Glaucoma: Macrocospm to Microcosm
The Friedenwald Lecture

Harry A. Quigley

Jonas Stein Friedenwald, the son and grandson of ophthalmologists, was born in Baltimore in 1897. He attended Johns Hopkins Medical School, graduating in 1920. After medical internship, he spent 1 year studying ophthalmic pathology with Fredrich Verhoeff (Harvard), had a 1-year preceptorship with George de Schweinitz (Philadelphia), and then began practice without further training. He seemed not to need it.

He was in charge of “Ophthalmic Pathology... and directed the lion’s share of research activities of the Wilmer Institute” from 1923 to his death in 1955. He excelled at the correlation of clinical and pathologic findings, as continued by A. Edward Maumenee and W. Richard Green at Wilmer after him. He was described as a “many faceted genius,” accomplished in physics, mathematics, chemistry, and ophthalmology. In his 1949 Proctor Lecture, he summarized evidence that the formation of aqueous humor was an energy-dependent, enzyme-driven process. These ideas led to the development of carbonic anhydrase inhibitors for glaucoma treatment. He placed the calibration of the Schiotz tonometer on an experimental, scientific footing and studied “ocular rigidity”—an area engaging the glaucoma field at present in the interaction between cornea and tonometry.

He wrote on the relation between art and vision mechanisms and dedicated legal theory with his friend, Supreme Court Justice Felix Frankfurter. Norman Ashton wrote of Jonas: “His intellectual grasp of scientific problems and his remarkable knowledge of many widely different fields of art and learning made him a quite exceptional person by any standards.”

He was instrumental in the development of Hadassah Hebrew University Medical Center in Israel, visiting in 1936 and 1945 and lecturing in Hebrew.

Robert Moses, his student and colleague, wrote: “He applied physics in his studies on tonometry, chemistry to his work on aqueous secretion... and optics in his design of an advanced ophthalmoscope. If a given problem needed knowledge he did not possess, he simply got some recent books on the subject, sat down and studied.”

Wilmer Chairperson Alan C. Woods stated: “When the pathogenesis of chronic glaucoma is finally resolved and understood, I am confident that the solution will rest largely on the foundations laid down by Jonas Friedenwald.”

During his 32 years of scientific work, he “devoted himself tirelessly to a large practice. He was never too busy or too tired to give his skill, his attention and his time to any needy or ill patient.” Thus, Jonas Friedenwald was the epitome of an ophthalmic clinician scientist. He is a role model to whom all of us can aspire. As I walk the halls of Wilmer, caring for glaucoma patients and chasing the mysteries of this disease, I have often felt the presence of this gentleman giant whose portrait gazes at us from the wall of the Friedenwald Library. I could not hope for a greater honor than to receive an award in his name.

The Setting

I had the good fortune to work as a student in the laboratories of Nobelists George Wald and past ARVO awardees Jay Enoch and John Dowling. I was first intrigued by glaucoma in 1973, challenged by friend and teacher Irvin Pollack and by my ophthalmic father Ed Maumenee. At that time, angle closure and open-angle glaucoma (OAG) had been conclusively distinguished by gonioscopy, while optic disc photography and Goldmann perimetry produced standardized evaluations of nerve damage, and eye drop therapy was becoming somewhat more acceptable. Laser iridotomy was in its infancy, and laser angle treatment was 5 years off. We did the first trabeculectomy at Wilmer that year.

But, OAG was then considered a disease of “elevated” intraocular pressure (IOP). We were puzzled by the occurrence of high IOP in many persons with no disease, while some OAG sufferers had normal IOP. Epidemiology had scarcely been applied to determine the prevalence of OAG (except by Mansour Armaly and Fred Hollows (Hollows and Graham)), nor were its risk factors clear. Clinical changes observed in the optic disc were not understood histopathologically. Fields seemed to remain “normal” while the disc increasingly “cupped,” then function rapidly worsened, confounding our understanding of the rate of progression. It was often said that OA was a disease that couldn’t be diagnosed properly and for which treatment wasn’t proven to work.

In this report, I will describe aspects of OAG that we now understand better, focusing on subjects that I have studied in collaboration with many colleagues. In each area, the remaining challenges will be highlighted.

The Macrocospm

OAG Defined

OAG is now defined as a disease of retinal ganglion cells (RGCs), characterized by structural change in the optic disc that is best described as excavation, and by a typical, slowly progressive loss of function that begins in the midperipheral field and expands both toward the center and peripherally. There is considerable variation in the normal appearance of the optic disc and in the number of RGCs from one person to another.

