High Resolution OCT Quantitative Analysis of the Space Between the IOL and the Posterior Capsule During the Early Cataract Postoperative Period

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Submitted: July 17, 2013
Accepted: September 13, 2013
Citation: Tao A, Lu P, Li J, et al. High resolution OCT quantitative analysis of the space between the IOL and the posterior capsule during the early cataract postoperative period. Invest Ophthalmol Vis Sci. 2013;54:6991-6997. DOI:10.1167/iovs.13-12849

PURPOSE. We quantitatively characterized the space between the IOL and the posterior capsule (IOL-PC space) during the early postphacoemulsification period, using high resolution optical coherence tomography (OCT).

METHODS. We recruited 30 eyes of 30 patients who underwent phacoemulsification and randomly divided them into two groups. Acrysof Natural IQ IOLs were implanted in one group (n = 15), and Adapt-AO IOLs were implanted in the other (n = 15). A custom-built OCT instrument was used to image the IOL-PC space at 1 day, 1 week, and 1 month after surgery. Slit-lamp examination and auto refraction were performed at each visit.

RESULTS. The IOL-PC spaces in the IQ group were 0.72 ± 0.35, 0.40 ± 0.24, and 0.23 ± 0.16 mm² at 1 day, 1 week, and 1 month after surgery, respectively. At each of these times, the values for the AO group were significantly smaller (P < 0.001). Compared to 1 day after surgery, significant changes in the ACDs and refractive errors occurred up to 1 month postoperatively in the IQ group; however, changes in the ACD and refractive error were significant only at 1 week in the AO group.

CONCLUSIONS. The decreases in IOL-PC space and in ACD during the early postoperative period were associated with a myopic shift. It appeared that the different IOL designs had a role in closure of the IOL-PC space. High resolution OCT was suitable for quantitative analysis of IOL-PC space. (ClinicalTrials.gov number, NCT01605812.)

Keywords: intraocular lens, posterior capsule, optical coherence tomography

Posterior capsule opacification (PCO) is the most common long-term complication of cataract surgery that causes nonrefractive decreases in postoperative vision.1,2 Therefore, understanding the mechanism of PCO and preventing it has drawn increased clinical attention.3-5 Previous studies have shown that IOL design and material, and the surgical technique have crucial roles in retarding the development of central PCOs.5-7 Single-piece hydrophilic acrylic IOLs are better for preventing PCO than hydrophilic IOLs.6,8 The PCO rate for hydrophilic IOLs with an improved 360° sharp edge is lower than with older hydrophilic models that have a sharp optic edge except at the optic-haptic junction.9 Several surgical techniques, including vacuuming or polishing the capsule, have been attempted to lower PCO rates.10,11 Previous studies used long-term follow-up to observe factors that influenced frequency of PCO development, the grade of PCO, and the frequency of neodymium-YAG (Nd:YAG) capsulotomy. According to the theory of “no space, no cell, no PCO,”12 many methods have been used to decrease the space between the IOL and posterior capsule (IOL-PC space). Previous studies reported the time needed for different IOLs to adhere to the anterior and posterior capsules.13-15 However, all of these studies were based on qualitative in vivo descriptions of the IOL-PC space. We have developed a high resolution, ultralong scan depth optical coherence tomography (UL-OCT) instrument that we used to describe qualitatively capsular apposition to the IOL in high myopes.16 Further in vivo quantitative analysis might better characterize the IOL position and IOL-PC space. Such analysis also could shed light on other factors, such as IOL design, that impact closure of the capsule. The aim of this study was to use UL-OCT to evaluate quantitatively the extent of capsular bag adhesion to two different IOLs during the early cataract postoperative period.

PATIENTS AND METHODS

We recruited 30 patients who had uneventful phacoemulsification and IOL implantation due to age-related cataracts. The patients were divided into two equal groups and each group was assigned to wear a different IOL as described below. The groups were composed of 10 females and 5 males with mean ± SD ages of 63.6 ± 2.10 years and 63.6 ± 2.21 years, respectively. There were no significant differences in age or sex between the two groups. All procedures followed the tenets of the Declaration of Helsinki, and the protocol was reviewed and approved by the Ethics Committee of Wenzhou Medical University. Informed consent was obtained from each patient before the commencement of the study. Exclusion criteria were history of uveitis or other intraocular surgery, high
myopia, the presence of corneal opacity, the development of postoperative uveits that required additional steroid treatment, or poor mydriasis. Patients with glaucoma also were excluded.

