH ₂ (12) | v ₅₀ | 934 | 26.16 | 2.85 | 3.35 |
| - | 912 | τHCCC(11) in phenyl | v ₄₉ | 913 | 28.48 | 1.93 | 2.35 |
| - | - | vC ₃₂ O ₄₅ (11)+vC ₁ C ₃₂ (11) | v ₄₈ | 900 | 11.42 | 1.94 | 2.40 |
| 893 | 890 | τHCCC(55) in phenyl | v ₄₇ | 897 | 12.92 | 3.01 | 3.75 |
| 861 | 870 | δcycl.(38) | v ₄₆ | 865 | 2.06 | 14.76 | 19.28 |
| - | 867 | vC ₁₇ O ₁₆ (22)+δO ₁₆ C ₂₄ C ₁ (11) | v ₄₅ | 857 | 1.18 | 12.21 | 16.16 |
| - | 838 | vC ₁₇ O ₁₆ (22)+γOCOC(12) | v ₄₄ | 846 | 2.23 | 1.71 | 2.30 |
| - | 829 | τHCCC(98) in phenyl | v ₄₃ | 827 | 0.22 | 0.58 | 0.80 |
| - | - | [vCC(24)+pCH ₂ (10)] in cycl. | v ₄₂ | 799 | 3.01 | 9.09 | 13.23 |
| 786 | 790 | δcycl.(10) | v ₄₁ | 791 | 1.39 | 1.21 | 1.78 |
| - | - | vNC(16) | v ₄₀ | 774 | 14.11 | 0.77 | 1.17 |
| 750 | 753 | vNC(41)+vC ₁₇ C ₂₀ (11) | v ₃₉ | 763 | 9.18 | 6.77 | 10.49 |
| 736 | 742 | τHCCC(13) in phenyl+γOCOC(12)+δOCO(10) | v ₃₈ | 734 | 6.61 | 0.78 | 1.27 |
| - | 720 | δOCO(17)+τHCCC(10) in phenyl | v ₃₇ | 719 | 39.70 | 2.00 | 3.36 |
| 703 | - | [pCH ₂ (25)+vCC(13)] in cycl. | v ₃₆ | 706 | 2.90 | 4.53 | 7.80 |
| - | - | [τHCCC(54)+τCCCC(29)] in phenyl | v ₃₅ | 690 | 39.03 | 0.23 | 0.40 |
| - | - | τHOCC(72) | v ₃₄ | 682 | 34.96 | 0.32 | 0.58 |
| 643 | 644 | δcycl.(16)+δphenyl(11) | v ₃₃ | 641 | 13.96 | 0.97 | 1.91 |
| - | 640 | δcycl.(29) | v ₃₂ | 638 | 0.12 | 0.63 | 1.24 |
| - | 621 | δphenyl(26)+γOCOC(13)+vC ₁ C ₃₂ (10) | v ₃₁ | 611 | 1.06 | 3.37 | 7.06 |
| 589 | 592 | δphenyl(85) | v ₃₀ | 577 | 19.88 | 3.85 | 8.71 |
| 552 | 554 | δNC ₂₀ C ₁₇ (23)+δC ₂₀ C ₁₈ O ₁₆ (20) | v ₂₉ | 536 | 1.54 | 0.33 | 0.83 |
| 501 | 502 | τphenyl(47) | v ₂₈ | 492 | 5.05 | 0.72 | 2.02 |
| 451 | 459 | δO ₄₅ C ₃₂ C ₃₄ (31)+γO ₄₅ C ₁ C ₃₂ C ₃₄ (23) | v ₂₇ | 443 | 2.72 | 1.03 | 3.38 |
| 422 | 424 | δC ₂₄ NC ₂₈ (53) | v ₂₆ | 425 | 2.29 | 0.36 | 1.23 |
| - | 410 | [τCCCC(75)+τHCCC(20)] in phenyl | v ₂₅ | 407 | 0.33 | 0.03 | 0.10 |
| 403 | - | γC ₃₄ C ₁ C ₃₃ C ₃₂ (19) | v ₂₄ | 401 | 1.04 | 1.53 | 5.78 |
| - | 392 | δC ₂₀ NC ₂₄ (33)+pCH ₂ (11) | v ₂₃ | 397 | 20.10 | 0.75 | 2.88 |
| - | - | δCOC(26)+γC ₂₈ C ₂₀ C ₄₄ N(18)+δOCO(10) | v ₂₂ | 386 | 13.45 | 0.94 | 3.73 |
| - | - | δC ₂₀ C ₁₇ O ₁₆ (11)+γC ₂₈ C ₂₀ C ₄₄ N(21) | v ₂₁ | 345 | 1.00 | 1.50 | 7.06 |
| - | 321 | γO ₄₅ C ₁ C ₃₄ C ₃₃ (30)+δO ₄₅ C ₃₂ C ₃₄ (11) | v ₂₀ | 319 | 8.24 | 0.63 | 3.32 |
| - | - | δO ₁₆ C ₁₄ C ₁ (18)+δC ₁ C ₃ C ₅ (18) | v ₁₉ | 303 | 1.07 | 1.19 | 6.83 |
| - | 283 | vC ₁ C ₃ (22)+τCH ₃ (14)+δO ₁₆ C ₁₄ C ₁ (12) | v ₁₈ | 275 | 0.81 | 3.85 | 25.57 |
| - | - | τCH ₃ (26) | v ₁₇ | 256 | 1.27 | 1.22 | 9.02 |
| - | 249 | τCH ₃ (15)+δC ₁ C ₃₂ C ₃₃ (13) | v ₁₆ | 248 | 0.45 | 1.33 | 10.44 |
| - | - | τphenyl(14)+τCH ₃ (11) | v ₁₅ | 241 | 1.21 | 1.41 | 11.55 |
| - | - | τCH ₃ (19) | v ₁₄ | 238 | 1.35 | 1.01 | 8.43 |
| - | - | δNCC(28) | v ₁₃ | 211 | 1.52 | 0.28 | 2.87 |
| - | - | δC ₁ C ₃ C ₅ (32)+τcycl.(13) | v ₁₂ | 182 | 2.55 | 0.46 | 5.98 |
| - | 146 | τcycl.(36)+τC ₁₇ O ₂₆ C ₁₄ C ₁ (18) | v ₁₁ | 152 | 1.92 | 0.48 | 8.36 |
| - | - | γC ₁₄ C ₃₂ O ₁ C ₃ (13)+τCNCC(11) | v ₁₀ | 129 | 0.77 | 1.29 | 30.43 |
| - | 112 | τCNCC(31)+γC ₁₄ C ₃₂ O ₁ C ₃ (11) | v ₉ | 120 | 0.55 | 0.08 | 2.08 |
| - | - | τC ₂₀ C ₁₇ O ₁₆ C ₁₄ (44) | v ₈ | 100 | 0.38 | 0.32 | 11.91 |