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another.\textsuperscript{10,11} These differences challenge our ability to distinguish normal from glaucoma as the RGCs die and their axons at the disc rim are lost. However, the study of population-based data allows us to define glaucoma operationally for the purpose of comparisons across studies by using the combined criteria: a cup/disc ratio so large that it is found in only 2.5\% of a population and visual field defects on automated perimetry in characteristic locations and severity.\textsuperscript{12} This definition has now been used relatively widely, and its usefulness has been evaluated by several epidemiologic groups.\textsuperscript{13} The level of IOP is no longer a defining criterion for OAG, but it is an important risk factor (discussed later).

**Prevalence**

The glaucomas comprise the second leading cause of blindness worldwide, after cataract, having surpassed trachoma during the past decade.\textsuperscript{14,15} Glaucoma affects more than 50 million persons and bilaterally blinds more than 7 million. More than two-thirds of those with primary glaucoma have OAG. These estimates were constructed from a meta-analysis of existing prevalence data 10 years ago that was based on age- and gender-specific world population data. To make the numbers more relevant to OAG, the world was divided into more logical groupings than simple geographic or national ones (all African-derived persons, regardless of continent, were placed in one group, for example). My teenage son, David, made this possible by performing the first download to a private home from the U.S. Census Bureau population data.

Much of the world’s OAG is undiagnosed, with only 50\% of cases recognized in developed countries. Even within the Johns Hopkins Health Care system, a sizable minority of those with OAG are unaware of their disease.\textsuperscript{16} In studies by colleagues at Wilmer’s Dana Center, it was reported that the burden of blindness from OAG and other eye diseases falls more on the elderly and the poor.\textsuperscript{17-19} Inspired by the epidemiologic approaches suggested by Alfred Sommer, groups led by Sheila West, Jim Tielsch, Joanne Katz, and Beatriz Muñoz continue to learn about the complete spectrum of glaucoma in populations, rather than trying to determine its nature by analysis of clinic-based chart data. The prevention of OAG clearly lies in understanding its fundamental nature and its contributing risk factors.

**Incidence and Progression**

To analyze how OAG affects populations, I estimated its incidence—the number of new cases per year at each age. While this might be calculated by serial examinations of large groups over extended periods, Leske, Ederer, and Podgor\textsuperscript{20} suggested that incidence could be inferred from age-specific prevalence of OAG. This results from two key features of OAG: once present, it does not go away; and persons with OAG do not die faster than the general population. Thus, the rate of new cases per year should be approximately the incremental increase in prevalence from younger age groups to older ones. Using this approach, Susan Vitale and I\textsuperscript{21} estimated OAG incidence for European- and African-derived persons. Direct estimates by follow-up examinations have corroborated our measures.\textsuperscript{22,25} It is now clear that OAG incidence increases with age, so that there is a more than linear increase in disease with age. Using incidence data, we showed how many persons among a defined population will develop OAG in their lifetime and how long the average OAG person has the disease. This ‘life-table’ analysis, though dependent on several assumptions, showed that the typical person with OAG lives approximately 15 years from initial field loss to death.\textsuperscript{21}

The progression rate for OAG with and without therapy has been studied recently. It was widely believed that many persons with glaucoma lose useful vision.\textsuperscript{24} On the contrary, population studies document that fewer than 10\% of those with OAG become bilaterally blind.\textsuperscript{25} Some clinic-based data appeared to show worse outcomes, but those in the care system typically have more severe disease. To estimate progression rate, we used a similar method to that for estimating incidence from prevalence—namely, we calculated mean damage in younger compared with older OAG patients.\textsuperscript{25} The result slow progression estimated by this method was confirmed in clinical trials,\textsuperscript{26} as well as in our own longitudinal studies.\textsuperscript{27} Approximately 4\% of those with OAG have progressive field loss each year of treated follow-up. With an average length of disease of 15 years, only 60\% would be expected to have any progression, and most do not become significantly impaired.

Some have (wrongly) concluded from this finding that "OAG isn’t that bad.” OAG blinds a modest proportion of those with the disease, but since it is a highly prevalent disorder, this small proportion is a large absolute number. Furthermore, our estimates are the mean worsening rate—there are some persons who are injured much more quickly than average. Those who develop OAG early in life are exposed to the risk of progression for longer times. It is vitally important that we develop better methods to measure progression so that aggressive treatment can be offered to these individuals at greater risk, while preventing those with a more benign course from suffering the side effects of therapy.

