Raman Spectroscopy of six explanted acrylic hydrophobic foldable intraocular lenses with glistening

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Purpose: To study and interpret Raman spectra of six explanted acrylic hydrophobic foldable intraocular lenses (HFIOLs) with grade six microvacuoles and to understand the possible mechanism for microvacuole formation. Methods: Clinical data, slit-lamp photographs, and optical microphotographs of the explanted analytes were obtained. RS of the analytes were registered using a confocal Raman microscope (Lab RAM HR Evolution, Horiba Jobin Yvon) and Horiba Lab Space 6 Spectroscopy Suite software. Data were interpreted by identifying the functional group and fingerprint region of the spectra about the available literature. Results: IOLs were explanted for visual impairment after an average interval of 11.2 years following implantation. Each of the HFIOLs exhibited distinctive and identical Raman bands at the frequency range of 200–1,800, 2,600–3,000, and 3,200–3,700 cm⁻¹ which were identified with those reported in the literature. The unique bands and peaks of the spectra were specific to the functional groups, its ring and other stretching variations, hydroxyl group, and water molecule. A spike at 1,640 cm⁻¹ revealed the presence of monomer and indicated material bioincompatibility of the samples. Conclusion: Raman spectroscopy (RS) was found specific and an effective tool to detect the material change in the HFIOL and constituents of polymer biomaterial about microvacuole formation and also suggested modification and development of a more biocompatible and non-biodegradable polymer blend where RS could be a monitoring tool.

Key words: Explanted hydrophobic foldable IOL, glistening, microvacuoles, Raman spectroscopy

Raman spectroscopy (RS) is an optical, non-destructive, analytical, and vibrational molecular technique, characterized by a very high level of spatial resolution. RS can identify phase and polymorphism, intrinsic stress/strain, contamination and impurity, and mineral distribution of a matter. Very quickly thousands of spectra can be obtained from an analyte and matched with the spectrum available in the library. The intensity of the spatial features of these spectra is directly proportional to the concentration of a particular substance and provides its precise chemical mapping.

Microvacuoles or so-called ‘glistening’ are myriads of spaces of various sizes ranging from 10 to 50 µm in diameter and 3 to 5 µm in height which may develop commonly within the intraocular lens (IOL) made of hydrophobic (HF), or rarely, in any IOL polymer, particularly in wet conditions.[1-3] Various grading scales of the glistening have been described.[4] The overall effect of glistening on vision is debatable as vision comprises both optical and neuronal mechanisms.[4,5] Non-polar carbon and carbon, and carbon and hydrogen bonds make a polymer hydrophobic. The chemistry of IOL biomaterial is one of the main factors responsible for glistening.[6,7] Spinodal decomposition resulting from incompletely connected polymer chain,[8] thermal stress,[9] osmotic cavitation,[10] hydrophilic impurities,[11] aging hydrolysis,[12] and hydrolytic biodegradation[13,14] of copolymers are considered to be the possible physical mechanism of glistening formation and its subsequent optical effect.

Cochrane Library and PubMed literature search for articles in English published to date were performed using keywords: Raman Spectroscopy, explanted hydrophobic foldable IOL, microvacuoles, and glistening. No RS study on explanted HFIOL with glistening was found. Only two pioneering experimental studies on glistening in HFIOL of two different polymer blends were available describing the possible chemical mechanism of glistening formation.[15,16] Besides these, only a handful of study reports are available where the Raman band of different IOL copolymers, mostly in vitro settings have been identified.[3,17-20] Considering the above facts, the present study was undertaken to study the RS finding of explanted acrylic HFIOL with glistening to understand the chemical mechanism responsible for microvacuole formation.