| | | | | | | | |
|---|---|--|---------|----|------|------|--------|
| - | - | τ NCCC(13)+ τ C ₂₀ C ₁₇ O ₁₆ C ₁₄ (13)+ δ C ₃ C ₁ C ₃₂ (11) | ν_7 | 86 | 0.66 | 1.92 | 93.62 |
| - | - | τ C ₁₇ O ₁₆ C ₁₄ C ₁ (26)+ τ C ₃₃ C ₃₂ C ₁ C ₃ (21) | ν_6 | 79 | 0.42 | 0.07 | 4.04 |
| - | - | τ C ₃₂ C ₁ C ₃ C ₄ (22)+ τ cycl.(15) | ν_5 | 71 | 0.46 | 2.47 | 172.03 |
| - | - | τ cycl.(19)+ δ C ₃ C ₁ C ₃₂ (13)+ ρ CH ₂ (12) in cycl. | ν_4 | 70 | 0.21 | 1.35 | 96.47 |
| - | - | τ C ₃₂ C ₁ C ₃ C ₄ (56) | ν_3 | 50 | 0.03 | 3.54 | 464.10 |
| - | - | τ O ₁₆ C ₁₄ C ₁ C ₃₂ (24)+ τ C ₃₃ C ₃₂ C ₁ C ₃ (21)+ τ C ₁₇ O ₁₆ C ₁₄ C ₁ (13)+ δ C ₃ C ₁ C ₁₄ (12) | ν_2 | 42 | 1.99 | 0.99 | 180.94 |
| - | - | τ O ₁₆ C ₁₄ C ₁ C ₃₂ (45)+ τ C ₃₃ C ₃₂ C ₁ C ₃ (27) | ν_1 | 34 | 0.46 | 0.16 | 45.87 |

R² and **RMSD** values are **0.99933** and **23.4 cm⁻¹** for IR wavenumbers and **0.99984** and **10.6 cm⁻¹** for Raman wavenumbers, respectively.

s, symmetric; as, asymmetric; ν , stretching; δ , in-plane bending; τ , torsion; γ , out-of-plane bending; δ_s , scissoring and symmetric bending; ρ , rocking; t , twisting; w , wagging; 1-hydroxycyclopentyl, cycl.; I_{IR} , IR intensity (km/mol); S_{Raman} , Raman scattering activity ($\text{\AA}^4/\text{amu}$); PED, potential energy distribution.

^a Raman intensities (I_{Raman}) and its spectrum were obtained by chemcraft program (www.chemcraftprog.com).

There is weak intramolecular hydrogen bond interaction in cyclopentolate molecule. This intramolecular hydrogen interaction is O45-H46...N23. The H46...N23 bond length and O45-H46...N23 bond angle in this weak interaction were theoretically obtained as 2.027 Å and 164.1°.

