Posterior capsular opacification and intraocular lens surface micro-roughness characteristics: An atomic force microscopy study

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\textbf{Objective:} Surface roughness parameters of various intraocular lenses (IOLs) biomaterials using atomic force microscopy (AFM) are compared. Variation, if any, in the micro-roughness properties of different IOLs made up of the same biomaterial is also explored. Retrospective analysis of posterior capsular opacification (PCO) incidence has been followed up for a period of four years post IOL implantation to evaluate the correlation of PCO formation with surface roughness of IOLs.

\textbf{Design:} Experimental materials study.

\textbf{Materials and participants:} Surface characteristics of 20 different IOL models were assessed using AFM. These IOL models were made up of PMMA or HEMA or acrylic hydrophobic or acrylic hydrophilic or silicone. Retrospective analysis of PCO incidence in 3629 eyes of 2656 patients implanted with the same IOL models was performed.

\textbf{Methods:} Topological characteristics of 20 different IOLs made up of 5 different biomaterials including (i) PMMA, (ii) HEMA, (iii) acrylic hydrophobic, (iv) acrylic hydrophilic and (v) silicone were evaluated using AFM in the tapping mode. Images were acquired with a resolution of $256 \times 256$ data points per scan at a scan rate of $0.5$ Hz per line and a scan size of $10 \times 10 \mu m$. Rate of PCO formation in 3629 eyes of 2656 patients implanted with the five different IOL biomaterials was retrospectively analyzed.

\textbf{Results:} AFM images of IOL optic surfaces showed a collection of pores, grooves, ridges and surface irregularities. Surface roughness parameters of the IOL optics were significantly different on comparing lenses of different materials. Acrylic hydrophobic IOLs had minimum surface roughness while acrylic hydrophilic IOLs showed the highest surface roughness. Different IOL models of the same biomaterial showed varied topological roughness characteristics. Retrospective analyses of PCO formation rate after IOL implantation was carried out, which revealed that rate of PCO incidence, was directly proportional to the increase in surface micro-roughness of IOLs.

\textbf{Conclusions:} AFM is a powerful technique for the topological characterization of IOLs. Acrylic hydrophobic IOLs showed minimum surface roughness properties as well as minimum PCO incidence over a period of four years post implantation. It is, therefore, tempting to consider acrylic hydrophobic IOLs over other IOL biomaterials as the ideal biocompatible material for lowering PCO incidence. These results suggest an urgent need for manufacturers to optimize the various steps involved in the fabrication of IOLs.

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1. Introduction

Posterior capsular opacification (PCO) remains the most common post-operative complication of cataract extraction and intraocular lens (IOL) implantation, with an incidence of nearly 20–50% within 5 years of surgery (Lloyd et al., 2001; Cheng et al., 2007). Conventional treatment of PCO with Nd:YAG laser capsulotomy is associated with a number of complications, such as damage to the IOL, intraocular pressure elevation, cystoid macular edema and retinal detachment (Murrill et al., 1995). Several studies conclude that lens epithelial cells (LECs) are the main cellular precursors of this process (Hollick et al., 1998; Van Tenten et al., 2000). It is well established that PCO occurs due to the regeneration proliferation, differentiation and migration of LECs onto the IOL surface leading to the opacification of the posterior capsule (Hayashi and Hayashi, 2004; Moreno-Montanes et al., 2005; Waddell et al., 2004). The incidence of PCO is also known to differ according to the
Fig. 1. AFM images of intraocular lens (IOLs) optics made of poly-methyl methacrylate (PMMA) biomaterial (i) I-55, iMAX; Vitreo labs, USA; (ii) SCB60E25, Universal Medical Products, USA; (iii) Model SP-65A2, Opthalmic Innovation International Inc., USA; (iv) 65T, Duralens II; AMO, Inc., USA; (v) SQ625, Prezio Ocular Technology Inc.; (vi) SE60125, Surgiye Medical International, USA; (vii) 202, Ocularvision; Biovision Ltd., UK). The PMMA lens surface is characterized by several grooves and ridge-like structures are irregularly distributed over the entire optic surface.
optic material of the implanted IOLs (Lombardo et al., 2006; Nishi et al., 2004). There is increasing evidence suggesting that acrylic IOLs are less damaging to the corneal endothelium than PMMA IOLs (Chaudhury et al., 2010).

