SRK Formula History

53

John Retzlaff and Donald R. Sanders

The seeds that grew into SRK began with the SRK authors, John Retzlaff in Medford Oregon and Manus Kraff and Don Sanders in Chicago, IL, after they independently became discontented with the large number of refractive surprises occurring in their IOL patients. Refractive surprises ocurred despite meticulously measurement of axial length (AL) by applanation, using corneal power (K) and precisely applying the RD Binkhorst formula (as described in his Power Calculation guide) [1].

They studied the IOL power calculation formulas [2–8] which had been published at that time and became familiar with them and their various constants and correction factors. They also noticed that when rearranged, all these formulas were algebraically similar. This is because they are all based on the classical vergence of light formula worked out by Maxwell [9] and others in the 1800s.

Rather than working with the theoretic formula model, Sanders, Retzlaff, and Kraff decided, unknowingly and simultaneously, to pursue the linear regression equation approach, even though they realized biological phenomena are rarely linear.

1977–1980

In 1978, Tom Lloyd, a technician in Jim Gills' office, developed the first linear regression formula for IOL calculation which Gills published in an Editorial [10] in a 1978 Journal of Cataract & Refractive Surgery (JCRS).

Don Sanders met Manus Kraff, while Kraff was the surgical attending during Sanders' last year of residency at Illinois Eye and Ear Infirmary. He finished his residency, accepted a faculty position at the University of Illinois, became the Chief of Ophthalmology at Westside VA Hospital in Chicago, and enrolled in a PhD program at Rush University which gave him access to the University's mainframe computer. While there, he became proficient in the leading statistical software packages of that time (SAS, Statistical Analysis System, and SPSS, Statistical Package for the Social Sciences) and became familiar with programming keypunch cards.

Kraff had the foresight to realize that the best way for him to contribute to ophthalmology would be to analyze clinical data from his extensive and prolific cataract and IOL practice; he was recording data on his cataract/IOL cases on index cards.

It was only natural that they both realized that they could draw on each other's strengths. This resulted in a more than 40-year collaboration with over 40 coauthored peer-reviewed publications, a quarter of which were on IOL power and

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database computerization. Their first two publications [11, 12] in 1980 were on IOL power calculation. Their first regression formula paper contained an analysis of 923 eyes with six different IOL styles, with each style having at least 120 eyes, a testament to Kraff's data collection skills. Sanders computerized his database, added more variables, and designed protocols. Keypunch cards were ultimately replaced by modem transmission of data for remote analysis as this technology became available.

Meanwhile, in Medford, Oregon, Retzlaff was very busy in his private practice. He had become comfortable with phacoemulsification and was well into IOL implantation. His IOL power calculation research began with his son Steven at Medford High School. This allowed access to the only computer in Southern Oregon powerful enough to do regression analysis.

Fortunately, the district's PhD computer instructor and overseer had John learn enough basic (Gate's and Allen's computer language) to enter data into the system, review the data to weed out entry errors, program the theoretic formulas needed for comparison, and manage the project in general. He procured a regression analysis program robust enough to easily include and test all necessary and available IOL calculation factors (variables) in its hierarchical analysis. He found that picking the brains of his two mathematician duplicate bridge-playing partners was extremely helpful in navigating his way through these unknown waters.

After many months, to his surprise, he found the regression formula he derived to be more accurate than other published formulas available at that time. He presented his positive findings in Portland OR on March 16, 1979, at the 38th Annual Convention of the Oregon Academy of Ophthalmology. By a total coincidence, Kenneth J Hoffer (Chairman of the ASCRS Symposium and Editor of JCRS) was invited to give their Orpha Ellen Reeh Lecture and heard Retzlaff's lecture. He enthusiastically complimented his work and virtually insisted he write up the study and submit it to him for publication in the AIOIS Journal which later became JCRS. Hoffer threatened him that if he did not, he would publish the idea himself. He also told him that his talk would be placed on the program at the next ASCRS Symposium and that if he did not show up, it would be given without him. Retzlaff came and delivered the talk perfectly.