It can be estimated that 1.3 million ocular hypertensive (OH) OAG suspects are receiving topical preventive therapy in the United States. If the life-table model is applied, it is estimated that the average OH lives 25.5 years from onset to death, with nearly 50\% moving from OH to OAG status in their lives (2\% per year). Treatment is estimated to cut this conversion rate in half, sparing 325,000 persons (25\% of the total) from OAG. Conservatively, the unilateral blindness rate from treated OAG is 20\%; hence, 65,000 eyes per year are likely to be saved from blindness by OH treatment. Annual prostaglandin therapy costs over $800 per year. Thus, with 25 years of therapy in 2004 dollars ($26 billion), the cost is $400,000 per eye saved from blindness. It is important that we evaluate both the individual and the public health consequences of our therapies.

**Case Identification (Screening)**

The identification of OAG cases in a population is more challenging than the screening for cataract. For adequate predictive power, we must combine two methods of examination: one for disc structure, one for visual function.\textsuperscript{28} However, screening is performed in various contexts, each with a different, optimal approach.\textsuperscript{29} Community screening programs in the United States have, unfortunately, a low yield at high cost.\textsuperscript{30} In the developing world, case identification is even more challenging and is impractical for most countries, though it can be accomplished with extraordinary effort for demonstration or research studies.\textsuperscript{31,32}

In medical care offices, screening with expensive technology may be practical,\textsuperscript{33} but this has not yet been applied in an effective way. Too often, a promising set of data generated in one group of patients is not generalizable to other groups.\textsuperscript{34} It is hoped that laser-based imaging devices can be tested in nonophthalmic care delivery offices with a national, central reading system to sort suspects from the population at risk.

**Risk Factors for OAG Prevalence**

To improve case identification, as well as to understand the causes of OAG, it is important to define its risk factors. Diseases rarely have only one “cause”; rather, they have groups of
necessary and contributing factors that differ among persons with identical phenotypes. A necessary factor in one person (higher than normal IOP) may be merely contributing in another and not at all present in others. Some risk factor analyses have dramatically changed our ideas about OAG.

OAG prevalence increases with age, with startlingly high rates of disease in the very elderly found by David Friedman in the Salisbury Eye Evaluation OAG study (Friedman DF, personal communication, December 2004). Since RGCs die during aging, OAG can be thought of as accentuated neuronal aging, associated with a sagging optic nerve head. Rohit Varma43 found that the nerve rim area of the optic disc was related to IOP level—higher IOP was associated with fewer nerve fibers among normal persons. Possibly, the level of IOP affects the age-related loss of RGC. Of course, aging could affect other putative factors of OAG progression. Furthermore, age is a surrogate for duration of exposure to the other risk factors for OAG.

The most fundamental change in our view of OAG and IOP came from observational studies of Stephen Drance,46 epidemiologic analyses by Al Sommer5 in the Baltimore Survey. The IOP levels of those with OAG overlapped with the normal population distribution, though, on average, OAG cases had a higher mean IOP. While OAG was more common at higher IOP, it occurred nearly as often at normal IOP. Since there were so many more persons in a population with lower IOP, the prevalence of OAG at lower IOP was substantial. Thus, there was no reason to differentiate between the mythical “low-tension” and “high-tension” OAG, except artificially.

Indeed, analyses of OAG that dichotomize using the ancient “magic number” 21 mm Hg do themselves a disservice. By looking only at those with IOP lower or higher than an arbitrary criterion value, they reduce study sample size and the statistical power to assess risk. In addition, they probably miss associations that occur in the “other” half of the IOP distribution. IOP should be treated as a parameter, not a cutoff criterion, in order better to understand and study OAG. In OAG treatment, IOP-lowering is now known to work in lower and higher IOP ranges, and we individualize the therapeutic approach by establishing baseline and target pressures for each patient, as described by Henry Jampel.40