IOL models composed of different optic materials have been recently developed to prevent postoperative migration and proliferation of LECs (Kurosaka et al., 2002). These range from the high water content hydrophilic acrylic material, low water content hydrophobic acrylic material, to hydrophobic silicone material and the traditional poly-methyl methacrylate (PMMA) or hydroxy ethyl methacrylate (HEMA) (Wejde et al., 2003; Klebe et al., 2006). Atomic force microscope (AFM) has emerged as a powerful tool to study topological features of IOLs at a nanometer level (Lombardo et al., 2010; Chaudhury et al., 2010). Dogru et al. (2000) have analyzed explanted IOL from a PCO patient using optical microscopy and AFM.

Although the influence of IOL surface properties on the adhesion and migration of LECs has been extensively examined, this is the first time various IOL biomaterials surface characteristics have been correlated with incidence of PCO. In the first part of the study, surface micro-roughness characteristics of various IOL biomaterials are assessed. Variation in the micro-roughness properties of different IOLs made of the same biomaterial is also explored. Finally, an attempt has been made to correlate PCO formation rate with the type of IOL implanted.

2. Materials and methods

Topological characteristics of 20 different IOLs obtained from various manufacturers and made up of 5 different biomaterials including (i) poly-methyl methacrylate (PMMA), (ii) hydroxy ethyl methacrylate (HEMA), (iii) acrylic hydrophobic, (iv) acrylic hydrophilic and (v) silicone were examined. Different IOLs made of the same biomaterial were also compared. 7 PMMA IOLs, 1 HEMA, 7 acrylic hydrophilic IOLs, 3 acrylic hydrophobic IOLs and 2 silicone IOLs were included. The IOLs were removed from their sterile packs with atraumatic forceps and placed on a magnetic stainless-steel sample holder using double sided adhesive tape for AFM. The person operating the AFM was kept unaware of the type of IOL used to prevent biased observations.

2.1. Atomic force microscopy

A commercial AFM (CP II, Veeco Instruments Inc., USA) was used in the tapping mode in ambient air conditions to measure the surface topological features of the IOL optics. All the IOLs were imaged in air to maintain a common environmental condition and minimize artifacts. However, it should be kept in mind that some drawbacks may occur when analyzing IOLs in ambient air using AFM because of the effect of attractive capillary forces which may threaten the sample surface integrity. A V-shaped, silicon nitride cantilever (MMP-11123, Veeco Instruments Inc., USA) with a tip curvature <10 nm, length 115–135 µm and a spring constant in the range of 20–80 N/m was used. All images were acquired with a resolution of 256 × 256 data points per scan at a scan rate of 0.5 Hz per line and a scan size of 10 × 10 µm.

Four samples of each type of IOL were used for analysis. The area scanned was limited to a maximum of 100 µm² owing to the gross curvature of the optics surface. At least eight sites taken from different areas close to the center of the optics surface were scanned to confirm the reproducibility of the observed features. Each single area on the optics was imaged twice to ensure that the force exerted by the tip did not damage the sample surface and cause artifacts. All images were processed and analyzed using Image Processing and Data Analysis software (version 2.1.15; copyright TM Microscopes USA) which included 4th order flattening to remove the background slope caused by the nonlinearities of the piezoelectric scanner. Region analysis of the scanned images was performed to measure the surface roughness.

2.2. Data analysis

Mathematical tools help in extracting quantitative information on surface roughness from AFM images. Various roughness parameters such as peak-valley height difference (R_{p-v})", average roughness (Rₐ), root mean square roughness (Rₗ), and height distribution were calculated. Rₐ and Rₗ are given by:

\[
Rₐ = \frac{1}{nₓnᵧ} \sum_{i=1}^{nₓ} \sum_{j=1}^{nᵧ} |Z(i, j) - Z_{ave}| 
\]

and

\[
Rₗ = \sqrt{\frac{\sum_{i=1}^{nₓ} \sum_{j=1}^{nᵧ} (Z(i, j) - Z_{ave})^{2}}{nₓnᵧ}} 
\]