Methods

The study protocol was in adherence to the Declaration of Helsinki and was conducted after qualifying approval of the institutional review board. Medical records, history, and physical examination were obtained from 6 patients who underwent cataract surgery and received an acrylic foldable IOL. The study patients were chosen based on the presence of glistening, grade 6 microvacuoles, and no history of intraocular surgery or trauma. Patients were excluded if there was any infection or ocular surface disease. The RS study was performed on six explanted HFIOLs with microvacuoles and was undertaken to study the RS finding of explanted acrylic HFIOL with glistening to understand the chemical mechanism responsible for microvacuole formation.

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clinical spectra registered in all the six acrylate hydrophobic IOLs were performed as the patients were not willing to take any further risk of vision loss from the possible development of glistening in the newly exchanged HFIOL. The IOLs were carefully dissected from adhesion in the capsular bag and prolapsed into the anterior chamber from where these were removed with titanium McPherson forceps. Throughout the maneuver, the anterior chamber was maintained by repeated injection of the intracameral ocular viscoelastic device (Viscoat, Belgium). Composition- sodium chondroitin sulfate, sodium hyaluronate, sodium dihydrogen phosphate monohydrate, sodium hydrogen phosphate, sodium chloride). Immediately after explantation, the IOLs were rinsed using double distilled water to remove any adhered viscoelastic device on the surface. The explanted IOLs were examined under high magnification and photographically documented using an optical microscope (S7/OPMI VISU 160. Carl Zeiss Meditec AG, Germany), camera (KODAK Easy share Mini. M200. ICE.003 Class B), and fiberoptic-guided xenon light. The selected IOLs fulfilling the inclusion and exclusion criteria of the study were stored in borosilicate glass vials (9710F12 Series borosilicate glass vial attached 2386C10 Series Cap) in deionized water at room temperature and shifted to the laboratory for RS.

Initially, deposition of any biological material on the IOLs was excluded by optical microscopy. The glass slides were treated with acetone and deionized water, cleaned, and air-dried and a single specimen was placed each on its own individual slide. Subsequently, each mounted glass slide underwent analysis in the confocal Raman microscope (Lab RAM HR Evolution, Horiba Jobin Yvon). The specimens were prevented from drying during spectroscopy. Laser wavelengths of 532 nm and 10X objective setup were used for analyzing the samples. The central section of the IOL optics was considered for spectroscopy. The Raman spectra were recorded over a range of 200–4000 cm\(^{-1}\) with 5-s acquisition time from the center of the IOLs. The impinging power of the Raman beam on the samples was 6 mW. Raman signals were repeatedly observed. An estimated signal fluctuation of less than 10\(^{\circ}\) was recorded. A charged coupled detector was used to record the dispersed photons. Spatial and spectral resolutions of the setup were 239.6 nm = 260 nm and = 1.8 cm\(^{-1}\), respectively, with 600 grooves/mm gratings. The results were plotted after optimized correction in Horiba Lab Spec 6 Spectroscopy Suite software. The frequency and intensity of the spectra were plotted on the X- and Y-axis, respectively. Raman intensity was interpreted as an arbitrary number (a.u.) determining the concentration of a specific functional group. The frequency or Raman shift was recorded in wavenumber in terms of a reciprocal centimeter (cm\(^{-1}\)). The frequency band determines the presence of a particular functional group in the specimen. The plots were then interpreted by detecting the functional group.

HF IOLs of the same make, having Stanojcic\(^{[4]}\) grade six microvacuoles causing impaired vision in the otherwise quiet eye, wherein the patients wanted IOL exchange, were included in the study. IOLs having any damage, surface deposit, or if they dried up during transportation were excluded from the study. After the investigation, the samples were disposed of as per standard biomedical waste disposal protocol.

**Result**

Altogether six explanted acrylic HFIOLs with glistenings were investigated. All the patients were males and the age range varied from 46 to 77 years. The duration of pseudophakia at the time of explantation varied between 4 and 16 years. The power of these IOLs ranged from + 20D to + 24D. All were single-piece IOLs. The comorbid ocular and systemic conditions of the patients are shown in Table 1. Two patients had glaucoma and were on topical anti-glaucoma medication (prostaglandin analog) for several years. One of them had pseudoexfoliation. Systemically, two patients were suffering from diabetes mellitus.

