An Introduction to Intraocular Lenses: Material, Optics, Haptics, Design and Aberration

Roberto Bellucci

Ophthalmic Unit, Department of Neurosciences, Hospital and University of Verona, Verona, Italy

Abstract
Several intraocular lens (IOL) materials and types are currently available. Polymethyl methacrylate IOLs used to be the gold standard, but the inability of folding limits their use to selected countries and patients. Silicone IOLs were used more in the past because they are less suitable for microincisions. Foldable hydrophobic acrylic is the most popular material, which is also available in yellow (blue light absorbing) models and several IOL shapes. Although a very effective and safe material, water penetration producing glistenings and some dysphotopsia has been reported with some IOL types. Foldable hydrophilic material is widely employed in Europe, and especially for microincision cataract surgery lenses because of its plasticity, even if rare optics opacification and higher posterior capsular opacification rates have been reported in the past. Single-piece IOLs are the most employed in modern cataract surgery, but 3-piece IOLs are preferred for sulcus implantation and in infants. The aspheric design to correct or to control spherical aberration in implanted eyes is now the rule after the problems of centration we had before the capsulorhexis era were solved. However, the optical quality of pseudophakic eyes will depend not only on aberration control, but also on good media transparency and low light scattering.

Definition and History
An intraocular lens (IOL) is a lens implanted in the eye to treat large refractive errors. IOLs usually consist of small optics with side structures, called haptics, to hold the lens in place within the capsular bag inside the eye. The most common type of IOL is inserted into the capsular bag after cataract (lens) removal and is known as ‘aphakic IOL’. The second type of IOL, more commonly known as a phakic IOL, is placed inside the eye without removing the existing natural lens, to correct large refractive errors.

The first IOL was implanted by Sir Harold Ridley on 29 November 1949, at St Thomas’ Hospital in London (fig. 1). That first IOL was manufactured from polymethyl methacrylate (PMMA, also known as Perspex or Plexiglas), that was chosen because Ridley noticed it was inert in the eyes of RAF pilots [1]. The IOL concept spread slowly until the 1970s, when new and lighter posterior chamber lenses were designed, introducing polypropylene haptics for ciliary sulcus fixation [2]. Currently, there are several types and models of IOLs designed for specific purposes.
Table 1. Classification of IOLs

<table>
<thead>
<tr>
<th>Destination</th>
<th>Capsular bag, ciliary sulcus, scleral fixation, iris fixation, angle supported</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall design</td>
<td>3 piece/1 piece</td>
</tr>
<tr>
<td>Overall length</td>
<td>10–13 mm</td>
</tr>
<tr>
<td>Optics material</td>
<td>Rigid (PMMA), flexible (silicone), foldable (hydrophobic acrylic, hydrophilic acrylic), Collamer</td>
</tr>
<tr>
<td>Refraction index</td>
<td>1.42–1.55</td>
</tr>
<tr>
<td>Optics shape</td>
<td>Biconvex, plano-convex, meniscus</td>
</tr>
<tr>
<td>Optics diameter</td>
<td>5–7 mm</td>
</tr>
<tr>
<td>Optics design</td>
<td>Spherical, aspheric, toric multifocal, multifocal toric</td>
</tr>
<tr>
<td>Optics color</td>
<td>Transparent, tinted</td>
</tr>
<tr>
<td>Haptics properties</td>
<td>3 piece/1 piece (PMMA, PVDF, polyamide, 2, 3, 4, 6 haptics)</td>
</tr>
<tr>
<td>Type of implantation</td>
<td>Injectable, not injectable</td>
</tr>
<tr>
<td>Type of packaging</td>
<td>Pre-loaded, not pre-loaded</td>
</tr>
</tbody>
</table>

ty. In recent years, a tendency has developed preferring foldable IOLs and especially those suitable for microincision cataract surgery (MICS), i.e. those IOLs that can be implanted through sub-2 mm incision. These lenses are usually hydrophilic acrylic single-piece IOLs. IOL materials are defined hydrophobic or hydrophilic according to the angle a drop of water makes with respect to the material surface. The more acute this angle is, the more hydrophilic the material is defined. Although hydrophilic lenses must be packaged immersed in normal saline, there is nothing against packaging the lenses made of hydrophobic materials wet. Every IOL is immersed in water once inside the eye.