The C3-C1-C14, C3-C1-C32 and C14-C1-C32 bond angles were calculated as 113.0°, 116.2° and 108.1°, respectively. The C-C-C bond angles in the phenyl ring of the title compound were calculated at the interval of 118.2°-121.3°, while these bond angles in 1-hydroxycyclopentyl group were theoretically obtained at the interval of 102.6°-105.9°. The C1-C32-O45, C33-C32-O45, C34-C32-O45, C1-C14-O15, C1-C14-O16, O15-C14-O16, C14-O16-C17 and O16-C17-C20 containing oxygen atoms were computed at 108.5°, 110.5°, 105.4°, 125.8°, 110.7°, 123.4°, 117.5° and 109.3°, while the C17-C20-N23, C20-N23-C24, C20-N23-C28 and C24-N23-C28 bond angles in 2-(dimethylamino)ethyl group were theoretically found at 114.3°, 112.6°, 110.5° and 110.7°, respectively.

It can be inferred from the optimized molecular structure and computed dihedral angles for conformer I that cyclopentolate is non-planar. As a result, the C4-C3-C1-C32, C5-C3-C1-C14, C3-C1-C32-C33 and O16-C14-C1-C32 dihedral angles were calculated as -100.6°, -46.2°, -61.9° and 102.2°, while the C14-O16-C17-C20, O16-C17-C20-N23, C17-C20-N23-C24 and C17-C20-N23-C28 dihedral angles were computed as 102.3°, -62.4°, -70.1° and 165.5°, respectively.

4.2. Vibrational Frequency Analyses

In the following discussion, the cyclopentolate molecule is experimentally examined. The observed and calculated vibrational frequencies, calculated FT-IR intensities, Raman scattering activities and vibrational assignments of the title molecule are given in Table 2. The experimental and simulated IR spectra of cyclopentolate are shown in Figure 2 and the experimental and simulated Raman spectra of cyclopentolate are shown in Figure 3. The computations of harmonic wavenumbers, IR intensities and Raman activities were performed with the B3LYP/aug-cc-pVDZ level. Cyclopentolate

consists of 46 atoms and accordingly it has 132 modes of vibrations. The linear correlation coefficient (R^2) and root-mean-square deviation (RMSD) values between the experimental and computed vibrational frequencies were found as 0.99933 and 23.4 cm^{-1} for IR wavenumbers and 0.99983 and 10.6 cm^{-1} for Raman ones, respectively. The experimental and simulated IR and Raman spectra of the title compound are given in Figures 2 and 3, respectively. In the present research, C-H, C-O, C-C and C-N vibrations were examined. As seen from Table 2, the experimental and calculated vibrational wavenumbers are in good agreement.

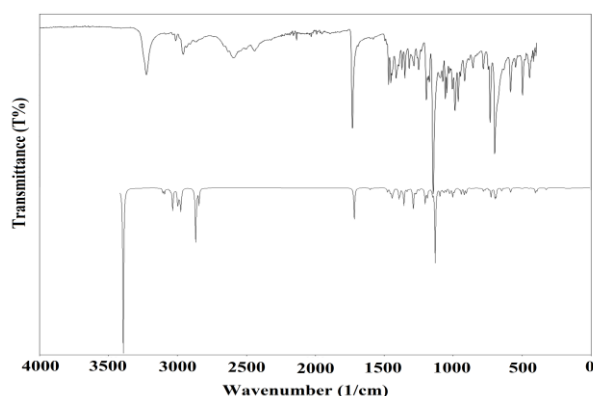


Figure 2. The experimental and simulated IR spectra of cyclopentolate

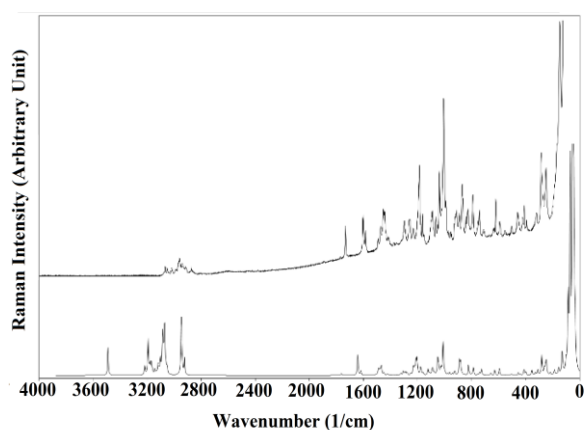


Figure 3. The experimental and simulated Raman spectra of cyclopentolate

4.2.1. C-H and O-H vibrations

The C-H stretching vibrations in phenyl ring are between 3100 and 3000 cm^{-1} (Akyıldırım et al, 2017; Silverstein et al, 2005; Bilkan, 2017; Stuart, 2004; Lambert and Shurvell, 1987; Colthup et al, 1964). The C-H stretching bands in phenyl ring were observed at 3090 and 3105 cm^{-1} in FT-IR spectrum and at 3068 cm^{-1} in Laser-Raman spectrum. These bands were computed in the range of 3123-3069 cm^{-1} in our calculations (Palafox, 2000). The C1-H2 stretching vibration was not observed in FT-IR and Laser-Raman spectra, whereas it was calculated at 2998 cm^{-1} . The HCC in-plane bending vibrational modes (δHCC) of phenyl ring were obtained at 1472 (IR)-1474 (R) (exp.)/1470 (cal.), 1429 (cal.), 1307 (IR)-1299 (R)/1311 (cal.), 1158 (R) (exp.)/1164 (cal.), 1136 (cal.) and 1067 (cal.) cm^{-1} as generally combined with CC stretching vibrations of ring, whereas the HCCC out-of-plane bending vibrations (τHCCC) were found at 967 (IR) (exp.)/967 (cal.), 952 (IR)-953 (R) (exp.)/952 (cal.), 912 (R)/913 (cal.), 893 (IR)-890 (R) (exp.)/897 (cal.), 829 (R)/827 (cal.) and 690 (cal.) cm^{-1} mainly as individual bands (Palafox, 2000).