The Journal submitted Retzlaff's paper [13] to Kraff and Sanders to be reviewed. They could have easily killed it. Instead, they wrote a letter to Retzlaff complimenting him on the paper and telling him they were recommending speedy publication. They noted that they themselves were in the midst of a linear regression project and included data, which showed that some of their preliminary regression constants were similar to Retzlaff's regression constants.

A short time later all three were invited individually to each give a presentation of their work at Hoffer's IOL Power Course at the 1979 American Academy of Ophthalmology meeting. They met and an immediate bond formed and intense collaboration began which has continued all these years. There were many phone calls since there was no email and no easy way to exchange data, graphs, and tables. Electronic data exchange was still years away from fruition.

Collaboration Examples

Collaboration 1: One afternoon, Sanders called Retzlaff while he was seeing patients and probably was already half an hour behind schedule. He pointed out the important principle that IOL power data from IOLs of different styles and from different manufacturers must be analyzed separately. Retzlaff quickly and emphatically responded, "Oh, I don't think that's necessary at all." However, Retzlaff quickly realized the irrefutable logic of this principle because, clearly, different IOL styles and manufacturers have different effective powers. He agreed with the principle and adopted it. He had to swallow the bitter fact he had erred by failing to do this in his paper already in publication. It may seem preposterous that John made this error; however, remember that in 1978, some were still, to some extent, in the era of the Standard Lens Method, meaning

every patient received the same power IOL (not everyone had an A-scan unit).

Collaboration 2: On another occasion, Retzlaff, referring to the regression equation of the form x = A + By + Cz, told Sanders: "I've started doing regression analysis on different data sets using a fixed 'B' and 'C' constant and allowing only the 'A' constant to vary." After getting an explanation of this peculiar process, Sanders told him, "You can't do that." He responded, "Well, I've done it and it works." This capricious "peculiar process" of doing regression equations with one or more of the constants fixed led to our realization that handling the regression equations in this manner, i.e., calculating an individual A-constant for each style of IOL, provides a single, specific index value for each IOL, a powerful piece of information. Manufacturers could then provide surgeons with the needed A-constants or the surgeons could calculate their own personal A-constants.

Most of our IOL discussions occurred on the weekends. We were doing extensive data analysis. We explored AL and K, preoperative anterior chamber depth (ACD_{PRE}) measured from epithelium to lens, possible correction factors, regression math using multiplicative and exponential terms, and curve fitting. Using regression analysis, we also investigated factors including preoperative refraction (recent and old), cataract type, gender, and age. We did not find that any of these factors improved prediction accuracy.

Preoperative ACD (ACD_{PRE})

During their research into IOL power using regression analysis, Kraff and Sanders measured ACD_{PRE} with the Haag-Streit optical anterior chamber pachymeter to test the predictive value of this variable (ACD_{PRE}) in IOL power calculation. $ACD_{PRE,}$ AL, and K were analyzed in hierarchical steps by the computer program, i.e., the factor most helpful in predicting IOL power was added to the equation first, the factor that was next in importance was added second, and so on. AL was the single most important factor in predicting implant power. K was second in importance. We found that ACD_{PRE} improved the prediction accuracy by less than 1%. Similarly, using ACD_{PRE} in various mathematical forms (exponents, etc.) was still, in our model, not any more predictive of IOL power than using AL and K alone. Bagan and Brubaker [14] reached the same conclusion in their study of $ACD_{PRE.}$ However, history has shown that this was not true.