![Figure 1](image1.png)

**Figure 1:** (a) Silt-lamp photographs showing grade six microvacuoles in the HFIOL optics according to the new glistening grading scale of 2019.\(^{[4]}\) (b) Documentation photographs under an optical microscope using Xenon oblique light illumination. Showing IOL optics crowded with grade six microvacuoles of different sizes and morphology

![Figure 2](image2.png)

**Figure 2:** Raman spectra registered in all the six acrylate hydrophobic IOLs with microvacuoles at the range 200–4000 cm\(^{-1}\). Laser wavelength 532 nm, (10X objective setup, 6 mW power, and spectral resolution = 1.8 cm\(^{-1}\)). In sample no. 3, the spikes were more prominent (bands and spikes determine various functional groups and their concentration).
Table 1: Clinical characteristics of the patients

| Sample no | Age/sex | Duration of pseudophakia (years) | Stanojcic\(^{4}\) Microvacoule grade in the IOL | Comorbidity | Ocular | Systemic |
|-----------|---------|----------------------------------|-----------------------------------------------|-------------|--------|---------|
| 1         | 68/M*   | 15                               | 6                                             | Uveitis     | Diabetes mellitus |
|           |         |                                  |                                               | Pseudoexfoliation | Hypertension |
| 2         | 58/M    | 13                               | 6                                             | Nil         | Nil |
| 3         | 75/M    | 14                               | 6                                             | Glaucoma.   | Diabetes mellitus |
|           |         |                                  |                                               | Decentration of IOL | Hypertension |
|           |         |                                  |                                               |              | Sensory neural deafness |
|           |         |                                  |                                               |              | Depression |
| 4         | 46/M    | 10                               | 6                                             | Nil         | Cardiac pacemaker |
| 5         | 75/M    | 11                               | 6                                             | Nil         | Nil |
| 6         | 77/M    | 4                                | 6                                             | Nil         | Nil |

NB: Indication of IOL explantation in all cases was clinically significant visual impairment (6/12 or less) due to microvacuoles in the IOL. *M=Male

All the explanted IOLs exhibited grade six crowding of glistening\(^{4}\) during the preoperative slit-lamp examination and immediate post-explantation optical microscopy [Fig. 1a and b]. The glistenings were rarefied and of different geometry and sizes distributed in the entire volume of the IOL optics in an overlapping pattern. Clinically significant visual impairment was the only indication for IOL explantation and exchange was done with single-piece PMMA IOL. The surgical explantation procedures were uneventful without any damage or mechanical deformation of the IOL optics. The surfaces of the explanted IOLs were free from any deposit in optical microscopy.

The RS registered from all the six specimens were easily identifiable and had identical patterns, but the bandwidth (wavenumber) and intensity (arbitrary energy count) of the spikes of each spectrum were variable. The plotted graphs were single line with some Doppler effect. Plotting of a single microvacoule was beyond the scope of the study. All the six samples exhibited Raman bands in the frequency range of 200–1,800, 2,600–3,200, and 3,200–3,700 cm\(^{-1}\) range. All the samples had a detectable peak at 1,640 cm\(^{-1}\). The peaks were smaller and had broader stretching in all the specimens except in specimen no. 3 where the peaks were stronger. In specimen no. 3, the spikes were noticeable at around 500, 600, 768, 1,000, 1,100, 1,500, 1,600, 2,000, and 3,000 cm\(^{-1}\) regions. The arbitrary number of the energy count of the spikes was 150, 345, 200, 1,500, 400, 450, 750, 730, and 600 a.u., respectively. In the remaining five samples (1, 2, 4, 5, and 6), the bands were noticeable at the same frequency range as sample 3 but the Raman intensity was 350 a.u. or less. Each of the five samples had noticeable spikes at 1,000 and 3,000 cm\(^{-1}\) but with lesser intensity in comparison to sample no. 3. In all the samples except in sample no. 3, an additional spike at 3,100 cm\(^{-1}\) was registered [Fig. 2].

