Conclusions 10

This thesis addresses the measurement of geometrical properties (surface geometry, tilt and decentration) of the crystalline lens in normal eyes, and their changes with accommodation. In addition, it addresses the impact of intraocular lens geometry, tilt, decentration and corneal aberrations on optical quality in pseudophakic eyes. We have demonstrated that knowledge of these structural properties allow us a deeper understanding of the optical quality of the normal eye (unaccommodated and accommodated) and the factors contributing to optical degradation in eyes with intraocular lenses.

1) We have developed a compact and reliable Purkinje-imaging based instrument to measure radii of curvature, tilt and decentration of the crystalline lens in normal eyes and of intraocular lenses in pseudophakic eyes. Equivalent mirror and Merit Function methods have been developed for phakometry, and linearity between Purkinje images locations and lens tilt, decentration and eye rotation were assumed. The system has been validated computationally (using computer eye models of various degrees of complexity) and experimentally (using physical model eyes, and in real eyes also measured with Scheimpflug imaging). Average reproducibility of the data is 0.308 mm for the anterior lens radius of curvature, 0.352 mm for the posterior lens radius of curvature, 0.39 deg for horizontal tilt, 0.45 deg for vertical tilt, 0.05 for horizontal and 0.04 for vertical lens decentration. We present in vivo measurements of lens tilt and decentration using this method on a total of 58 normal eyes, 43 eyes with intraocular lenses (spherical and aspheric monofocal lenses) and in 4 monkey eyes. **(Goal 1)**

2) We have developed processing algorithms to correct for geometrical distortion and optical distortion of a new Scheimpflug imaging system (Pentacam, Oculus). Those algorithms include an optimization routine to obtain the Scheimpflug camera lens nodal point. Those algorithms have been tested on normal crystalline lens and physical model eyes. **(Goal 2)**

3) Purkinje imaging and Scheimpflug imaging have been cross-validated for phakometry in normal young subjects and for tilt and decentration measurements in pseudophakic eyes. For the anterior lens radius of curvature, Scheimpflug and Purkinje data show highly statistically significant correlations.

On average, measurements from each technique are not statistically significantly different to each other. Individually, there are no significant differences across techniques in the anterior radius of curvature, while there are significant differences in half of the eyes in the posterior radius of curvature. Discrepancies can arise from the aspheric geometry of the lens. **(Goal 3)**

4) Validations of the Purkinje and Scheimpflug methods to measure lens tilt and decentration perfomed on physical model eye with set nominal values of tilt and decentration show absolute discrepancies between nominal and measured values of 0.279 deg (Purkinje) and 0.243 deg (Scheimpflug) for tilt and 0.094 mm (Purkinje) and 0.228 mm (Scheimpflug) for decentration. Scheimpflug and Purkinje imaging measurements of lens tilt around the vertical axis and lens horizontal decentration in pseudophakic eyes show highly statistically signifincant correlations across both techniques. **(Goal 3)**

5) Lens radii of curvature vary significantly in the population. In 58 young human eyes the anterior lens radius of curvature of the unaccommodated human lens ranged from 7.23 ± 0.04 mm to 13.45±0.59 mm (average 10.77±0.32 mm) and the posterior lens radius of curvature ranged between -4.73 ±0.43 mm to -9.49±0.18 mm for the posterior lens radius (average: -6.54±0.35) Average anterior and posterior lens radii of curvature in unaccommodated iridectomized monkey eyes were 11.11±1.58 mm and -6.64±0.62 mm respectively. **(Goals 4 and 5)**

6) Anterior and posterior lens radii changed systematically with accommodation. In young human eyes, the anterior lens radius of curvature decreased at a rate of 0.57±0.03 mm/D and the posterior lens radius of curvature at 0.29±0.05 mm/D, for static accommodation and as a function of accommodative demand. In iridectomised anaesthetized monkeys, the anterior lens radius of curvature decreased at a rate of 0.48±0.14 mm/D and the posterior lens radius of curvature at 0.17±0.03 mm/D, for dynamic accommodation and as a function of accommodative response. **(Goals 4 and 5)**