where Z(i, j) denotes the topography data for the surface after specimen tilt-correction, Z_{ave} is the average surface height, i and j correspond to pixels in x and y direction. The maximum number of pixels in the two directions are given by nₓ and nᵧ (Chaudhury et al., 2010). In the present study, nₓ = nᵧ = 256. Rₗ is the standard deviation of the Z values within a given area whereas Rₐ is the mean roughness of the surface relative to the center plane.
Fig. 3. AFM images of intraocular lens (IOLs) optics made of Acrylic hydrophilic biomaterial (i) ANU 6, Ocuflex, Biovision Ltd., UK; (ii) XLSTABI SKY, Carl Zeiss, Meditec SAS; (iii) IOLTECH, Carl Zeiss; (iv) SQRYCF, Ocular Technology Inc., USA; (v) ADAPT-AO, Akreos; Bausch & Lomb Surgical Inc., USA; (vi) 570C, C-Flex, Rayner, England; (vii) BIOCRYL-600-ROH, O & O mdc Ltd., UK). A distinct pattern consisting of regular depressions and bumps is observed at the posterior optic surface of acrylic hydrophilic IOLs.
2.3. Roughness analysis

A surface profile is composed of a superposition of spatial waves of increasing frequencies due to the multi-scale nature of roughness. Hence, to characterize such a profile it becomes necessary to determine the amplitude of the roughness component at each spatial frequency. This is typically accomplished by calculating the power spectrum (PS) of the roughness profile using the relation:

\[
PS(f) = \frac{1}{L} \left| \int_0^L e^{2\pi i f x} [h(x) - \langle h \rangle] \, dx \right|^2
\]

where PS \((f)\) is the power of the surface roughness wave of frequency \(f\) and has the units of \(\mu m^2\), \(L\) represents the total scan length in \(\mu m\) and \(x\) is the spatial variable in \(\mu m\) (Chaudhury et al., 2010). PS of a single image, i.e. five line spectra separated equidistantly on the optics surface, were recorded and averaged.

2.4. Post implantation PCO incidence correlated with IOL biomaterial

Retrospective analysis of PCO formation rate in 3629 eyes of 2656 patients [1781 eyes of 1281 men and 1848 eyes of 1375 women] with senile cataract was performed. The age of patients included in this study (March 2005–January 2006) varied from 50 to 80 years. Different types of IOLs were implanted in these patients using conventional phacoemulsi-fication technique at B. B. Eye Foundation, Kolkata, India. Briefly, phacoemulsification was carried out with a clear corneal temporal incision of 2.8 mm when using a foldable IOL, while a scleral tunnel was used in case of a non-foldable PC IOL. All IOLs were implanted within the capsular bag and post operative steroid antibiotic combination was used over a period of six weeks. Only those cases were selected which did not show any post surgical complications such as posterior capsular rupture, vitreous loss and haptic/optic pre-existing uveitis. Cases involving non-fixation of IOL in bag as well as congenital and developmental cataract were also excluded. PCO formation was checked one year post-implantation onwards and then annually.
for three subsequent years. PCO grading was based on appearance of IOL on slit lamp examination by three different clinicians independently (Sellman and Lindstrom, 1988; Saika, 2004). Grade 1 corresponds to slight/absent PCO without reduced red reflex, it also includes no pearls at all or pearls not to the IOL edge. While Grade 2 includes cases with mild PCO reducing the red reflex and Elschnig pearls to the IOL edge. Grade 3 corresponds to moderate fibrosis or Elschnig pearls inside IOL edge but with a clear visual axis. Cases with acute fibrosis or Elschnig pearls covering the visual axis thereby severely reducing the red reflex are categorized as Grade 4. Grade 4 PCO patients were recommended YAG laser capsulotomy and were subsequently excluded from further follow-up. These patients have not been included in the study. Grades 1–3 PCO patients were sub-divided into five groups based on the biomaterial of IOLs implanted. Group A included patients with PMMA IOLs (1620 eyes of 1009 patients); Group B included HEMA IOLs (49 eyes of 35 patients); Group C included acrylic hydrophilic IOLs (880 eyes of 662 patients); Group D comprised of patients with acrylic Hydrophobic IOLs (1022 eyes of 911 patients) and Group E included patients with silicone IOLs (58 eyes of 39 patients).