Discussion

The biomaterials of HFIOLs are heterogeneous, thermoplastic, cross-linked, copolymers manufactured by a random polymerization process. Such acrylic copolymer is constituted by a chemically and physically connected complex copolymer chain. The backbone of the polymer is a carbon-carbon double bond to the monomers which are open but may join with each other due to the variable nature of the dynamics and kinetics of polymerization. Monomers are never connected uniformly in a piece of IOL. Pockets of low-density polymer always persist. In HFIOL material, the side chain of the polymethylmethacrylate is substituted with hydroxyethyl or polyethyl or any suitable group which determines the water content of a copolymer. The phenyl ring in the copolymer makes an IOL hydrophobic. The IOL material in the present investigation was a copolymer of phenyl ethyl acrylate, phenyl ethyl methacrylate, 1,4-butanediol diacrylate, and some cross-linkers.\(^{[8]}\)

Properties of Raman spectra of different polymers including HF IOL polymers have been documented by the researchers. Depending on the chemical composition of the material, the Raman bands appear at 800–1,800, 2,600–3,200, and at 32,00–3,700 cm\(^{-1}\) locations. The bands ranging from 200 to 1,800 cm\(^{-1}\) (i.e., at 496, 622, 768, 1,004, 1,032, 1,157, 1,181, 1,204, 1,346, 1,449, 1,585, and 1,605 cm\(^{-1}\)) are due to ring variation and presence of alkyl group in the polymer substance. But the band at 1,460 and 1730 cm\(^{-1}\) are due to δ(C-H) of O-CH\(_2\) and ν (C=O), respectively. The wideband at 2,600–3,200 cm\(^{-1}\) range is due to many symmetrical and asymmetrical variations and convolution of CH\(_2\)\(^{21-26}\) Moreover, in hydrophobic polymer around 3,540 cm\(^{-1}\), a small but detectable peak is also noticeable. This band is accountable for the free hydroxyl group. The OH stretching bands in a water molecule are distinguishable from that of the free hydroxyl group, and OH stretching bands (O-H symmetrical and asymmetrical stretching) are much broader and detectable at 3,200–3,700 cm\(^{-1}\). The peak at 1,001 cm\(^{-1}\) indicates the presence of a phenyl ring. Stretching of the bond depends on the internal or external effect. Raman frequency changes in a reciprocal manner where a shorter bond length denotes a higher wavenumber and vice versa. Raman intensity variation is directly proportional to the concentration of the functional group. Low-line variations <200 cm\(^{-1}\) originate from skeletal deformation or interchain reaction in the polymer.\(^{[3,6,21-27]}\)