The O-H stretching band in 1-hydroxycyclopentyl group of the title molecule was observed at 3230 cm^{-1} in FT-IR spectrum, while it was computed at 3386 cm^{-1} . The OH in-plane bending vibrations (δHOC) were found at 1375 (IR)-1372 (R)/1379 (cal. with 34% contribution of PED) cm^{-1} and 1386 (cal. with 37% contribution of PED) cm^{-1} . The OH out-of-plane bending mode (τHOCC) was not observed in both FT-IR and Laser-Raman spectra, whereas it was computed at 682 cm^{-1} with 72% contribution of PED.

4.2.2. CO vibrations

The C=O stretching band in the carboxyl group gives strong absorption band in the region 1870-1540 cm^{-1} (Akyıldırım et al, 2017; Silverstein et al, 2005; Bilkan, 2017; Stuart, 2004; Lambert and Shurvell, 1987; Colthup et al, 1964). The C=O stretching vibration of cyclopentolate was observed at 1735 (IR)-1734 (R) cm^{-1} and the computed scaled wavenumber value for this band was obtained at 1710 cm^{-1} . The C-O stretching vibrations of cyclopentolate were observed at 991 (IR)-990 (R), 867 (R) and 838 (R) cm^{-1} . The computed values (with X% contribution of PED) for this C-O stretching bands (νC16O16 , νC17O16 and νC32O45) were obtained at 1124 (33%), 997 (21%), 986 (13%), 900 (11%), 857 (22%) and 846 (22%) cm^{-1} .

4.2.3. C-N vibrations

Mani et al. assigned C-N stretching absorption at 1169 cm^{-1} in FT-IR and 1120 cm^{-1} in FT-Raman (Mani et al, 2008). The C-N stretching vibrations were found in the region of 1260-763 cm^{-1} for cyclopentolate molecule in Table 2. The bands observed as mixed with other vibrational bands at 1186 (IR)-1186 (R), 1034 (IR)-1038 (R), 921 (IR)-920 (R), 750 (IR)-753 (R) cm^{-1} can be assigned to CN stretching modes. The computed values for CN stretching modes in 2-(dimethylamino)ethyl group of the title molecule were obtained at 763 (41%), 774 (16%), 934 (35%), 1020 (43%), 1044 (29%), 1188 (15%) and 1260 (14%) cm^{-1} . These observed and calculated values coincide with similar structures in the literature (Sroczyński and Malinowski, 2017; Sert et al, 2017).

4.2.4. C-C vibrations

The CC stretching vibrations of aromatic rings usually occur at the interval of 1400-1650

cm^{-1} (Palafox, 2000; Hirschler et al (1994; Angelova et al, 1992; Sroczyński and Malinowski, 2017; Akyıldırım et al, 2017; Silverstein et al, 2005; Bilkan, 2017; Stuart, 2004; Lambert and Shurvell, 1987; Colthup et al, 1964; Mani et al, 2008; Sert et al, 2017; Temel et al, 2015). The νCC stretching bands in this region are called skeletal vibrations of aromatic ring. The CC bands can also be observed as combined with other vibrations (Akyıldırım et al, 2017) below 1400 cm^{-1} as given in Table 2. The vibrational bands observed at 1605 (IR)-1604 (R), 1584 (IR and R), 1307 (IR)-1299 (R), 1028 (IR)-1031 (R) cm^{-1} were assigned to the CC stretching vibration modes in phenyl ring. The vibrational bands observed at 1101 (IR)-1090 (R), 991 (IR)-990 (R), 929 (R), 750 (IR)-753 (R) and 703 (IR) cm^{-1} are assigned to the CC stretching vibration in 1-hydroxycyclopentyl ring. The vibrational bands observed at 589 (IR)-592 (R), 621 (R) and 973 (R) cm^{-1} were assigned to the CCC in-plane bending vibration modes (δ_{phenyl}). Similarly, the CCCC torsional modes in phenyl ring gave rise to absorption bands at 410 (R) and 501 (IR)-502 (R) cm^{-1} (Palafox, 2000). The CCC in-plane bending vibrations (δ_{cycl}) in 1-hydroxycyclopentyl group were found at 640 (R)/639 (cal. with PED contribution of 29%), 643 (IR)-644(R)/641 (cal. with PED contribution of 16%) and 861 (IR)-870 (R)/865 (cal. with PED contribution of 38%) cm^{-1} . The CC stretching (νCC) and CCCC torsional modes (τ_{cycl}) in 1-hydroxycyclopentyl group are listed in Table 2.