2.5. Statistical analysis

Surface roughness parameters are summarized as mean ± SEM. Data were compared using independent two sample 't' test, Chi square test and one way variance analysis (ANOVA), wherever appropriate. \( p \leq 0.05 \) was considered to be significant. Results were statistically analyzed using version 2.0 beta 13 software (software developed by Koichi Yoshioka and available online: http://www.woundedmoon.org/win32/kypplot.html), SPSS software (version 11; SPSS, Inc., Chicago, IL) and MATLAB 7.1.0 (service pack 3, Mathworks Inc., USA).

3. Results

3.1. Topological characteristics of IOLs

Typical two dimensional and three dimensional AFM images of each of the six types of IOL biomaterials examined are shown in Figs. 1–5. AFM images were color mapped to represent height distribution, with the dark areas depicting dents on the surface and the bright areas representing protuberances. AFM images of IOL optic surfaces showed pores, grooves, ridges, very small peaks and various other surface irregularities. Several grooves were present on PMMA lens surface and ridge-like structures were irregularly distributed over the entire surface optic (Fig. 1(i)–(vii)). Sporadic high-rise peaks surrounded by area of depression were a typical characteristic feature of HEMA IOLs (Fig. 2). Crater-like features appeared on acrylic hydrophilic IOLs (Fig. 3) whereas, a distinct pattern of regular depressions and bumps was observed at the posterior optic surface of acrylic hydrophilic IOLs (Fig. 4). Pores of varying densities and sizes with several protruding microgranular features were observed on silicone IOLs, respectively (Fig. 5). Table 1 summarizes the surface roughness and height parameters of the five different IOL biomaterials. The acrylic hydrophilic IOL optics showed maximum surface irregularities as compared to the other types of biomaterials \( (p < 0.001) \). On the other hand, acrylic hydrophobic IOLs exhibited lowest surface roughness
characteristics. PMMA, HEMA and silicone IOL surfaces comprised of the intermediate range values. Surface roughness parameters for different IOLs made of the same biomaterial are summarized in Table 2. Interestingly, for various IOL models made of the same biomaterial, the surface micro-roughness characteristics varied significantly.

3.2. Power spectrum analysis

Fig. 6 shows average PS of the five different IOL optics biomaterials on a log scale. Results suggested a similar trend as summarized earlier in Table 1; a significant increase in the spatial roughness of acrylic hydrophilic IOLs and a significant decrease in acrylic hydrophobic spatial characteristics were observed as compared to the other biomaterials \( p < 0.001 \). PMMA and silicone IOLs showed an almost identical PS.

3.3. Post implantation PCO follow-up

Table 3 summarizes PCO formation in patients following IOL implantation. Interestingly, PCO formation in patients implanted with acrylic hydrophobic IOLs was found to be significantly less in all post-operative follow-ups (up to 4 years) as compared to other IOL biomaterials \( p < 0.001 \). PMMA and silicone IOLs showed an almost identical PCO formation rate. The acrylic hydrophilic IOLs were associated with maximum rate of PCO formation after HEMA as compared to other types of biomaterials \( p < 0.001 \). Correlation analysis between the