In an experimental study, two different hydrophobic copolymer-based IOLs with a similar polymer hydration coefficient but a different internal hydrophobicity were analyzed before and after thermal induction of microvacuoles.
in the laboratory. In this experiment, optical imaging of a single microvacuole, RS, and principal component analysis of Raman data, both inside and outside of the microvacuole, were investigated. The hydrophobicity of IOL copolymer A was more than that of IOL B. Before the induction of microvacuoles, similar Raman spectra were detected in the frequency range from 500 to 3,000 cm\(^{-1}\) in both the IOL copolymers. Most of the observed Raman bands in these two hydrophobic copolymers were identified with those already been reported by the other researchers as mentioned above. But after induction in both the types of HFIOLs (A and B), new peaks were detected inside the microvacuoles at the spectral regions 3,200–3,700 cm\(^{-1}\) and 2,800–2,900 cm\(^{-1}\) which were attributed to the copresence of typical water bands (OH stretching) and polymer bands, respectively. Notably, the intensity of this polymer band at the spectral region 2,800–2,900 cm\(^{-1}\) was weaker inside the microvacuole in comparison to the surrounding area, suggesting low-polymer density within the microvacuole. Raman spectra of the copolymer outside the microvacuole were different wherein IOL A (more hydrophobic), negative CH\(_3\) band and a positive peak at 1,001 cm\(^{-1}\) were present. On the contrary, these Raman features were absent in IOL B (less hydrophobic) where alkyl (meth) acrylate was replaced by the hydroxyalkyl (meth) group. The water content inside the microvacuole of IOL A was 23% against 18% in IOL B. Based on the above Raman analysis, the authors reasonably speculated that microvacuoles in the IOL were spaces of low-polymer density (inherent to the polymerization process) where water remained trapped and confined due to the presence of enhanced hydrophobic phenyl moieties in the surrounding copolymer. Polymer arrangement within the microvacuole was also found casual whereas the surrounding polymer was highly cross-linked. Ring polymer is a variant of cross-linked polymer which act as an adhesive force and hydrogen of two water molecules acts as a cohesive force to water. Naturally, water accumulates over there in the IOL due to the slow hydration process following implantation in the eye. The ring openings also exert a diaper-like effect. The confined water in the spaces of low-polymer density within the microvacuoles cannot come out due to the water-repellent hydrophobic nature of the surrounding HFIOL polymer exerted by the phenyl ring present in it. These findings in the Raman spectra founded the probable chemical mechanism of microvacuole formation and agreed with most acceptable physical theories. Moreover, it could explain the cause(s) accountable for the genesis of microvacuoles, which always develop at non-specific, variable intervals and progressively enlarge in size as well as in number and density along over time after implantation in the eye.

In our study, except for sample no. 3, in all the five HFIOLs, spike intensity was relatively low probably due to variations in the concentration of the functional groups. The spikes were well detectable and had some Doppler effect in the plots. Peaks at 400, 2,800, 3,100, and 3,200–3700 cm\(^{-1}\) were due to ring variations, presence of alkyl group, convolution of symmetrical and asymmetrical stretching variations of CH\(_3\) bonds, free hydroxyl group, and OH stretching, respectively. A small but detectable peak around 3,100 cm\(^{-1}\) in our samples indicated a free (OH) hydroxyl group as the band was narrower in comparison to the broader OH stretching bond in the water molecule. These spikes also indicated ring variations of the alkyl group suggesting hydrolytic degradation of the HFIOL copolymer. These findings were in general agreement with the limited available literature on the subject. As there was no RS study available on explanted HFIOL with microvacuoles, we compared our study findings with that of an experimental in vitro study conducted on different polymer blends. In our study, a new peak was detected at 1,640 cm\(^{-1}\) in all the six explanted HFIOLs with microvacuole. Apart from this, the rest of the registered Raman spectra matched with the studies reported in the literature. The peak at 1,640 cm\(^{-1}\) is a recognized indicator of monomer. The presence of monomer in our samples might be due to progressive biodegradation of the HFIOL biomaterial in vivo by the process of hydrolysis and ring variation of the alkyl group that we also reported earlier. These findings explain the probable mechanism responsible for developing microvacuoles in HFIOL substance after an interval following implantation and its progressive increase in size and numbers along with time. The Pi-bond in HFIOL polymer substance was inherently weaker than sigma bond, unstable and responsible for the induction of chain growth reaction and free radical initiation. The double bond of the functional group of the HFIOL copolymer (V (C = C), (C = 0)) absorbs infrared light at wave number 1,600–1,900 cm\(^{-1}\), and thus, increases the risk of carbonyl stretch, stretching and enlargement of electron cloud responsible for the deterioration of polymer characteristics.

