Online Supplementary Material 2: Description of the Castrop IOL Formula

The basic IOL power formula is quite old, to our knowledge it was first described by Fyodorov[1] and by Gernet and Ostholt[2].

$$P_{IOL} = \frac{n_{vitreous}}{AL - ELP} - \frac{1}{\frac{1}{\frac{1}{\frac{1}{P_{spectacle}} - d_{vertex}} + P_{cornea}} - \frac{ELP}{n_{aqueous}}}$$

All classical Gaussian optics IOL formulae date back to this approach. Many derivates exist. They differ mostly how "ELP" (effective lens position) is dealt with. We used this equation as the basis for our IOL calculation. In daily practice, it makes sense to solve the equation for $P_{spectacle}$ instead of P_{IOL}.

In recent years, many formulae have emerged that are not published nor disclosed or documented. Some of them deliver great results, some don't. We feel it is better to understand what the formula actually does, how it uses the input data. Therefore, we would like to document our own approach in detail.

In classical formulae, we identified four typical sources of error that can be cured quite easily.

1. Most conventional formulae treat the cornea as an infinitesimally thin lens and use a fictious refractive index of either 1,3375 or 1,332 to convert the mean radius measured paracentrally to "corneal power" K. As this approach tends to overestimate the corneal power by 0.4 to 1.1 D, the IOL power is underestimated accordingly. To compensate for this, the ELP is assumed deeper than is realistic in a biconvex lens. This will lead over to the next problem. To avoid this, corneal power is calculated using a thick lens model and the measured radii[3]. If no data of the posterior curvature is available, the widely accepted Liou & Brennan[4] ratio assumes $r_{posterior} = 0,8312 * r_{anterior}$ for an untreated cornea. To avoid confusion with traditional "K", we will call this P_{cornea}.

$$P_{cornea} = \frac{n_{cornea} - n_{air}}{\frac{r_{anterior}}{1000}} + \frac{n_{aqueous} - n_{cornea}}{\frac{r_{posterior}}{1000}} - \frac{CCT \cdot 10^{-6}}{n_{cornea}} \cdot \frac{n_{cornea} - n_{air}}{\frac{r_{anterior}}{1000}} \cdot \frac{n_{aqueous} - n_{cornea}}{\frac{r_{posterior}}{1000}}$$

2. As the corneal power is overestimated, a given lens power with a realistic ELP (ELP is located inside the physical IOL) would lead to a hyperopic error. When ELP is assumed behind the physical IOL, calculated IOL power will be higher and the error be compensated for on average. However, in eyes with unusual combinations of axial length and corneal radii, this will lead to systematic deviations. This can be avoided if the ELP is very close to its real position inside the eye. In most IOL models, the principal plane of the IOL will be a little bit forward of the haptic plane. A very simple equation according to Olsen[5] had been used in an early version of the Castrop formula:
   $ELP = -0,18 + \frac{CCT}{1000} + AQD + C \cdot LT$
   "C" describes the fraction of crystalline lens thickness where the ELP will be presumed. It can vary with haptic and optic design. Typical values will be between 0,36 and 0,42.
   However, IOL position prediction can be further improved when axial length and corneal radii are included in the regression. WTW did *not* prove to be a reliable coefficient. The following equations were derived from a very large set of eyes where crystalline lens thickness and position and IOL position were measured with a Swept Source OCT.
   $ELP = 0,61 + 0,049 \cdot AL + 0,000729 \cdot CCT + 0,680 \cdot AQD - 0,123 \cdot r_{mean} + C \cdot LT$

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[1] Fyodorov SN, Kolinko AI. Estimation of optical power of the intraocular lens. VestnOftalmol. 1967;4:27–7.
[2] Gernet H, Ostholt H, Werner H. Die präoperative Berechnung intraocularer Binkhorst-Linsen. In: 122 Versammlung des Vereins Rheinisch-Westfälischer Augenärzte. Zimmermann. Balve; 1970. pp. 54–5.
[3] all distances and radii [mm], CCT [µm]
[4] Liou HL, Brennan NA. Anatomically accurate, finite model eye for optical modeling. J Opt Soc Am A Opt Image Sci Vis. 1997 Aug 1;14(8):1684–95.
[5] Olsen T, Hoffmann PC. C constant: New concept for ray tracing-assisted intraocular lens power calculation. J Cataract Refract Surg. 2014 May;40(5):764–73.