1980: SRK Is Born

Determination of the order of the letters in the formula name (what order would the initials be placed: KRS, RKS, SRK) was decided with a coin toss. Kraff contends that the coin toss agreement was, "Retzlaff heads, Sanders tails, and Kraff if the coin lands on its edge and stays there." When that was settled, we developed a logo (Fig. 53.1). We were satisfied that we had thoroughly explored the available variables using multiple mathematical tools. We were delighted we had boiled all this information and all these possibilities down into a truly simple mathematical form:

$$P = A - 2.5^{*}AL - 0.9^{*}K$$

This needed only AL, K, and a constant "A" for each IOL. The predictive accuracy of the new formula was compared to previously published formulas, and the SRK was found to be consistently more accurate. Our first two-principle SRK papers were published in 1980, Retzlaff's in April [13] and Sanders and Kraff's in July [12].

Fig. 53.1 SRK formulas logo

Paper Summary: Retzlaff

> "Data from 166 eyes with iridocapsular implants were analyzed and different prediction methods were compared. A new formula was derived which predicted implant power better than any other method. The theoretic formulas and correction factors of Fyodorov, Colenbrander, and others were examined in detail and compared to the more accurate, simpler linear regression formula derived in this study."

Paper Summary: Sanders Kraff

> "It can be produced with different constants (A, B, and C) for each type of lens implant and each manufacturer. We have determined the constants for iris-fixated, anterior chamber, and posterior chamber lens implants, based on data from 923 cases. The results have been more accurate than those from presently available theoretical formulas, and the well-known phenomenon of predicting too much dioptric power in eyes with short axial lengths has been avoided. Only 1% of the cases had a predicted lens power more than 3 diopters in error."

The addendum, below introduced the exact, first SRK formula.

Addendum: In an attempt to simplify the regression formula even further, in cooperation with Dr. John Retzlaff , we have set the constants B and C the same for all implants and determined the best-fit A-constant. The following formula: Predicted implant power = $A - 2.5 \times AL - 0.9 \times K$ was tested with A = 115.5 (medallion-style lenses, Medical Workshop); A = 114.8 (medallion-style lenses, Intermedics Intraocular); A = 115.7 (Choyce-style lenses, Rayner/Coburn); A = 114.3 (Tennant-style lenses, Precision-Cosmet); and A = 116.0 (single-plane and angulated Shearing-style lenses, IOLAB).

After it was introduced, the simple SRK regression formula was used extensively by ophthalmologists worldwide for many years. During this early period, some ultrasonic AL measuring units did not have built-in IOL power calculation formulas. The most common method of calculation was the use of a Texas Instruments (TI) handheld programmable calculator with the R Binkhorst formula built into a PROM (programmable read-only) chip. A dedicated thermal printer was attached. This was sold by Sonometrics, the most prominent A-scan manufacturer at the time.

Sanders and Retzlaff decided that to truly gain widespread acceptance of the SRK formula at this early period, they had to make the formula available for the same TI system used by R Binkhorst and Sonometrics. They soon learned that they had to program the PROM chip and purchase a minimum of 1000 chips from TI at a cost of tens of thousands of dollars; any coding errors required scrapping the PROMs.

Fortunately, they tested the step-by-step PROM programming meticulously and repeatedly and our PROM was accurate the first time around. In a short period of time, the SRK team, in conjunction with Sonometrics, sold all of the PROMs and the SRK formula became the most widely used IOL power calculation formula worldwide. Soon thereafter, IOL calculation formulas became more available in A-scan devices further increasing the reach of the SRK formula.

Early 1980s

During the 1980s, the IOL frenzy settled down to a merely exhilarating, challenging, and constantly changing activity. IOL power courses were plentiful. RD Binkhorst, Kenneth J Hoffer and John Shammas, Jack Holladay, Michael Cravy, Bobby Osher, Jim Gills, and Gale Martin, as well as ourselves, were active doing courses. We pounded away on practical issues emphasizing meticulous measurement of AL and K and avoiding mix-ups of data, power calculation reports, and IOLs themselves. During these courses, formulas were not discussed much; the main formulas being used at the time were SRK, R Binkhorst, and less frequently Hoffer; so, there was not much to talk about.