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>Summary analysis of surface roughness parameters of different intraocular lens (IOLs) biomaterials using atomic force microscopy (AFM). The data represents mean ± SEM. PMMA: poly-methyl methacrylate; HEMA: hydroxy ethyl methacrylate; S: significant; NS: not significant.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Roughness parameters</th>
<th>Type of IOLs material</th>
<th>(a) PMMA</th>
<th>(b) HEMA</th>
<th>(c) Acrylic hydrophilic</th>
<th>(d) Acrylic hydrophobic</th>
<th>(e) Silicone</th>
<th>( p ) value</th>
</tr>
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<tbody>
<tr>
<td>( R_{\text{sc}} ) (nm)</td>
<td>102.67 ± 9.12</td>
<td>149.17 ± 9.78</td>
<td>189.65 ± 24.83</td>
<td>29.12 ± 2.07</td>
<td>93.48 ± 12.87</td>
<td>ab: NS</td>
<td>ac: S</td>
</tr>
<tr>
<td></td>
<td>ac: S</td>
<td>ad: S</td>
<td>ae: NS</td>
<td>bc: NS</td>
<td>bd: S</td>
<td>be: NS</td>
<td>cd: S</td>
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<td>ce: S</td>
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<tr>
<td>RMS roughness [( R_{\text{rms}} )] (nm)</td>
<td>5.83 ± 0.49</td>
<td>6.44 ± 0.56</td>
<td>13.47 ± 1.14</td>
<td>3.29 ± 0.62</td>
<td>6.22 ± 1.66</td>
<td>ab: NS</td>
<td>ac: S</td>
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<tr>
<td></td>
<td>ac: S</td>
<td>ad: S</td>
<td>ae: NS</td>
<td>bc: S</td>
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<td>be: NS</td>
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<tr>
<td>Average roughness [( R_{\text{a}} )] (nm)</td>
<td>3.95 ± 0.31</td>
<td>2.79 ± 0.54</td>
<td>9.02 ± 0.86</td>
<td>2.61 ± 0.41</td>
<td>4.21 ± 1.32</td>
<td>ab: NS</td>
<td>ac: S</td>
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<td></td>
<td>ac: S</td>
<td>ad: S</td>
<td>ae: NS</td>
<td>bc: S</td>
<td>bd: S</td>
<td>be: NS</td>
<td>cd: S</td>
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<td>ce: S</td>
<td>de: S</td>
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<tr>
<td>Mean height (nm)</td>
<td>32.77 ± 2.74</td>
<td>47.39 ± 5.60</td>
<td>72.68 ± 9.01</td>
<td>13.67 ± 0.76</td>
<td>24.59 ± 7.21</td>
<td>ab: S</td>
<td>ac: S</td>
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<td></td>
<td>ac: S</td>
<td>ad: S</td>
<td>ae: S</td>
<td>bc: S</td>
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<tr>
<td>Median height (nm)</td>
<td>32.67 ± 2.79</td>
<td>47.31 ± 5.62</td>
<td>72.47 ± 9.17</td>
<td>13.64 ± 0.75</td>
<td>24.49 ± 7.38</td>
<td>ab: S</td>
<td>ac: S</td>
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<td></td>
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<td>ad: S</td>
<td>ae: S</td>
<td>bc: S</td>
<td>bd: S</td>
<td>be: S</td>
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<td></td>
<td>ce: S</td>
<td>de: S</td>
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</table>

ab: PMMA/HEMA; ac: PMMA/acrylic hydrophilic; ad: PMMA/acrylic hydrophobic; ae: PMMA/silicone; bc: HEMA/acrylic hydrophilic; bd: HEMA/acrylic hydrophobic; be: HEMA/silicone; cd: acrylic hydrophilic/acrylic hydrophobic; ce: acrylic hydrophilic/silicone; de: acrylic hydrophobic/silicone.
<table>
<thead>
<tr>
<th>IOL material</th>
<th>IOL model</th>
<th>$R_{p-v}$ (nm)</th>
<th>RMS roughness [$R_{q}$] (nm)</th>
<th>Average roughness [$R_{a}$] (nm)</th>
<th>Mean height (nm)</th>
<th>Median height (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMMA (ANOVA; Turkey)</td>
<td>(a) I-55, IMAX, Vitreo labs, USA</td>
<td>118.29 ± 2.39</td>
<td>3.13 ± 0.13</td>
<td>1.24 ± 0.16</td>
<td>29.54 ± 0.51</td>
<td>29.42 ± 0.53</td>
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<tr>
<td></td>
<td>(b) SCB60ES, Universal Medical Products, USA</td>
<td>84.11 ± 2.62</td>
<td>5.38 ± 0.37</td>
<td>3.95 ± 0.22</td>
<td>32.29 ± 0.48</td>
<td>32.13 ± 0.43</td>
</tr>
<tr>
<td></td>
<td>(c) Model SP-65A2, Ophthalmic Innovation International Inc., USA</td>
<td>70.88 ± 2.23</td>
<td>4.05 ± 0.05</td>
<td>3.86 ± 0.06</td>
<td>26.17 ± 1.17</td>
<td>24.82 ± 0.49</td>
</tr>
<tr>
<td></td>
<td>(d) 65T, Duralens II, AMO, Inc., USA</td>
<td>162.89 ± 3.36</td>
<td>10.21 ± 0.42</td>
<td>7.21 ± 0.45</td>
<td>57.71 ± 0.50</td>
<td>58.07 ± 0.53</td>
</tr>
<tr>
<td></td>
<td>(e) SQ625, Prezio Ocular Technology Inc.</td>
<td>68.06 ± 10.02</td>
<td>5.18 ± 2.01</td>
<td>3.24 ± 0.81</td>
<td>21.93 ± 0.02</td>
<td>21.75 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>(f) SEE61025, Surgieye Medical International, USA</td>
<td>87.39 ± 3.25</td>
<td>3.44 ± 0.05</td>
<td>2.62 ± 0.04</td>
<td>27.04 ± 0.59</td>
<td>26.65 ± 0.76</td>
</tr>
<tr>
<td></td>
<td>(g) 202, Ocularvision, Biovision Ltd, UK</td>
<td>131.03 ± 1.84</td>
<td>8.37 ± 0.05</td>
<td>5.82 ± 0.46</td>
<td>33.51 ± 2.07</td>
<td>33.68 ± 1.89</td>
</tr>
</tbody>
</table>