In eyes with prior corneal refractive surgery or severe corneal pathology, corneal radii should be left out and the following equation used instead.

$$ELP = -0,09 + 0,037 \cdot AL + 0,000602 \cdot CCT + 0,715 \cdot AQD + C \cdot LT$$

The constant “C” should be optimized first. IOLs with planar haptics and steeper anterior radii will have a smaller “C“ than IOLs with angulated of stepped haptics and/or designs where the main power is located on the posterior curvature. It is important that “C” optimization does not yield a significant skewness (median is significantly different from arithmetic mean). Remaining small offsets can be compensated for by adding an offset to the presumed refraction (“R” for “Rauxel”).

3. Axial length is measured optically. This means that the length of an *optical* path has to be converted into a *geometrical* path by dividing it by the refractive index. However, the refractive index of the eye is not constant. For the average eye, the group refractive index will be ≈ 1,3549.[6] In very long eyes, the fraction of vitreous will be larger and consequently the group refractive index will be smaller leading to hyperopic error. The opposite is true for short eyes. To overcome this problem, the best solution would be to avoid the group refractive index and use a sum-of-segments approach with different indices for each segment of the eye instead. There will still be some imprecision as the index of the cataractous lens material is not known exactly, but systematic errors will be largely avoided. Unfortunately, none of the biometers able to *measure* sum-of-segments will *indicate* “new” AL but use the “old” value instead (FDA, compatibility issues). We have to thank Cooke[7] for publishing a regression formula that allows to approximate the sum-of-segments from a Lenstar data set. We used Cooke’s formula to transform traditional optical AL to “AL_{new}”.

$$AL_{new} = 1,23854 + 0,95855 \cdot AL_{old} - 0,05467 \cdot LT$$

Some small systematic error will remain due to lens properties, surgical and optometric technique and needs to be adjusted. In conventional formulae, several influencing variables are squeezed into the ELP (e.g. A constant). The most important ones will be distance of fixation target, ambient light, haptic design, asphericity, spherical aberration, decentration and capsulotomy properties. We feel that every surgeon should do subsequent work on his refractive outcomes. We also think it is more appropriate to add a second constant (simple offset in diopters) instead of fudging the ELP. We call this constant “R” for “Rauxel”. For spherical IOLs, R will typically be close to zero when “C” has been optimized first. For aspherical IOL designs, “R” will typically be positive.

To summarize, our formula is identical to the basic IOL power formula. Corneal power will be derived from radii using thick-lens Gaussian optics; if posterior radii are not available they will be modelled according to Liou & Brennan. ELP is predicted from a multiple regression developed from true anatomical data enhancing Olsen’s C (“Castrop” constant). If the cornea has been tampered with or is difficult to measure, a simplified regression omitting corneal data is recommended. Axial length is transformed according to Cooke. Remaining systematic offsets are accounted for by adding an offset R (“Rauxel”).

The formula will be free of systematic errors (axial length, cornea, chamber depth) to a great extent. It can also be used in post LASIK eyes with great success if the true corneal power can be measured and calculated separately, eg using cornea OCT. The derived corneal power can be used to overwrite P_{cornea}. Alternatively, P_{cornea} can also be used, but it must be kept in mind that our simple Gaussian formula cannot deal with aspheric surfaces appropriately. It can be used in minus power cases as well as IOL powers up to 40 D without specific adjustments.

The formula is available as an Excel spreadsheet. The following screenshot will give an impression. It also includes optimized constants[8] for six different acrylic IOLs used in our clinic.

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[6] Haigis W, Lege B, Miller N, Schneider B. Comparison of immersion ultrasound biometry and partial coherence interferometry for intraocular lens calculation according to Haigis. Graefes Arch Clin Exp Ophthalmol. 2000 Sep;238(9):765–73.

[7] Cooke DL, Cooke TL. Approximating sum-of-segments axial length from a traditional optical low-coherence reflectometry measurement. J Cataract Refract Surg. 2019 Mar;45(3):351–4.