**Surgical Technique**

All operations were performed by the same surgeon (JL). After a 3.0-mm clear corneal incision, a continuous curvilinear capsulorrhexis of approximately 5.5 mm was created. The capsulorrhexis overlapped the IOL optic zone in all cases. Then, the routine coaxial phacoemulsification and other surgical steps were performed, and using an injector, the IOL was implanted into the capsular bag. The surgery procedure was free of complications for each patient. Patients with secondary ocular hypertension following surgery were not included. Postoperatively, topical steroidal eye drops (tobramycin and dexamethasone; Alcon Laboratories, Inc., Fort Worth, TX) and antibiotic eye drops (levofloxacin; Santen, Inc., Suzhou, China) were given for all patients 4 times a day for 1 month.

**Intraocular Lenses**

One of the groups of patients, designated the “IQ” group, was assigned to wear the Acrysof Natural IQ aspheric IOL (SN60WF; Alcon Laboratories, Inc.). The other group, designated the “AO” group, was assigned to wear the Aspheric Akreos Adapt AO IOL (Bausch & Lomb, Rochester, NY). These lenses differed in material and design (see Table, Fig. 1). The Acrysof IQ IOL had a hydrophobic acrylic composition with an overall length of 13.00 mm and two haptic fixation points. The anterior surface of the optic zone had a biconvex asphericity. The Akreos Adapt AO IOL was of hydrophilic acrylic composition with an overall length of 11.00 mm. It had a 360°, double-squared edge and 4 haptic fixation points. Both IOLs had zero-degree haptic angulation.

**Visual Acuity and Refractive Error**

The uncorrected visual acuity was recorded in logMAR units using high-contrast Bailey–Lovie wall-mounted charts. Autofraction was performed to determine the refractive error at each visit.

**Postoperative Measurements by UL-OCT**

A custom built UL-OCT instrument with 7.5-μm axial resolution in tissue was used to visualize the whole IOL and interaction with the capsule. The instrument used a custom spectrometer with an experimental scan width of up to 20 mm and a scan depth of 7.7 mm in air. The light delivery system was combined with a standard slit-lamp that incorporated a digital video system. The scanning length was set as 12 mm. After full dilatation of the pupil with 0.2% tropicamide, the patient was asked to sit in front of a slit-lamp on which the OCT probe was mounted. Patients were asked to fixate straight ahead, using the fellow eye, on the instrument’s external target. To ensure consistent scanning of the meridians, the central OCT beam, indicated on the OCT monitor, was set on the corneal apex, where a specular reflection normally was detected. The X-Y cross-aiming was applied to align the UL-OCT scanning position to image the entire IOL and capsule. The scan meridian was set horizontally at the central level of the iris, and the images at horizontal meridian were recorded when the specular reflection was observed. Due to the limitation of the OCT scan depth, two different focus images were acquired for each patient at each time point: one image showing the IOL and posterior capsule (Fig. 2), and another image showing the cornea and anterior chamber depth (ACD). 17

**Image Processing**

Using custom-built software (J-OCT-1), the ACD was calculated as the distance between the back surface of the cornea and the front surface of the IOL. 17 18 The software semiautomatically detected the boundary of each layer to obtain the biometry. Briefly, the software searched for the nearest peak on the surface of interest and marked a point. When several peak locations were identified, the software outlined the boundary by fitting a curve to describe the intermediate points. The thickness along the axis was computed using the appropriate refractive index and converted from the coordinate dimension to the geometric distance. We used the refractive index of 1.335 for the aqueous humor for calculating ACD. The J-OCT1 software also was used to identify semiautomatically the boundaries of the IOL and posterior capsule (Fig. 2). Then, the meridional area of the IOL-PC space was calculated based upon the number of pixels between these two landmarks and

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**Table.** Characteristics of the Acrysof IQ SN60WF and Akreos Adapt AO IOLs

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<th>Akreos Adapt AO</th>
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<td>Design</td>
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Acrysof IQ SN60WF IOLs were used by the IQ Group (n = 15); Akreos Adapt AO IOLs were used by the AO Group (n = 15).