In the Raman spectra, a wealth of information remains engraved. Findings of the RS of the HFIOL biomaterial can be utilized for further development of the IOL material, as in the near future due to an increase in human life expectancy, the IOLs would be staying inside the eye for a longer period. The findings of the present study suggested that the composition, as well as the hydrophobic nature of the polymer, and the molecular changes that developed inside the eye, are responsible for microvacuole formation in the IOL substance. Comparison of our study with a different polymer blend where microvacuoles were artificially induced and non-acquisition of Raman spectra at points inside and outside the microvacuoles was the limitation of the present study, considering that functional groups have specific positions in the spectra. Moreover, the chemo physical properties of a copolymer depends on the flexibility of the side-chain substituents, the amount of single monomer, and cross-linking between polymer chains. All these have a direct influence on Raman spectra. The application of principal component analysis could also throw some more light.

**Conclusion**

In conclusion, we believe microvacuoles or clinical glistening are spaces containing a mixture of water and polymer of low density in places of hydrophobic functional groups in the surroundings. This structure prevents the escape of water from the encaged spaces. The entire phenomenon is in vivo progressive biodegradation of HFIOLs. Raman spectra can detect these biochemical changes. It could also specifically determine the detailed chemical composition of the IOL biomaterial in the human eye in a non-invasive manner. So, not only in the industry, but also in clinical settings, RS can be used as a monitoring tool for detecting the polymerization process and its biodegradation in vivo. Further research is needed to enrich the data bank on RS in HFIOL.
The present investigation is the first report on RS study on naturally developed microvacuoles in the HFIOL that needed explantation due to visual indication in Indian literature.

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Conflicts of interest
There are no conflicts of interest.