[8] Approx. 700 eyes from former studies were used to validate the formula and derive the constants

		not required for IOL calc	not required for IOL calc	not required for IOL calc	0 = normal cornea, 1 = LVC or other pathologies	central corneal thickness	internal chamber depth	externel chamber depth, derived from CCT+AQD	lens thickness (optical)	axial length (optical)	flat r [mm]	steep r [mm]	flat axis (not required for power calc)	derived from anterior r according to Liou & Brennan, can be overwritten if reliable r	not required in current version	*comparable to Olsen's C constant, refers to LT*	*2nd constant to adjust residual offsets*	AL as "sum of segments" according to Cooke	ELP calc with or without corneal radii depending on column "F"	derived corneal power (diopters, thick lens calc) in rare cases like LVC, it would make sense to overwrite this with a total K measured by tomography	**IOL to implant**	**expected refraction (6 m = 20 ft)**
J&J ZCB00	Name	Gender	Date of birth	Eye	LVC	CCT	AQD	ACD	LT	AL	R1	R2	AXIS	rpmean	WTW	*CAS*	*RAUX*	ALnew	ELP	K	**IOL**	**Rx**
Calibration	1000	1	19.06.1948	OD	0	612,00	2,35	2,96	4,27	23,64	8,07	8,07	-----	6,71	12,34	*0,41*	*0,27*	23,67	4,57	40,75	**23,50**	**-0,41**
Calibration	1001	1	18.05.1947	OS	0	566,00	2,62	3,19	4,46	23,14	7,51	7,47	150,00	6,23	12,08	*0,41*	*0,27*	23,18	4,84	43,91	**21,50**	**-0,35**
Calibration	1002	1	22.11.1990	OS	0	493,00	3,48	3,97	4,50	23,48	7,69	7,54	171,00	6,33	12,41	*0,41*	*0,27*	23,50	5,39	43,17	**22,00**	**-0,09**
Calibration	1003	1	12.06.1934	OS	0	556,00	2,73	3,29	4,86	23,80	7,99	7,50	79,00	6,44	11,95	*0,41*	*0,27*	23,79	5,05	42,46	**21,00**	**0,06**
Calibration	1004	1	29.03.1929	OD	0	515,00	3,08	3,60	4,46	24,49	7,98	7,89	86,00	6,60	12,95	*0,41*	*0,27*	24,47	5,13	41,43	**20,50**	**-0,23**
Calibration	1005	1	18.05.1954	OS	0	566,00	2,90	3,47	4,62	24,31	7,74	7,66	80,00	6,40	11,92	*0,41*	*0,27*	24,29	5,13	42,71	**19,50**	**-0,35**
Calibration	1006	1	13.09.1965	OD	0	637,00	1,82	2,46	4,19	20,43	7,92	7,58	177,00	6,44	11,64	*0,41*	*0,27*	20,59	4,06	42,45	**33,50**	**-0,85**
Calibration	1007	1	07.11.1945	OS	0	506,00	2,93	3,44	4,93	22,90	7,67	7,52	100,00	6,31	11,83	*0,41*	*0,27*	22,92	5,17	43,29	**23,50**	**0,10**
Calibration	1008	1	19.03.1940	OD	0	565,00	2,70	3,27	4,56	23,56	7,91	7,72	103,00	6,50	12,41	*0,41*	*0,27*	23,57	4,91	42,08	**22,50**	**-0,24**
Calibration	1009	1	30.06.1929	OD	0	568,00	2,23	2,80	4,94	23,19	8,12	7,90	114,00	6,66	11,24	*0,41*	*0,27*	23,20	4,70	41,05	**25,00**	**-0,29**
Calibration	1010	1	07.11.1933	OS	0	578,00	2,64	3,22	4,50	23,55	8,04	7,91	162,00	6,63	12,95	*0,41*	*0,27*	23,57	4,84	41,23	**23,50**	**-0,21**
Calibration	1011	1	26.10.1942	OD	0	521,00	1,67	2,19	4,93	22,02	7,43	7,35	138,00	6,14	11,91	*0,41*	*0,27*	22,08	4,31	44,49	**24,50**	**-0,67**
Calibration	1012	1	16.01.1941	OS	0	602,00	1,99	2,59	5,31	23,24	8,02	7,76	126,00	6,56	12,19	*0,41*	*0,27*	23,22	4,73	41,68	**24,00**	**-0,23**