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**Figure 1.** Schematic of Acrysof IQ SN60WF and Akreos Adapt AO intraocular lenses. (A) The Acrysof IQ SN60WF IOL was of hydrophobic acrylic composition with an overall length of 13.00 mm and two haptic fixation points. The anterior surface of the optic zone had a biconvex asphericity. (B) The Akreos Adapt AO IOL was of hydrophilic acrylic composition with an overall length of 11.00 mm. It had a 360°, double-squared edge and 4 haptic fixation points. Both IOLs had zero-degree haptic angulation.
The Space Between the IOL and Posterior Capsule

FIGURE 2. OCT images of an IOL intraocular lens (IOL) and posterior capsule. (A) Raw image. (B) Processed image. Custom built software (J-OCT-1) was used to identify semiautomatically the boundaries of the IOL and the posterior capsule (red line, posterior surface of IOL; blue line, posterior capsule). Then, the meridional area between the IOL and posterior capsule wall was calculated based upon the number of pixels between these two landmarks and the spatial area of each pixel, 22 mm². The total meridional area between the IOL and posterior capsule was calculated as the sum of all pixels. Scale bars: 1 mm. Eyes with AO IOLs were imaged and semiautomatically segmented in the same way.

the spatial area of each pixel, 22 mm². The total meridional area of the IOL-PC space was calculated as the sum of all pixels.

Experimental Procedure

The patients were asked to return for postoperative follow-up visits at 1 day, 1 week, and 1 month. Routine assessment included visual testing (logMAR units), IOP measurement (Canon TX-F; Canon, Tokyo, Japan), slit-lamp examination (Topcon SL-1E; Topcon, Tokyo, Japan), and auto refraction (Topcon RM-8900; Topcon). At each visit, the pupil was maximally dilated, and UL-OCT images were taken by the same operator (PL) to reduce the error between different operators.

Data Analysis

A statistical package (Statistica 7.0; Stat Soft, Inc., Tulsa, OK) was used for descriptive statistics and data analysis. Data were presented as means ± SDs. Repeated measurement ANOVA was used for overall statistical testing. Post hoc testing was used to determine if there were differences in the meridional area among the different visits. Differences in the two groups were tested by independent sample t test. The Fisher exact test was performed to compare categoric data. Spearman correlations among meridional area, refractive error, and ACD were determined. Statistical significance was accepted when P < 0.05.

RESULTS

The boundaries of each IOL and posterior capsule were clearly visualized by UL-OCT in all cases (Fig. 2). To evaluate the repeatability of measuring the area of the IOL-PC space, 8 patients were imaged twice on the first day after surgery. The SD of the difference between two measurements was 0.036 mm², the intraclass correlation coefficient (ICC) was 0.990.

For both groups, the IOL-PC space became smaller between the follow-up visits on the first day and 1 month after surgery (Fig. 3). For the IQ group, the area of the IOL-PC space was 0.72 ± 0.35 mm² at 1 day after surgery, and 0.40 ± 0.24 and 0.23 ± 0.16 mm² at 1 week and 1 month after surgery, respectively (Fig. 4). For the AO group, the area of the IOL-PC space was 0.19 ± 0.34 mm² 1 day after surgery, and 0.02 ± 0.05 and 0.01 ± 0.02 mm² at 1 week and 1 month, respectively. At each of these times, the values for the AO group were significantly smaller (P < 0.001, Fig. 4A). For both groups, the IOL-PC space became significantly smaller between the first and seventh postoperative days (P < 0.001 for the IQ group, P = 0.038 for the AO group, Fig. 4A). For the IQ group, the space continued to narrow between 1 week and 1 month after surgery (P < 0.001, Fig. 4A); however, for the AO group, the IOL-PC space was almost nonexistent at 1 week; therefore, no significant change in the area of IOL-PC space occurred between 1 week and 1 month (P = 0.150, Fig. 4A). Thus, the speed with which the space became smaller differed for the IQ and AO groups. No eye in the IQ group had complete contact between the IOL and the capsule at 1 month after surgery. In contrast, in the AO group, complete closure between the IOL and the capsule was observed in 4 eyes (26.7%) at 1 day (P = 0.010), 11 eyes (73.3%) at 1 week (P < 0.001), and 13 eyes (86.7%) at 1 month (P < 0.001).