References
1. Weindler JN, Labuz G, Yildirim TM, Tandogan T, Khoramina A, Auffarth GV. The impact of glistenings on the optical quality of a hydrophilic acrylic intraocular lens. J Cataract Refract Surg 2019;45:1020-5.
2. Yildirim TM, Fang H, Schickhardt, Wang Q, Merz PR, Auffarth GU. Glistenning formation in a new hydrophobic acrylic intraocular lens. BMC Ophthalmol 2020;20:186.
3. Miura K, Sakai S, Yokota S, Tada T, Katayama S, Nagasaka S, et al. Physical and chemical factors underlying glistenning formation in hydrophobic acrylic intraocular lens materials. Invest Ophthalmol Vis Sci 2018;59:263.
4. Stanojcic N, O’Brart DPS, Maycock N, Hull CC. Effects of intraocular lens glistenings on visual function: A prospective study and presentation of a new glistenings grading methodology. BMJ Open Ophthalmol 2019;4:e000266.
5. Gunenc U, Oner FH, Tongal S, Ferliel M. Effects on visual function of glistenings and folding marks in AcrySof intraocular lenses. J Cataract Refract Surg 2001;27:1611-4.
6. Pérez-Vives C. Biomaterial influence on intraocular lens performance: An overview. J Ophthalmol 2018;2018:2687365.
7. Yildirim TM, Fang H, Schickhardt, Wang Q, Merz PR, Auffarth GU. Glistenning formation in a new hydrophobic acrylic intraocular lens. BMC Ophthalmol 2020;20:186.
8. Tenz M, Jorgensen R. New hydrophobic IOL materials and understanding the science of glistening. Curr Eye Res 2015;40:969-81.
9. Kato K, Nishida M, Yamane H, Nakamae K, Tagami Y, Tetsumoto K. Glistenning formation in an AcrySof lens initiated by spinodal decomposition of the polymer network by temperature change. J Cataract Refract Surg 2001;27:1493-8.
10. Saylor DM, Coleman Richardson D, Dair BJ, Pollack SK. Osmotic cavitation of elastomeric intraocular lenses. Acta Biomater 2010;6:1090-8.
11. Thomas A, Muniandy K. Adsorption and desorption of water in rubbers. Polymer (Guildf) 1987;28:408-15.
12. Gautier L, Mortaigue B, Bellenger V, Verdu J. Osmotic cracking in unsaturated polyester materials under humid environments. J Appl Polym Sci 2001;79:2517-26.
13. Bhattacharjee H, Buragohain S, Javeri HJ, Das D. Scanning electron microscopic feature of explanted degraded hydrophobic acrylic intraocular lens which were in vivo for a prolonged period. Indian J Ophthalmol 2020;68:1086-9.
14. Bhattacharjee H, Buragohain S, Javeri H, Das D, Bhattacharjee K. Delayed postoperative opacification of three hydrophobic acrylic intraocular lens: A scanning electron microscopic and energy dispersive spectroscopy study. Indian J Ophthalmol 2021;69:1105-7.
15. Rusciano G, Capaccio A, Pesce G, Sasso A. Experimental study of the mechanisms leading to the formation of glistenings in intraocular lenses by Raman spectroscopy. Biomed Opt Express 2019;10:1870-81.
16. Rusciano G, Martinez A, Pesce G, Zito S, Sasso A. Micro-Raman analysis of glistenings in intraocular lenses. Proc SPIE 10333. Optical Methods for Inspection, Characterization, and Imaging of Biomaterials III, 103331A (26 June 2017); https://doi.org/10.1117/12.2271830.
17. Ercken RS, Jongsm FH, Hjwiks KC, Hendrikse F, March WF, Motamed M. Raman spectroscopy in ophthalmology: From experimental tool to applications in vivo. Lasers Med Sci 2001;16:236-52.
18. Smith EE, Ercken RS, Hendrikse F, Massoud M, Wicksted JP, March FW. Identification of intraocular lens material using confocal Raman Spectroscopy. J Cataract Refract Surg 1999;25:1498-504.
19. Ercken RS, March WF, Jongsm FH, Wicksted JP, Hendrikse F, Smith EE, et al. Noninvasive Raman Spectroscopic Identification of Intraocular lens material in living human eye. J Cataract Refract Surg 2001;27:1065-70.
20. Bertoluzza A, Fagnano C, Moti P, Semeano G, Gracia-RV, Caramazza R, et al. Raman spectra of intraocular lens before and after implantation in relation to their biocompatibility. J Raman Spectrosc 1987;18:151-2.
21. Xu X, Ming H, Qiang Z, Zhang. Properties of Raman spectra and Laser induced birefringence in polymethyl methacrylate optical fibers. J Opt A Pure Appl Opt 2002;4:237-42.
22. Thomas KJ, Sheeba M, Nampoori VPN, Vallabhan CPG, Radhakrishnan P. Raman spectra of polymethyl methacrylate optical fibers excited by a 532nm diode pumped solid state laser. J Opt A Pure Appl Opt 2008;10:055303.
23. Schneider J, Štork A, Schmidt P, Mihelov M, Dirilovic S, Peeva N. Stretching and deformation variations of CH₃, (CH₂)ₙ and O (CH)₄ groups of poly (methyl methacrylate). Polymer (Guildf.) 1974;20:705-12.
24. Dirilovic S, Koenig J. Assignment of the Carbon-hydrogen stretching and bending vibrations of poly (methyl methacrylate) by Selective deuteration. Appl Spectrosc 1979;33:555-61.
25. Goheen SC, Saunders RM, Harvey SD, Olsen PC. Raman spectroscopy of 2 hydroxyethyl methacrylate-acrylamide copolymer using gamma irradiation for cross-linking. Raman Spectrosc. 2006;37:1248-56.
26. Zhu H, Jha KC, Bhatta RS, Tsige M, Dinhovjala A. Molecular structure of poly (methyl methacrylate) surface. 1. Combination of interface-sensitive infrared-visible sum frequency generation, molecular dynamics simulations, and ab initio calculation. Langmuir 2014;30:11609-18.
27. Choe C, Lademann J, Darvin ME. Depth profiles of hydrogen bound water molecules types and their relation to lipid and protein interaction in the human stratum corneum in vivo. Analyst (London) 2016;141:6329-637.