4.2.5 CH₃ and CH₂ vibrations

The asymmetric and symmetric stretching vibrations of methyl and methylene (CH₃ and CH₂) groups were expected to be in the range of 3000-2800 cm^{-1} (Roeges, 1994;

Ambujakshan et al, 2008; Gökce and Bahceli, 2013). The asymmetric stretching bands can sometimes rise up to 3050 cm^{-1} . The experimental and calculated wavenumbers for scissoring, twisting and rocking modes for methyl and methylene groups are summarized in Table 2. In the present study, CH_3 asymmetric stretching appeared at 3039 cm^{-1} in FT-IR spectra and 3045 cm^{-1} in Laser-Raman spectra. The six asymmetric stretching vibrations in two CH_3 groups were computed at 3041, 3029, 2994, 2992, 2988 and 2986 cm^{-1} with various contributions of PED. The CH_3 symmetric stretching bands appeared at 2880 and 2885 cm^{-1} in FT-IR spectra and at 2872 cm^{-1} in Laser-Raman spectra and they were calculated at 2854 and 2862 cm^{-1} . The two asymmetric and two symmetric stretching modes for CH_2 groups in aliphatic chain were obtained at 3051 (R) (exp.)/ 3052 (cal.) and 3039 (IR)- 3045 (R) (exp.)/ 3041 (cal. with PED contribution below 10%) cm^{-1} and at 2994 (cal.) and at 2990 (IR-R) (exp.)/ 2992 (cal.) and 2988 (cal.) cm^{-1} , respectively. Similarly, the four asymmetric stretching modes for CH_2 groups in cycl. ring were computed at 3028 , 3022 , 3009 and 2993 cm^{-1} , whereas the symmetric modes for these groups were calculated at 2980 , 2972 , 2969 and 2962 cm^{-1} . The recorded bands for these asymmetric and symmetric stretching modes of CH_2 groups in cycl. ring were observed at 3017 (IR)- 3020 (R) cm^{-1} and at 2964 (IR)- 2962 (R), 2953 (IR)- 2943 (R) and 2927 (IR)- 2915 (R) cm^{-1} , respectively. The bending modes for CH_3 and CH_2 groups were observed in the ranges of 1456 - 1375 cm^{-1} in IR spectrum and 1454 - 1372 cm^{-1} in Laser-Raman spectrum, while they were calculated in the range of 1463 - 1379 cm^{-1} . The scissoring vibrations for CH_3 groups were found at 1456 (IR)- 1454 (R) (exp.)/ 1450 (cal.), 1452 (IR-R) (exp.)/ 1446 (cal.), 1440 (cal.), 1438 (cal.), 1435 (cal.) and 1421 (R) (exp.)/ 1426 (cal.)

cm^{-1} , while the symmetric bending modes (or umbrella vibration) were obtained at 1399 (IR) (exp.)/ 1406 (cal.), 1386 (cal.) and 1375 (IR)- 1375 (R) (exp.)/ 1379 (cal.) cm^{-1} . The four CH_3 rocking vibrational modes were found at 1149 (IR) (exp.)/ 1143 (cal. (48%)), 1080 (IR) (exp.)/ 1078 (cal. (66%)), 1034 (IR)- 1038 (R)/ 1044 (cal. (18%)) and 1020 (cal. (10%)) cm^{-1} . These values are consistent with the experimental FT-IR values at 1149 , 1080 and 1034 cm^{-1} and the Laser-Raman value at 1038 cm^{-1} . The two CH_3 torsional vibrational modes were found at 256 and 238 cm^{-1} by the B3LYP/aug-cc-pVDZ calculation. The scissoring, wagging, twisting and rocking modes for CH_2 groups in aliphatic chain and 1-hydroxycyclopentyl were listed in Table 2.

4.3. ^1H and ^{13}C NMR Chemical Shift Analyses

NMR analysis, used in organic structure determination, is associated with the spin orientation direction. In NMR analysis, chemical shifts are measured in parts per million (ppm). ^1H and ^{13}C NMR chemical shift calculated with gauge-including atomic orbital (GIAO) approach using Gaussian09 software shows good agreement with the experimental chemical shift. Figure 4 shows the experimental ^1H and ^{13}C NMR chemical shift spectra of cyclopentolate. The experimental ^1H and ^{13}C chemical shift values measured in DMSO- d_6 solvent and the chemical shift values calculated at the B3LYP/aug-cc-pVDZ level in vacuum and DMSO solvent are shown in Table 3. The R^2 and RMSD values between the experimental and computed ^{13}C NMR chemical shifts were found as 0.99452 and 3.8 ppm, respectively.