The art of selecting the best IOL power for each individual patient was by considering the patient's previous refraction and spectacle use, then discussing the patient's desires and expectations including monovision, then checking the

IOL power printout for both eyes looking for errors, and finally, selecting the best IOL power for that patient, not necessarily 20/20 distance vision.

Late 1980s SRK II

By the late 1980s, IOL implantation had become an almost universal part of cataract surgery. Patient selection had expanded from only healthy average-length eyes to virtually all cataract surgery eyes. The Holladay 1 formula [15] was published and became available on a TI calculator. It became quite popular, and results showed it superior to the SRK regression. With time, it became increasingly apparent that a pure linear formula was inaccurate in extremely long and short eyes. This led to modifying the original SRK formula by developing the SRK II [16]. The goal was to create a new formula more accurate than existing formulas and to retain simplicity. Extensive modeling and analysis improved the accuracy of the original SRK formula for short (>22 mm) and long (≥25 mm) eyes.

Similar in form to the existing SRK regression formula, power was added to the SRK formula in a stepwise fashion for short eyes and subtracted for long eyes. The SRK II formula was developed from seven data sets: 2068 eyes (which included 167 short eyes, 306 long eyes, and 1595 average eyes). Extensive modeling and analysis improved the accuracy of the original SRK formula and yet retained the simple, do-it-in-your-head characteristic of the original.

Secret Formulas

As a group, the SRK collaborators have always felt that formulas that had hidden or secret relationships between variables were unwise in scientific discourse. They make it more difficult to perform head-to-head comparisons between formulas and methods. Proprietary secret IOL formulas first appeared with the Holladay 2 formula which was marketed in a proprietary software program and later in some biometers. The code was never published. Since that time, almost all new formulas have been relatively secret. Interestingly, most cataract surgeons are not aware that so many IOL power calculation formulas are secret.

From Fyodorov [2] to SRK/T [18, 19], Hoffer Q [20], and Haigis [21], formulas have all been published in detail so others could test them independently**,** program and modify them, and learn from them. Having the SRK family of formulas published in detail has certainly not harmed its popularity and commercial success. On the other hand, with the modern use of artificial intelligence (AI) and complex algorithms, it would not be easy for a clinician to duplicate them even if they were published, as has been recently done for the PEARL-DGS formula [17] from France.

1990 SRK/T

In 1987, the SRK II had been completed and was published. Retzlaff was planning retirement from his surgical practice but due to the success of the Holladay 2 formula over the SRK formulas, it was decided to re-evaluate the formula. Retzlaff sets out to (1) create "an empiric formula that uses the nonlinear terms of theoretical formulas" (as so elegantly stated by Rasooly et al. [22]) and (2) compare a new formula to other formulas using an entirely separate independent data set. Thus, two separate data sets were used for the project. Development of the SRK/T formula was done with the first of these data sets (1677 eyes); the comparison of the accuracy of the new formula was done with the second data set (2068 eyes).

SRK/T Development

The project plan was to work with the vergence of light formula [9], which is the basic structure of all theoretic formulas. Early theoretic formulas were restudied. Particular attention was focused on Fyodorov's [2] 1967 corneal height work (which Holladay had used) by utilizing anterior segment measurements. Factors considered in the

first SRK publications were tested using regression analysis within the framework of the theoretic formula structure. Extensive optimization efforts including curve fitting and regression using multiplicative and exponential terms were carried out. We presented our development methods and code, in considerable detail, to facilitate continued research into IOL power calculation.

The new IOL power calculation SRK/T formula was developed using the nonlinear terms of the theoretical formulas as its foundation but using empirical regression methodology for optimization. Postoperative anterior chamber depth prediction (ELP), retinal thickness AL correction, and corneal refractive index were systematically and interactively optimized using an interactive process on five data sets consisting of 1677 posterior chamber lens cases. The new SRK/T formula performed slightly better than the Holladay 1, SRK II, R Binkhorst, and Hoffer formulas, which was the expected result as any formula performs superiorly with the data from which it was derived. The comparative accuracy of this formula upon independent data sets is addressed in a follow-up report. The formula derived provides a primary theoretical approach under the SRK umbrella of formulas and has the added advantage of being useable with the SRK A-constants that have been empirically derived over the previous 9 years or using converted anterior chamber depth estimates.