*Table 2* AFM measurements of surface roughness parameters of different IOL models made up of the same biomaterial. The data represents mean ± SEM.
RMS roughness and PCO rate indicates that there is a significant positive correlation between increased surface roughness of IOL models and higher incidence of PCO (Table 4).

4. Discussion

Prevention of PCO, a common postoperative complication following cataract surgery, has become one of the major challenges in ophthalmologic research. Several studies have shown that IOL material properties influence LEC proliferation, adhesion and migration (Saika, 2004; Tanaka et al., 2005). The amount of surface irregularities is reported to be linearly correlated to the number of inflammatory cells adhering to the IOL optic surface and to the rate of LEC migration (Lombardo et al., 2006). Adhesion of LEC on IOLs surface may also be due to the limited biocompatibility of the IOLs (Tehrani et al., 2004). However, the mechanism by which the IOL biomaterial influences LEC behavior is still not well understood and requires further investigation. This may be achieved by analyzing the IOL surface or the mechanical properties of the IOLs (Lombardo et al., 2006).

Recently, AFM has become an effective tool in the investigation of surface roughness of biomaterials, as it provides microscopic information with a spatial resolution relevant to the size of polymeric functional group proteins and cells (Guryca et al., 2007). Valuable information on height distribution can also be obtained from AFM images. Several groups have suggested AFM to be the most preferred technique for exploring IOL surfaces due to its high surface sensitivity and simplicity of sample preparation as compared to SEM (Lombardo et al., 2006; Chaudhury et al., 2010). AFM images of IOL optic surfaces showed a collection of pores, grooves, ridges, very small peaks and surface irregularities (Figs. 1–5). Similar distinct depressions on the surface of hydrophilic IOLs are reported by another group (Lombardo et al., 2006). Differences in the topological features of IOL materials may be attributed to the differences in their physical and chemical properties (Lombardo et al., 2009).

AFM studies showed statistically significant differences in the surface micro-roughness properties of various IOL biomaterials (Table 1). Acrylic hydrophilic IOLs had maximum surface roughness and more surface irregularities than other IOLs. Out of the 5 commonly used IOL biomaterials, hydrophobic IOLs showed minimum roughness. These findings are in accordance with a similar study by Lombardo et al. (2006). In a subsequent study, the same group concluded that hydrophobic acrylic IOLs have the largest

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**Table 3**

Posterior capsular opacification (PCO) incidence rate in patients after IOLs implantation.

<table>
<thead>
<tr>
<th>PCO formation rate</th>
<th>Type of IOLs material</th>
<th>p value</th>
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<tbody>
<tr>
<td></td>
<td>(a) PMMA</td>
<td>(b) HEMA</td>
</tr>
<tr>
<td>1st year</td>
<td>7.35%</td>
<td>10.20%</td>
</tr>
<tr>
<td></td>
<td>119/1620</td>
<td>5/49</td>
</tr>
<tr>
<td>2nd year</td>
<td>9.75%</td>
<td>12.24%</td>
</tr>
<tr>
<td></td>
<td>158/1620</td>
<td>6/49</td>
</tr>
<tr>
<td>3rd year</td>
<td>13.46%</td>
<td>16.33%</td>
</tr>
<tr>
<td></td>
<td>218/1620</td>
<td>8/49</td>
</tr>
<tr>
<td>4th year</td>
<td>15.49%</td>
<td>18.37%</td>
</tr>
<tr>
<td></td>
<td>251/1620</td>
<td>9/49</td>
</tr>
</tbody>
</table>