The ACD of the IQ group was 4.08 ± 0.56 mm at 1 day postoperatively, 4.00 ± 0.56 mm at 1 week, and 3.86 ± 0.64 mm at 1 month. For the AO group, the ACD was 3.98 ± 0.45 mm at 1 day, 3.90 ± 0.46 mm at 1 week, and 3.89 ± 0.45 mm at 1 month. The ACDs in the AO group were similar to those of the IQ group at each time point (P > 0.05, Fig. 4B). All of the IOLs in the IQ group and most in the AO group moved forward postoperatively. Two IOLs at 1 week and 3 IOLs at 1 month in the AO group moved backwards after the operation. There were significant differences in the IQ group ACDs among the different time points (P values ranged from 0.002-0.014, Fig. 4). In the AO group, the ACD at 1 week postoperatively was significantly smaller than that at 1 day (P = 0.043, Fig. 4), whereas it did not change at 1 month after surgery (P = 0.703, Fig. 4).

The mean preoperative axial length of all patients was 23.2 ± 1.30 mm. Due to the cataracts in 17 patients, we were able to measure preoperative refractive errors in only 13 patients. The mean preoperative refractive error of those patients was −1.80 ± 2.80 dipters (D). The refractive error in the IQ group was 0.42 ± 0.35 D, −0.15 ± 0.32 D, and −0.45 ± 0.33 D at 1 day, 1 week, and 1 month after surgery (Fig. 4). For the AO group, the refractive errors were 0.45 ± 0.27 D at 1 day, −0.10 ± 0.35 D at 1 week, and −0.18 ± 0.41 D at 1 month. The refractive errors in the IQ group were not significantly different from those of the AO group at the comparable time points (P > 0.05, Fig. 4C). The increases in IQ group refractive error at each follow-up visit were statistically significant (P < 0.001, Fig. 4). For the AO group, refractive errors increased only at 1 week after surgery (P < 0.001, Fig. 4).

The visual acuity (VA) of the IQ group was 4.9 ± 0.12 at postoperative day 1, 4.9 ± 0.10 at 1 week, 4.9 ± 0.10 at 1 month (Fig. 4D). Similar values were present in the AO group at each time point (P > 0.05). For each group, the values did not change significantly during the following period.
The meridional area of the IOL-PC space in the IQ group was correlated inversely with the ACD at 1 day after surgery \((r = -0.554, P = 0.052).\) However, the meridional area of the IOL-PC space in the AO group was not correlated with the ACD at 1 day after surgery \((P > 0.05).\) In each group, the decrease in IOL-PC space was not correlated with the change in refractive error between 1 week and 1 month after surgery \((P > 0.05).\) However, when the two groups were combined, the decrease in IOL-PC space was correlated with the change in refractive error between 1 week and 1 month after surgery \((r = 0.624, P < 0.001).\)

**DISCUSSION**

Advanced imaging methods are needed to assess the capsular dynamics after cataract surgery, including the interaction between the IOL and capsular bag. The anatomic relationship between the IOL and capsular bag has been evaluated by different methods.\(^{15,19-21}\) Slit-lamp observation after maximum pupil dilation showed 4 stages of capsular bend formation.\(^{20}\) The contact between the IOL and the anterior and posterior lens capsule always progresses from the periphery to the center. Using the Scheimpflug videophotography system, Hayashi et al.\(^{15}\) evaluated the elapsed time for the anterior and posterior capsules to adhere to the IOL. Ultrasound biomicroscopy has been used to visualize the posterior chamber phakic IOL position and study its relationship to posterior chamber structures.\(^{21}\) However, due to resolution limitations, all of the above methods were adequate for only qualitative analysis of the apposition pattern. The OCT is a noncontact imaging technology that has been widely used in ophthalmology. For instance, Elghohary et al.\(^{14}\) used a Humphrey OCT scanner to image the in vivo apposition of the posterior capsule to the IOL surface. The distance between them was defined as “close apposition” or not. Sacu et al.\(^{15}\) used a similar system to assess the distance between the anterior capsule and three types of open-loop IOLs. Finally, Moreno-Montañes et al.\(^{22}\) used an OCT instrument of 10 μm axial resolution to measure quantitatively thickening of the posterior capsule after cataract surgery. With the recent developments of OCT, ultrahigh resolution OCT images from human autopsy eyes showed the extent of capsular bag apposition to the IOL.\(^{19}\) The OCT images agreed well with the histologic sections of the same eyes. Zhao et al.\(^{16}\) used long scan depth OCT to evaluate the capsular apposition in highly myopic eyes. They found weak and incomplete adhesion in their patients. In our study, boundaries of the IOL and the lens capsule were defined clearly with our UL-OCT system. This enabled us to calculate quantitatively the meridional area between them and observe the time course after cataract surgery during which the posterior capsule became apposed to the two IOL designs.