Calibration	1013	1	23.09.1927	OD	0	576,00	1,74	2,32	5,53	22,41	7,62	7,58	47,00	6,32	11,90	*0,41*	*0,27*	22,42	4,64	43,27	**25,00**	**-0,31**
Calibration	1014	1	13.10.1941	OD	0	540,00	2,46	3,00	4,80	22,87	7,56	7,50	109,00	6,26	11,94	*0,41*	*0,27*	22,90	4,84	43,67	**22,50**	**-0,03**
Calibration	1015	1	17.05.1938	OS	0	592,00	2,87	3,46	4,13	23,05	7,84	7,76	113,00	6,48	11,96	*0,41*	*0,27*	23,11	4,85	42,16	**24,00**	**-0,18**
Calibration	1016	1	01.11.1943	OD	0	550,00	3,45	4,00	4,75	25,18	8,14	8,02	179,00	6,72	13,73	*0,41*	*0,27*	25,12	5,54	40,69	**19,50**	**0,12**
Calibration	1017	1	29.06.1951	OD	0	564,00	1,91	2,47	4,59	22,61	7,90	7,82	11,00	6,53	12,06	*0,41*	*0,27*	22,66	4,34	41,83	**25,50**	**-0,49**
Calibration	1018	1	27.07.1968	OD	0	558,00	2,85	3,41	4,14	26,68	8,25	8,00	7,00	6,75	12,69	*0,41*	*0,27*	26,59	4,94	40,47	**14,50**	**0,00**
Calibration	1019	1	31.05.1933	OD	0	538,00	2,68	3,22	4,77	23,52	7,62	7,46	91,00	6,27	11,94	*0,41*	*0,27*	23,52	5,00	43,61	**20,50**	**-0,09**
Calibration	1020	1	22.06.1936	OD	0	497,00	2,74	3,24	4,42	23,78	7,51	7,40	93,00	6,20	11,66	*0,41*	*0,27*	23,79	4,89	44,10	**18,50**	**-0,03**
Calibration	1021	1	17.06.1944	OS	0	553,00	2,30	2,85	4,71	23,32	7,96	7,84	90,00	6,57	12,36	*0,41*	*0,27*	23,33	4,67	41,62	**23,50**	**-0,20**
Calibration	1022	1	11.09.1935	OD	0	557,00	2,66	3,22	4,99	24,53	8,00	7,66	101,00	6,51	12,18	*0,41*	*0,27*	24,48	5,09	41,99	**19,50**	**-0,16**
Calibration	1023	1	05.02.1957	OS	0	514,00	2,24	2,75	4,83	23,79	8,29	8,16	138,00	6,84	11,96	*0,41*	*0,27*	23,78	4,63	39,96	**24,00**	**-0,20**
Calibration	1024	1	30.12.1944	OS	0	495,00	3,48	3,98	4,34	26,34	8,50	8,32	79,00	6,99	12,17	*0,41*	*0,27*	26,25	5,36	39,08	**18,00**	**-0,02**
Calibration	1025	1	17.05.1950	OS	0	574,00	2,03	2,60	5,04	22,66	7,53	7,31	116,00	6,17	12,24	*0,41*	*0,27*	22,68	4,66	44,33	**22,50**	**-0,33**
Calibration	1026	1	29.12.1936	OS	0	547,00	2,74	3,29	4,33	24,29	7,68	7,50	50,00	6,31	13,18	*0,41*	*0,27*	24,28	4,89	43,32	**18,00**	**-0,17**
Calibration	1027	1	12.02.1981	OS	0	639,00	3,38	4,02	3,77	26,49	7,70	7,67	62,00	6,39	12,47	*0,41*	*0,27*	26,42	5,27	42,81	**12,50**	**-0,34**
Calibration	1028	1	19.11.1946	OS	0	563,00	2,62	3,18	4,57	22,45	7,59	7,40	13,00	6,23	11,90	*0,41*	*0,27*	22,51	4,84	43,88	**24,00**	**-0,14**
Calibration	1029	1	15.08.1926	OS	0	522,00	2,15	2,67	5,27	24,05	8,21	7,21	170,00	6,41	12,33	*0,41*	*0,27*	24,00	4,78	42,64	**19,50**	**0,03**
										data input, mandatory columns						*IOL constants*			derived values, no entry!			output
constants optimized on real refraction data so far																						
J&J ZCB00	**91**															***0,41***	***0,25***					
Alcon SA60AT	**296**															***0,37***	***0,00***					
Alcon Clareon	**40**															***0,40***	***0,24***					
B&L MX60	**136**															***0,42***	***0,01***					
Hoya Vivinex	**30**															***0,40***	***0,14***					
J&J AAB00	**85**															***0,39***	***-0,15***					