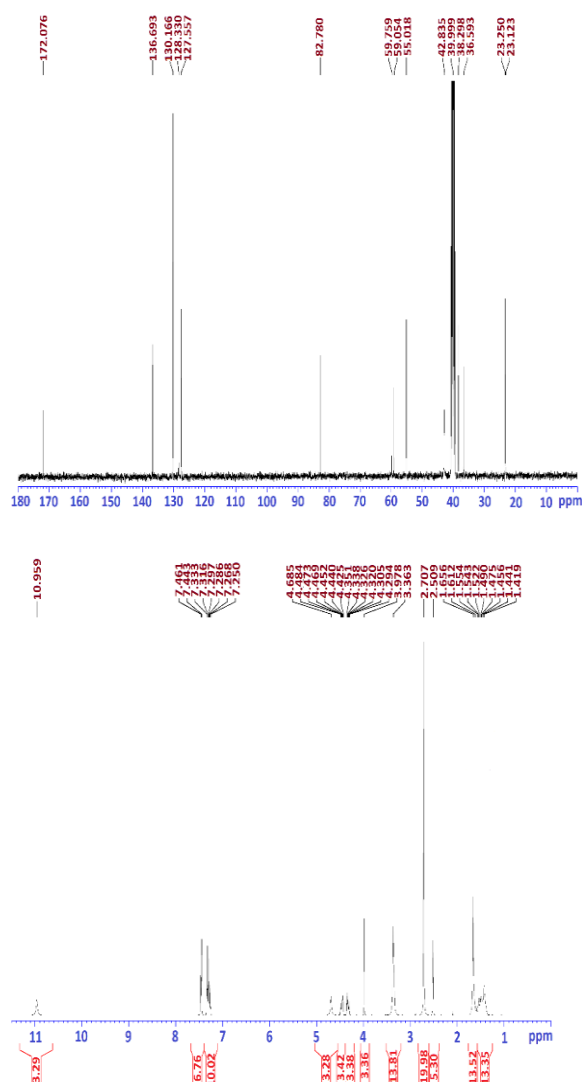


Figure 4. The experimental ¹H (bottom) and ¹³C (top) NMR chemical shift spectra of cyclopentolate

Table 3. The experimental and computed ¹H and ¹³C NMR isotropic chemical shifts (with respect to TMS, all values in ppm) in DMSO of cyclopentolate.

| Atom | δ_{exp} | δ_{cal} | Atom | δ_{exp} | δ_{cal} | |
|----------------------|-----------------------|-----------------------|------|-----------------------|-----------------------|-------|
| C1 | 55.018 | 64.600 | H2 | 3.978 | 4.065 | |
| C3 | 136.693 | 139.343 | H7 | 7.250- 7.461 | 7.573 | |
| C4 | 130.166 | 130.788 | H9 | | 8.468 | |
| C5 | 130.166 | 128.689 | H11 | | 7.681 | |
| C6 | 128.330 | 126.450 | H12 | | 7.743 | |
| C8 | 128.330 | 126.204 | H13 | | 7.685 | |
| C10 | 127.557 | 125.906 | H18 | 4.294- | 3.754 | |
| C14 | 172.076 | 179.336 | H19 | 4.484 | 5.512 | |
| C17 | 59.759 | 60.796 | H21 | 3.363 | 2.164 | |
| C20 | 59.054 | 60.353 | H22 | | 2.961 | |
| C24 | 42.835 | 40.243 | H25 | 2.707 | 2.264 | |
| C28 | 42.835 | 46.103 | H26 | | 1.572 | |
| C32 | 82.780 | 89.952 | H27 | | 2.955 | |
| C33 | 36.593 | 34.734 | H29 | 2.707 | 2.437 | |
| C34 | 38.298 | 38.752 | H30 | | 2.379 | |
| C35 | 23.250 | 23.633 | H31 | | 2.104 | |
| C38 | 23.123 | 24.318 | H36 | 1.419- 1.656 | 2.040 | |
| R² | 0.99452 | | H37 | | 1.535 | |
| RMSE | 3.8 ppm | | H41 | | 1.427 | |
| | | | H42 | | 1.033 | |
| | | | H43 | | 1.843 | |
| | | | H44 | | 1.616 | |
| | | | H39 | | 1.778 | |
| | | | H40 | | 1.472 | |
| | | | H46 | | 4.685 or 10.959 | 5.442 |

¹H chemical shift values were computed at the intervals of 1.033-8.468 ppm in DMSO. The experimental chemical shifts of ¹H are measured in the range of 1.419-10.959 ppm. The chemical shift for H2 is experimentally located at 3.978 ppm. The experimental chemical shifts of hydrogen atoms (H7, H9, H11, H12, H13) in phenyl ring are measured in the range of 7.250-7.461 ppm and they were calculated in the region of 7.573-8.468 ppm. The experimental chemical shifts of H18 and H19 hydrogen atoms are measured in the range of 4.294-4.484 ppm and H18 and H19 hydrogen atoms were calculated at 3.754 ppm and 5.512 ppm, respectively. The experimental chemical shifts of H21 and H22 hydrogen atoms were measured as 3.363 ppm and H21 and H22 hydrogen atoms were calculated at 2.164 ppm and 2.961 ppm, respectively. The experimental chemical shifts of H25, H26 and H27 hydrogen atoms were measured as 2.707 ppm and H25, H26 and H27 hydrogen atoms were calculated at 2.264 ppm, 1.572 ppm and 2.955 ppm,