The close apposition of the IOL optic zone to the posterior capsule has been well documented.\(^{15,20-25}\) The IOL first was fixed mechanically by haptics to the capsular bag.\(^{13,24}\) Because the surface areas of the IOLs were much smaller than the natural crystalline lens, the capsular bag shrank and collapsed after cataract surgery. From the OCT images, crimping of the posterior capsular bag was noted during the early postoperative period.\(^{2,3,5}\) In time, the surface appeared smooth. The square edges of the IOLs may be an important factor that contributes to this characteristic appositional relationship. Based on a mathematical model, mechanical compression exerted by the IOL on the posterior capsule has been proposed.\(^{20,25}\) Based on research and clinical studies, Nishi et al.\(^{20}\) proposed that capsular bend formation inhibited the migration of lens epithelial cells (LECs). Histologic sections of the IOLs showed LEC migration is inhibited by sharp capsular bends created at the optic zone edge.\(^{20}\) These results suggest that good IOL–capsule adhesion is required for long-lasting PCO inhibition. However, it takes time to create such a bend, and the LECs may migrate before the bend formation is finished. The UL-OCT is a good tool to observe the dynamics process of capsular bend formation.

**Figure 3.** Postoperative OCT images of IQ and AO IOL, and posterior capsules. Images of the IQ lenses (A–C) and of the AO lenses (D–F) were taken at postoperative day 1 (A, D), week 1 (B, E), and month 1 postoperatively (C, F). For the IQ group (A–C), the area between the posterior surface of the IOL and posterior capsule became smaller at each follow-up time, but there still was a space at 1 month postoperatively (C). In contrast, in the AO group (D–F), there was no space between the IOL and the posterior capsule at 1 week and 1 month postoperatively (E, F). In this example, the space was very small at day 1 after operation (D). Arrows show posterior capsule. 4-point stars show anterior hyaloid membrane. 1D, 1 day postoperatively; 1W, 1 week postoperatively; 1M, 1 month postoperatively. Scale bar: 0.5 mm.
In our study, the time needed by the IQ group for complete adherence of the IOL to the posterior capsule was more than 1 month. The elapsed time was longer than reported by other studies, but this might be attributed to the high resolution of the OCT instrument used in our study that could reveal smaller gaps between the surfaces that could otherwise be missed. All of the above studies used techniques that probably did not have adequate sensitivity or precision. Using the Humphrey OCT system with a resolution of 10 µm, Sacu et al. found in some cases that distinguishing the contact between the IOL and the posterior capsule was difficult, and they assessed the adhesion relationship in these patients by slit-lamp examination. This might explain the shorter apposition time in their studies compared to our study.

Capsular apposition to the IOL was impacted by IOL design. The tendency for capsular apposition to the IOL was similar for the two types used in this study. However, the apposition of the AO IOL to the capsule was complete in most patients at 1 week, while none of the eyes with IQ IOLs was adherent at 1 month after surgery. There could be two reasons for the difference in appositional rates. First, we believe that the 360° enhanced square edge of the AO IOL increased the rate at which the bend of the capsule formed, as shown in a previous study. The IQ IOL did not have the sharp design edge at the optic–haptic junction, and this absence may have delayed the creation of capsular bend. Second, the number of haptics may have a role in determining the speed of adherence between the IOL and the capsule. The four haptics of the AO IOL might have increased the force between the IOL and lens capsule, leading to more rapid adhesion. Further studies are needed regarding this point.