PMMA: poly-methyl methacrylate; HEMA: hydroxy ethyl methacrylate; S: significant; NS: not significant; ab: PMMA/HEMA; ac: PMMA/acrylic hydrophilic; ad: PMMA/acrylic hydrophobic; ae: PMMA/silicone; bc: HEMA/acrylic hydrophilic; bd: HEMA/acrylic hydrophobic; be: HEMA/silicone; cd: acrylic hydrophilic/acrylic hydrophobic; ce: acrylic hydrophilic/silicone; de: acrylic hydrophobic/silicone.

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**Fig. 6.** Average power spectra (PS) of different biomaterials used in intraocular lens (IOLs) optics on a log scale indicating decreased spatial roughness of acrylic hydrophobic IOLs.
mean adhesive force which may result in the prevention of PCO (Lombardo et al., 2009). Surface roughness of PMMA IOLs was significantly less as compared to acrylic hydrophilic IOLs in the present study; interestingly this was contrary to the findings of Lombardo et al. (2006). They reported highest roughness parameters of PMMA IOLs as compared to other biomaterials. This disparity in result may be attributed to the fact that the present study included a large number of IOLs made up of various biomaterials thereby providing a wider platform for comparison purposes. Moreover, it has been previously demonstrated that the sample surface of silicone IOLs may be damaged by the presence of hydrophobic interactions between the tip and the sample when imaged in an aqueous environment (Lombardo et al., 2006). Despite the fact that various IOL models were made up of the same biomaterial, surface micro-roughness properties varied significantly (Table 2). This variation may have arisen due to differences in manufacturing procedures, intrinsic polymerization (Lombardo et al., 2006, 2009; Findl et al., 2007) and dissimilarities in fabrication processes (Escobar-Gomez et al., 2003).

PS offers quantitative information not only on the height deviation of the roughness profile but also on its lateral distribution (the spatial extent of the height variations in the roughness profile). Hence, PS analysis gives a more definite description than the standard roughness parameters (Chaudhury et al., 2010). Significant increase was observed in the spatial roughness of acrylic hydrophilic IOLs as compared to other biomaterials. Interestingly, PMMA and silicone IOLs followed a similar PS pattern suggesting a close resemblance in the surface characteristics of PMMA and silicone IOLs (Fig. 6).

Rate of PCO formation in 3629 eyes of 2656 patients implanted with five different IOL biomaterials is retrospectively analyzed. This is the largest follow-up study on incidence of PCO formation following IOL implantation. Although HEMA IOLs reported highest rate of PCO formation, acrylic hydrophilic IOLs, with maximum surface roughness, were associated with next highest rate of PCO formation (Table 3). Acrylic hydrophilic IOLs, with maximum surface roughness, were associated with highest rate of PCO formation (Table 3). It is important to mention that the method for grading PCO described above is subjective in nature and computerized image analysis should be the first choice due to its considerably low measurement error.

The high incidence of PCO in case of HEMA IOLs may be attributed to the small sample size as compared to the other groups. In contrast, decrease in PCO incidence in patients implanted with acrylic hydrophilic IOLs indicates its suitability as an ideal IOL biomaterial. Our findings are further supported by clinical studies and meta analysis of PCO formation by other research groups (Shah et al., 2007; Cheng et al., 2007). We have also found a significant positive correlation between PCO rate of different IOL models with increased surface roughness (Table 4). Our AFM findings in conjunction with clinical data analysis suggest that IOLs with smooth micro-structural characteristics prevent PCO incidence considerably. It is, therefore, evident that not only the IOL biomaterial, but also the manufacturing process needs attention in order to reduce the risk of PCO formation. Accreditation of IOL surface micro-roughness parameters assessed by AFM may provide flexibility to the surgeons to select the most suitable IOL for their patients undergoing cataract surgery, thereby reducing the risk of PCO incidence to a great extent.

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