Materials

*Polymethyl Methacrylate*

PMMA was the first material used for IOLs (fig. 2). It is a rigid, non-foldable, hydrophobic (water content <1%) material. The refractive index is 1.49, and the usual optic diameter is 5–7 mm. PMMA IOLs are usually single piece, with fragile and low memory haptics, unless a compression molding production is employed. PMMA lenses are usually thin as the rigidity of the material bal-

Fig. 1. Sir Harold Ridley.
ances the low refraction index. Because of the required large incision, PMMA IOLs are seldom preferred today. They are currently used in developing countries because of the low cost, and in children given the proven long life in implanted eyes [3].

As any material immersed in water, PMMA may be penetrated by aqueous humor sometimes. This will cause small vacuoles to appear within the lens optic, a phenomenon called ‘glistenings’. Glistenings are very rare with PMMA IOLs, but they have been observed, and at least on one occasion have caused optic opacification [4].

**Silicone**

Polymers of silicone and oxygen have been employed as IOL material since 1984 [5], with the purpose of implanting the IOL through an incision narrower than IOL diameter (fig. 3). Silicone is hydrophobic, with a contact angle with water of 99°, higher than that of hydrophobic acrylic material. Silicone IOLs must be handled dry if folder and holder forceps are employed for implantation, because it is slippery when wet. Giant cell coverage of this material is similar to that of hydrophobic acrylic IOLs. The refractive index is usually between 1.41 and 1.46, the optic diameter is 5.5–6.5 mm. Current models are 3 piece, with PMMA, polyvinyl difluoride (PVDF) or polyamide haptics. Because of the low refractive index, the optics is rather thick, requiring incisions larger than 3.2 mm to implant higher-power lenses. Recently, injectors for 3-piece silicone lenses have been developed, allowing better and safer handling. However, the abrupt opening of silicone IOLs inside the anterior chamber remains a problem for surgeons. Silicone lenses have been suspected to favor bacterial adhesion, with increased risk for postoperative infection – an item never demonstrated in surgical setting [6]. After implantation, the anterior capsule rim opacifies quickly (fig. 4), while the posterior capsule may remain clear for many years. Despite the low posterior capsular opacification (PCO) rate and the good resistance to Nd:YAG laser shots, silicone is less used today because it is not suitable for MICS. Recently, a two-component silicone IOL was designed, in which power can be adjusted after implantation through UV exposure. The light-adjustable lens is entering clinical practice, and the ability to correct for spherical and cylindrical errors might overcome the 3.2 mm incision disadvantages [7, 8].

We should remember that the lens capsule will never adhere to silicone, and therefore the optics
will be kept in place by the haptics and by capsule coalescence. Therefore, we should refrain from implanting silicone lenses with damaged haptics, an issue unfortunately emerging only after the lens optics is inside the eye. When removing the lens, cutting the haptics will impede any extraction through small incision.

Silicone can be penetrated by aqueous humor too, and glistenings may appear within silicone optics [9]. However, the main problem with silicone IOLs is the adherence of silicone droplets in the case of silicone oil tamponade after retinal detachment repair [10]. These eyes always require Nd:YAG posterior capsulotomy, and silicone droplets deposit onto the posterior IOL surface after silicone oil removal, causing IOL explantation and exchange. For this reason, silicone material may not be preferred in highly myopic eyes that are at increased risk for posterior segment surgery.

**Hydrophobic Foldable Acrylic**

Hydrophobic foldable acrylic materials are a series of copolymers of acrylate and methacrylate derived from rigid PMMA, with the purpose of making them foldable and durable. The typical angle of contact with water is 73° [11]. Hydrophobic foldable acrylic lenses can be folded, pushed, and pulled, always regaining their original shape in a matter of seconds [12].