The hydrophilic acrylic composition of the AO IOL may promote a different adherence rate than the hydrophobic acrylic composition of the IQ IOL. We expected the hydrophilic AO IOL adherence to the capsule to be weaker than that of the hydrophobic IQ IOL. However, in fact, the AO had better apposition than the IQ in our study. Therefore, the difference in capsular bending may be more associated with the optic zone design, rather than the material. The sharpness and the speed of capsular bend formation have important effects on preventing PCO. The migration of LECs onto the posterior capsule is minimal after the IOL firmly adheres to it. Thus, a relatively fast capsular bend formation in the early postoperative period may be responsible for preventing PCO. After comparing the capsular apposition in high myopic and emmetropic eyes after cataract surgery, Zhao et al. presumed that weak and incomplete capsular bend formation during the early postoperative period increased the likelihood of PCO in high myopes.

The precise postoperative refractive outcome was affected by the position of the IOL in the eye, which was predicted by the ACD. Changes in ACD may lead to unexpected refractive prediction errors. Changes in IOL position also may reflect the dynamic apposition of the capsular bag to the IOL. Previous studies showed that the ACD becomes shallower over time after surgery, which
means that the IOL shifted toward myopia after the operation. In agreement with these studies, the ACD of most eyes in our study shifted toward myopia in the 1-month follow-up. However, two AO IOLs at 1 week and three at 1 month moved backwards after the operation. Several other studies also noted a deeper ACD during the early postoperative period. The varying results may be caused by unknown individual variations that affect the interaction between the capsule and IOL. The backwards movement of 5 IOLs in the AO group might be related to the size of the capsular bag, which was not determined in our study. The difference in pressure between the anterior and posterior chambers in each individual may be another possible factor that affected the IOL position. These speculations may be tested in future studies. The AO group showed significant anterior chamber change and myopic shift up to 1 week, whereas the IQ group showed significant myopic shift up to 1 month. These results suggest that the AO group became stable earlier than the IQ group. This might be explained by posterior capsule apposition to the AO IOLs, most of which were adhered completely to the posterior capsule at 1 week postoperatively compared to IQ IOLs, which took more than 1 month. As previous studies have shown, we assumed that the anterior and posterior capsules become mechanically stabilized by the IOL, which then reduced the changes of refraction. In our study, the spatial difference over the postoperative time was correlated with the difference of refractive error between 1 week and 1 month. The time required for the IOL to adhere completely to the capsule might contribute to the difference of ACD and refractive error between the two groups. When the IOL was adhered completely to the capsule, the IOL became stable, and the movement then decreased. The final fixation in the capsular bag is not completed until the fibrous tissue or LECs firmly adhere to the IOL. We assume that the IOL is mechanically enclosed and stabilized by the anterior and posterior capsule before tissue adhesion.

There were some limitations in our study. First, because the scan depth was 7.7 mm in air, we could not obtain the whole anterior segment from the cornea to the IOL in one OCT image; therefore, optical correction was not performed in this study. This would have caused some measurement errors. However, the apparent IOL-PC space could be used to track the changes over time. The UL-OCT instrument with a longer scan depth that we recently developed could be used in the future. Second, we did not use three dimensional (3D) scanning due to the limitation of our UL-OCT speed. Using fast scanning UL-OCT may enable us to perform 3D scanning. Third, although significant differences between IOL designs were evident, the sample size may be too small and the follow-up may be too short to assess fully the implications of IOL design and postoperative time on the development of PCO. Future work may focus on studies with large sample sizes and more IOL designs for better understanding the IOL geometric factors that impact the IOL-PC space in each individual’s eye and development of PCO.

CONCLUSIONS

The IOL-PC space and the ACD decreased during the early postoperative cataract surgery period. These changes were correlated with a myopic shift that occurred simultaneously. It appeared that different IOL designs, two of which were tested in our study, had a role in closure of the IOL-PC space. High resolution UL-OCT was suitable for quantitative analysis of this dynamic process.

Acknowledgments

Supported by research grants from the National Natural Science Foundation of China (81170869 [FL]), the National Basic Research Program (973 Program) of China (2011CB504601), and the Development Program Project Grant from Wenzhou, China (Y2010100192 and Y20100296 [AT]). The authors alone are responsible for the content and writing of the paper.

Disclosure: A. Tao, None; P. Lu, None; J. Li, None; Y. Shao, None; J. Wang, None; M. Shen, None; Y. Zhao, None; F. Lu, None

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