respectively. The experimental chemical shifts of H29, H30 and H31 hydrogen atoms were measured as 2.707 ppm and H29, H30 and H31 hydrogen atoms were calculated at 2.437 ppm, 2.379 ppm and 2.104 ppm, respectively. The experimental chemical shifts of hydrogen atoms (H36, H37, H41, H42, H43, H44, H39, H40) were measured in the range of 1.419-1.656 ppm and H36, H37, H41, H42, H43, H44, H39, H40 atoms were calculated at 2.040 ppm, 1.535 ppm, 1.427 ppm, 1.033 ppm, 1.843 ppm, 1.616 ppm, 1.778 ppm and 1.472 ppm, respectively. The largest deviation between the calculated and experimental ^1H NMR chemical shifts ($\delta_{\text{exp.}}-\delta_{\text{cal.}}$) was observed for H46. The weakest interaction was observed for H46 with 4.685 ppm and the strongest interaction was observed for H46 with 10.959 ppm in experimental ^1H chemical shift spectra. The experimental NMR chemical shifts of protons in phenyl and dimethylamino groups of cyclopentolate molecule were recorded at the interval of ~ 7.38 - 7.50 ppm and at ~ 2.8 ppm by Roy and Guillory (1996) respectively. These values are in a good agreement with the recorded and computed data in our study.

The ^{13}C chemical shifts were calculated in the range of 24.318-179.336 in DMSO ppm, while they were experimentally recorded in the range of 23.123-172.076 ppm. The largest deviation between the calculated and experimental ^{13}C NMR chemical shifts ($\delta_{\text{exp.}}-\delta_{\text{cal.}}$) was obtained for C1 with 9.582 ppm, whereas the smallest deviation was found for C35 with 0.383 ppm. The NMR chemical shift value for C14 carbon atom in ester group of cyclopentolate was obtained at 172.076 (exp)/179.336 (cal.) ppm, due to attached to electronegative oxygen atoms. Likewise, the C32 carbon atom bonded to O45 atom was given at 82.780 (exp.)/89.952 (cal.) ppm NMR signal. The NMR signals for aromatic sp^2 carbons were recorded at the interval of

127.557-136.693 ppm, whereas the sp^3 carbon atoms in aliphatic and 1-hydroxycyclopentyl groups were observed in the region of 23.123-59.759 ppm.

4.4. UV-Vis. Analysis

The UV-Vis. spectrum of cyclopentolate dissolved in methanol was recorded in the region of 200-600 nm. UV-Vis. calculation was performed using TD-DFT method in methanol. The simulated and measured UV-Vis. electronic absorption spectra are given in Figure 5. Additionally, the experimental and computed electronic absorption wavelengths, electronic transitions, oscillator strengths, excitation energies and major contributions are listed Table 5. The major contributions for the computed electronic wavelengths were obtained by GaussSum 3.0 program (O'boyle et al, 2008).

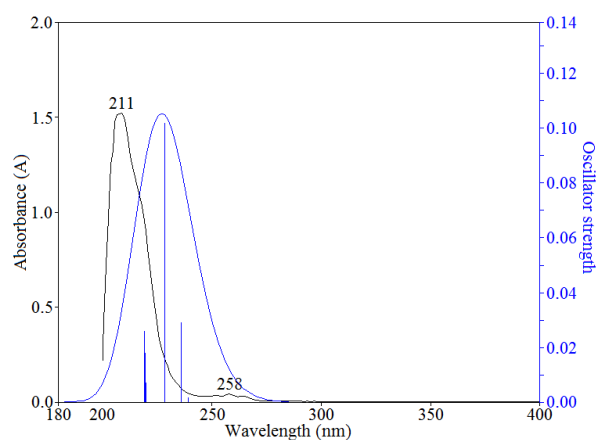


Figure 5. The recorded (black) and simulated (blue) UV-Vis. spectra in methanol of cyclopentolate

The wavelength recorded at 258 nm in experimental UV-Vis. spectrum can be assigned to $n \rightarrow \pi^*$ transition. This transition can be ascribed from dimethylamino group to phenyl ring in cyclopentolate molecule. The calculated wavelength corresponding to this experimental value was obtained at 235.78 nm with 0.0291 values of oscillator strength. The

major contribution for these computed values were found as H→L (85%). Similarly, the wavelength recorded at 211 nm corresponds to $\pi\rightarrow\pi^*$ electronic transition that can be attributed to the phenyl ring. The computed wavelengths and oscillator strength values were found as 228.29 nm and 0.1017 (the band with the highest intensity in the computed UV-Vis. wavelengths), respectively. The major contributions computed for this computed value were obtained as H-1→L (70%) and H-1→L+3 (10%). The other computed wavelengths and their major contributions were listed in Table 4. The experimental and computed wavelengths and electronic transitions are in good harmony (Szwed et al, 2013).