Hydrophobic acrylic foldable lenses were introduced in 1993 with the first Acrysof 3-piece lens (Alcon, Forth Worth, Tex., USA; fig. 5), and have been probably the most successful IOLs thereafter. Hydrophobic acrylic IOLs are available in 3-piece or 1-piece designs (fig. 6), optic diameter between 5.5 and 7.0 mm, overall length between 12 and 13 mm, transparent or yellow, with a refractive index between 1.44 and 1.55. Hydrophobic acrylic foldable lenses are easy to implant, however require at least a 2.2-mm incision. Some of them can receive permanent fingerprints or scratches by implantation instruments, while others claim to be harder. As a common feature,
these lenses show low tendency to self-centering, and care must be taken to position them properly at implantation.

In the postoperative period, they elicit low degrees of posterior capsule opacification and receive little damage from Nd:YAG laser posterior capsulotomy. Moreover, they show little tendency to attract silicone droplets after silicone oil tamponade, albeit hydrophilic acrylic material is still better. At the moment (2012) hydrophilic acrylic IOLs are the most popular worldwide, especially in the US because of the FDA approval.

Hydrophobic foldable intraocular lenses have been associated with photopsias more frequently than other types of acrylic IOLs, an item related to low anterior curvatures and high refractive index [13, 14]. In addition, some of them are easily penetrated by aqueous humor, and develop glistenings in the form of water microvacuoles within the IOL optics (fig. 7), a problem not pertaining to all hydrophobic foldable materials [15]. Glistenings seem to be clinically important only when dense or with special (multifocal) design. To overcome this drawback, new materials have been introduced that are prehydrated to equilibrium and will not accept further water, thus avoiding the formation of glistenings. These IOLs are hydrophobic because the contact angle with water is that of hydrophobic acrylic, but are packaged in BSS to absorb the eventual 4% water content before implantation [16].

Hydrophilic Foldable Acrylic

Hydrophilic acrylic materials are composed of a mixture of hydroxyethylmethacrylate (polyHEMA) and hydrophilic acrylic monomer [17]. Compounds specifically prepared for IOLs appeared at the end of the 1980s and underwent several modifications thereafter, giving rise to a list of materials of different copolymers and water content, usually between 18 and 26%. A typical refractive index is 1.43, and some materials can be yellow tinted (fig. 8). Hydrophilic acrylic lenses are soft, somewhat compressible, and have excellent biocompatibility because of their hydrophilic surface. The contact angle with water is lower than 50°. Most IOLs are single piece, and designed for capsular bag implantation with few exceptions. Hydrophilic acrylic material is the easiest to handle, with low tendency to receive scratches from instruments or damage from Nd:YAG laser shots. They can be implanted through sub-2-mm incisions and are the ideal lenses for MICS [18] (fig. 9). The number and

Fig. 7. Optic microvacuoles known as glistenings.

Fig. 8. Foldable hydrophilic acrylic IOL.
shape of haptics varies widely, but these lenses are rarely found displaced if properly implanted. In the postoperative period, the induction of photopsias is low, but the PCO rate is considered to be higher than with other materials, although recent research seems to contradict this statement [19]. Hydrophilic acrylic material is considered weaker than hydrophobic, with lower resistance to capsular bag contraction [20]. Therefore, they may not be preferred when high contraction forces are anticipated, as in some eyes with pseudoexfoliation.

The main concern with hydrophilic acrylic lenses is optic opacification due to calcium deposits, a rare event that led to IOL exchange in a number of patients (fig. 10). In the past, this calcification has been associated with certain IOL types and/or certain viscoelastic substances, but its mechanism is still unclear [21, 22]. Hydrophilic IOLs are very popular in Europe because of the easy handling, the sub-2-mm implantation, the low risk for capsular bag damage during implantation, and the improving results with PCO.

Collamer

Collamer is the name of the material used exclusively in making STAAR® Company phakic and aphakic lenses, including the Visian ICL (fig. 11). The name comes from the combination of ‘collagen’ and ‘polymer’. IOLs made of Collamer are highly biocompatible, and easy to implant because of the softness of the material and the gentle unfolding [23]. Water content is very high, at about 40%, which makes this material very soft and also suitable for aphakic IOLs.

The collagen in the Collamer attracts fibronectin, a substance found naturally in the eye. A layer of fibronectin forms around the lens, inhibiting white cell adhesion to the lens. This coating prevents the lens from being identified as a foreign object, and the lens remains unnoticed and ‘quiet in the eye’ indefinitely. In addition, like the collagen it contains, Collamer carries a slight nega-