SRK/T Accuracy Comparison: Independent Data Sets

In 1988, Richard Brubaker, chief of ophthalmology at Mayo Clinic, commented to Retzlaff: "You cannot test a formula's prediction accuracy with the data you used to derive the formula." After asking why, Brubaker smiled and said, "You just can't!" The logic of using independent data is so compelling that it should be self-evident but it was not evident to us until it was pointed out by Brubaker. Examination of papers presenting new formulas shows that this principle was also violated by Fyodorov and Galin [4], R Binkhorst [5], Colenbrander [3], Thisson [6], Holladay [16], and Haigis [20]. Also, how the creators of unpublished formulas handled data set selection to test their formulas' prediction accuracy is impossible to determine because it is secret.

SRK/T Accuracy Comparison 1990

We compared the predictive accuracy of the SRK/T formula to the SRK II, R Binkhorst II, Hoffer, and Holladay 1 formulas in seven series of cases totaling 1050 eyes. In the combined group, the SRK/T and Holladay formulas performed only slightly better than the other formulas. In short eyes (<22 mm), all formulas performed well, with the SRK/T, SRK II, and Holladay formulas performing marginally better (not statistically better). In moderately long eyes (>24.5 and ≤27 mm), the Hoffer and R Binkhorst II formulas had a greater proportion of cases with >2 diopters (D) of error and the SRK/T and Holladay 1 were again marginally better. In the very long eyes (>27 and ≤28.4 mm), there were only 11 cases and all formulas performed well since none had >2.00 D of prediction error. In an extremely long eye data set (>28.4 mm), the SRK II formula clearly gave the poorest result. Eyes of this length occurred in only 0.1% of cases in this unselected series. Results support the contention that the present second- and third-generation formulas give fairly equivalent accuracy. Other factors, such as availability, ease of use, and ability to tailor or individualize them, become major considerations.

SRK/T Errata

It is important to note that, unfortunately, there have been two published errata for the SRK/T 1990 publication (1990;16(3):333–340), one in 1990 and another in 1993.

Immediately after it was first published, Hoffer was attempting to program the formulas of Hoffer, Holladay 1, and the SRK/T into a Casio calculator and discovered a problem with the SRK/T that seemed to be caused by the L_{COR}

(corrected AL formula). He immediately called Retzlaff and luckily reached him right away. Retzlaff knew exactly what the problem was, corrected it, and submitted the erratum to JCRS which was published in the very next issue (JCRS 1990;16(4):528). It specifically corrects two formulas: the first defined the AL correction L_{COR} as $= -3.466 + 1.715*AL-0.237*AL^2$ if the AL was >24.2 and if AL was ≤24.2, then the actual AL was used unaltered. The second was that if the AL was <24.5, then C = 0 but if ≥24.5, then C = −0.50.

The second occurred in 1993 after a published letter to the editor in JCRS by Haigis, who pointed out several issues with the formula leading to a response letter from the authors and a full explanation of the issues raised (1993;19(5):444–446). In the part of the formula for ELP prediction, they left out the limitation on H: "If H < 0, H = 0" creating meaningless results in some cases. The other issue was the sudden drop in results of IOL power when the AL >26 mm.

Since almost all use of the SRK/T formula was through legitimately licensed instruments that were correct and properly programmed, these issues only caused problems for the few who were programming it themselves based only on the original publication.

Closing Remarks and Thoughts

We find it remarkable that a concept and a brand that took shape more than 40 years ago still have relevance and use in clinical ophthalmology today, while the original IOL designs, most of the companies that made them, and the axial length measuring devices upon which SRK formulas were based are no longer used. We feel blessed to be some of the "last men standing" in this field.

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