| Table 4. The experimental and computed UV-Vis. parameters and electronic transitions in methanol of cyclopentolate. | | | | | |
|--|-----------------------|--------------------------------|---------------------------|---------------------|--|
| The experimental | | The calculated parameters | | | |
| λ_{exp} (nm) | Transitions | λ_{cal} (nm) | Excitation energy (eV) | Oscillator strength | Major contributions |
| 258 | $n\rightarrow\pi^*$ | 238.90 | 5.1898 | 0.0018 | H-1→L+1 (50%), H-2→L (42%) |
| | | 235.78 | 5.2585 | 0.0291 | H→L (85%) |
| 211 | $\pi\rightarrow\pi^*$ | 228.29 | 5.4309 | 0.1017 | H-1→L (70%), H-1→L+3 (10%) |
| | | 219.83 | 5.6399 | 0.0072 | H→L+1 (82%), H→L+2 (14%) |
| | | 219.60 | 5.6460 | 0.0179 | H-4→L (22%), H-3→L (19%), H-4→L+3 (16%), H-1→L (11%) |
| | | 219.16 | 5.6571 | 0.0258 | H→L+2 (64%), H→L+1 (17%), H→L+4 (10%) |

4.5. HOMO-LUMO Analyses

The highest and the lowest occupied molecular orbitals (HOMO and LUMO) are also referred to as the frontier molecule orbitals (FMOs) (Fukui, 1982). The HOMOs and LUMOs are donor and acceptor groups filled and unfilled by electrons, respectively (Buyukuslu et al, 2010). The simulated

HOMO and LUMO surfaces, energy values and their shapes for the title molecule are given in Figure 6. The calculated HOMO-1, HOMO, LUMO and LUMO+1 energy values are -6.8339 eV, -6.6306 eV, -0.7614 eV and -0.5714 eV, respectively at the DFT/B3LYP/aug-cc-pVDZ level. The energy gap between HOMO and LUMO is computed at 5.8692 eV. The energy gap between HOMO-1 and LUMO+1 is computed at 6.2625 eV. The HOMO is localized on the dimethylamino group excluding phenyl ring and 1-hydroxycyclopentyl group, while the LUMO is placed on overall molecular structure except (dimethylamino)-ethyl and 1-hydroxycyclopentyl groups. The HOMO and LUMO localizations on cyclopentolate are formed by n molecular orbitals on nitrogen atom and π^* molecular orbitals of aromatic ring, respectively. Similarly, the HOMO-1 is mainly localized on the bonding π molecular orbitals of aromatic ring, whereas the LUMO+1 is placed on anti-bonding π^* molecular orbitals of phenyl ring. As a result, the $n\rightarrow\pi^*$ electronic transition can be associated with HOMO→LUMO and HOMO→LUMO+1, whereas the $\pi\rightarrow\pi^*$ electronic transition can be assigned to HOMO-1→LUMO and HOMO-1→LUMO+1. These notations can be confirmed by electronic transitions observed and assigned in UV-Vis. spectrum of cyclopentolate.

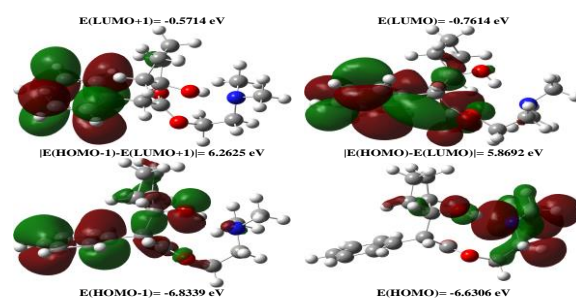


Figure 6. The HOMO-1, HOMO, LUMO and LUMO+1 plots and their energy values of cyclopentolate

5. Conclusion

In this research, conformational analysis was carried out to obtain the ground stable molecular structure with the minimum energy of cyclopentolate. As a result of conformational analysis, four molecular geometric forms in at the lowest energies were optimized with the B3LYP/aug-cc-pVDZ level. The computed molecular energy for the most stable conformer I was obtained as -943.40481341 Hartrees. By considering conformer I, the structural, spectroscopic (IR, Raman, NMR and UV-Vis.) and HOMO-LUMO analyses for cyclopentolate were performed using theoretical computational methods. The computed spectral properties were compared with the experimental data. A weak intra-molecular hydrogen bond interaction in cyclopentolate molecule was observed in O45-H46...N23 ($r(\text{H46...N23})=2.027 \text{ \AA}$ and $\angle(\text{O45-H46...N23})=164.1^\circ$). Due to the influence of this interaction, the OH stretching band was observed at 3230 cm^{-1} . The electronic transitions in UV-Vis. spectra supported with charge transfers in the HOMO and LUMO analyses of the molecule were determined as $\pi \rightarrow \pi^*$ (211 nm) and $n \rightarrow \pi^*$ (258 nm).

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