7) In normal young eyes, crystalline lens tilt ranged from 2.8±0.4 to -2.87±0.34 deg horizontally (average 1.31±0.76 deg) and from 2.58±0.27 to –1.00±0.31 deg vertically (average 1.21±0.81 deg), with respect to the pupillary axis. Crystalline lens decentration ranged from 0.09±0.031 to 0.45±0.02 mm horizontally (average 0.28±0.12 mm) and from -0.22±0.82 to 0.39±0.03 mm vertically (average 0.11±0.08 mm), with respect to the pupil center. Lens tilt and decentration tend to be mirror symmetric across right and left eyes. **(Goal 4).**

8) Lens tilt and decentration of the crystalline lens did not change significantly with dynamic accommodation in Rhesus Monkeys. However vertical tilt changed systematically with accommodation in some eyes, in agreement with reported increased vertical coma with accommodation in some monkey eyes. **(Goal 5)**

9) In pseudophakic eyes (after phakoemulsification and intracapsular lens implantation) lens tilt ranged from -0.72±0.52 to 3.6±0.58 deg horizontally (average 1.63±0.87 deg) and –3.39±0.4 to 5.97±0.82 deg vertically (average 1.77±1.30 deg), with respect to the pupillary axis. Lens decentration ranged from -0.53±0.06 to 0.54±0.03 mm horizontally (average 0.31±0.15 mm) and -0.4±0.06 to 0.54±0.03 vertically (average 0.14±0.13 mm), with respect to the pupil center. Lens tilt and decentration tend to be mirror symmetric across right and left eyes, suggesting that lens misalignment is determined by the capsule position, rather than being induced during the surgical procedure. **(Goal 6)**

10) Some corneal high order aberrations (trefoil and tetrafoil) increase significantly with cataract surgery, both for large and small pupil sizes. For vertical incision locations (3.2 mm) the changes occur in the vertical Zernike terms. No significant change occurs for spherical aberration. Slight differences in the amount and significance of the change appear to be associated to the design of intraocular lens implanted. **(Goal 7)**

11) Customized computer eye models of pseudophakic eyes (with individual data of corneal topography, lens geometry, lens tilt and decentration and fovea

misalignment) predict the high order aberrations of pseudophakic eyes. Measured and simulated aberrations agree 66% on average. These individual models have allowed to evaluate the effect of corneal aberrations, lens geometry, lens misalignment and angle lambda on the optical quality of eyes with implanted aspheric IOLs. Aspheric IOLs are able to correct the spherical aberration on average (although the exact amount of correction depends on the amount of corneal spherical aberration and several other biometric factors). Corneal aberrations play a major role in optical degradation is pseudophakic patients. The contribution of lens tilt and decentration to optical quality degradation is relatively minor. In 60% of the cases, the presence of lens tilt and decentration contributed favourably to high order aberrations prediction (with respect to the centered case). **(Goals 8 and 9)**

12) The active or passive nature compensation of horizontal coma has been tested using pseudophakic eyes with aspheric IOLs (with negative spherical aberration). While the spherical aberration is compensated on average, but not individually in these eyes, coma appears to be compensated individually (there is significant correlation between corneal and internal aberration). This compensation does not occur in eyes with spherical IOLs, but occurs in eyes with different aspheric designs. This indicates that lens shape, gradient index or foveal position do not need to be fine-tuned to achieve a compensation of horizontal coma (so it would be a passive mechanism) although, because the cataract surgery seems to preserve the position of the capsule a fine-tuning for the orientation of the crystalline lens cannot be completely excluded. **(Goal 10)**

The results can establish the basis for future research line directions:

1) The study of dynamic changes of lens geometry and misalignment with accommodation, in relationship with the dynamic changes of ocular aberrations, which would shed mechanism into the mechanism of lenticular accommodation and presbyopia.

2) The study of the contribution of gradient index distribution in the lens to the optical aberrations of the eye, expanding the customized model eyes developed

in this thesis for pseudophakic eyes to phakic eyes. This development involves the development of new regression techniques to retrieve the gradient index profile in vivo, and further developments of the optical distortion correction algorithms for Scheimpflug imaging (considering more complicated surfaces in the crystalline lens and the effects of a gradient index structure).

3) The development of new intraocular lens designs, and cataract surgery directions, considering realistic ocular component misalignments and the effect of corneal incision.