OAG has a familial occurrence,41 but persons are more likely to report a positive family history if they have been previously diagnosed. deJong (Wolfs et al.15) examined all available family members of a population-based OAG cohort, estimating 10 times greater risk for first-degree family members. I suggest that targeted projects to increase surveillance among first-degree relatives would be more highly productive than random screening. The exciting era of specific OAG genes began with the discovery of myocilin by Stone, Fingert, and Alward,42 but we must heed the lesson of other disorders in the era of specific OAG genes. The Baltimore Survey53 found greater OAG risk for African-derived than European-derived persons. Since higher OAG prevalence is also true of African-derived persons in Tanzania54 and Barbados,55 this risk crosses large differences in culture, economy, diet, and health delivery among these populations. Yet, no genes have been identified among African-derived persons—an area demanding investigation. We must be cautious about ascribing a disease association to gene effects when the result may be socioculturally derived. Even the designations of ethnicity (“race”) are challengeable on scientific grounds. Ethnic differences in risk may be partly explained by lack of access to care, differential response to therapy, cultural attitudes that inhibit compliance, and the many consequences of lower economic status. Compared to European-derived persons, OAG prevalence is higher in U.S. Hispanics,40 and in
Indians, but is similar in prevalence among Chinese. Paul Foster and coworkers report that tonometric IOP in Asians may read differently from Europeans. Whether this is a tonometric artifact or an important pathophysiological difference in ocular biomechanics remains to be investigated.

**CLINICAL OAG DAMAGE**

**Optic Disc**

The most fundamental difference between OAG and other optic neuropathies is the physical excavation of the disc. Douglas Anderson and Anita Hendrickson demonstrated that acute IOP elevation in monkeys produces axonal transport obstruction at the nerve head, and I had the joy of working for 2 years in Doug’s laboratory, detailing how this block was localized to the portion of the nerve head at the level of the sclera, reversed after short IOP elevations, and correlated with RGC death after chronic blockade.

In human OAG eyes, clinical-pathologic correlation shows that the connective tissue of the lamina cribrosa stretches backward, collapses its successive plates, and rotates outward on its scleral insertion to give the typical excavated appearance. This does not happen in ischemic optic neuropathy, in which RGC death follows a similar distribution, nor in primary atrophy after optic nerve transection. The connective tissue alteration underlying excavation can be produced in monkey eyes that have high IOP, as demonstrated by John Morrison or in human OAG, whether IOP is high or not, implying that biomechanical effects on nerve head tissue underlie the clinical uniqueness of OAG and its pathophysiology.

The fact that excavation occurs in eyes with OAG at normal IOP suggests that their lamina cribrosa stretches under forces that do not distort normal nerve heads and that require higher IOPs to produce in many eyes. Hence, abnormal connective tissue response is a likely factor in those with OAG at normal IOP. Connective tissue structural genes would be good candidates for study in persons with OAG at lower IOP.

The regional architecture of normal nerve heads explains, in part, why RGCs whose axons pass through the upper and lower disc die first in OAG. The connective tissue in the nerve head polar regions is quantitatively thinner, providing less resistance to deformation and contributing to RGC death in an hourglass pattern. This is the only known feature of ocular anatomy or physiology that corresponds to the OAG pattern of optic neuropathy. It is important to see whether new methods of blood flow measurement in regions of the nerve head can detect regional differences prospectively linked either to connective tissue movement or axon loss. Point-in-time studies will never solve etiologic issues in OAG, as we know that blood vessels and flow decrease simply as an effect of RGC loss.

**Nerve Fiber Layer**

Hoyt et al. recognized that nerve fiber layer (NFL) atrophy in OAG was visible ophthalmoscopically in green light. Neil Miller (Sommer et al.) brought the method to Wilmer, where Al Sommer (Quigley et al.) led our efforts to show that detectable NFL damage predicted future OAG visual field loss. With disc rim change and disc hemorrhage, NFL examination remains one of the few prospectively documented predictors of functional OAG damage. Through clinical-pathologic comparisons in human OAG eyes and monkeys, NFL thickness was shown to be useful in detecting and monitoring OAG damage, especially when implemented in laser imaging devices. The digital imagers may soon show prospective predictive power. Part of our difficulty in implementing new technology is the tendency to force machines to duplicate what humans do best. Disc imaging devices can be forced to yield a cup-disc ratio, but they detect and follow damage much better by use of parameters like cup shape measure, neural network analysis, and average change in superpixel zone topography. What the human eye does well should be complemented by what machines can uniquely do better.

**Visual Field**

We strengthened the concept that structural alteration in the disc and NFL precedes functional abnormality by showing in human OAG eyes that a substantial minority of RGCs die before manual or automated perimetric defect. This does not necessarily be used as evidence that all OAG suspects should be treated, rather it may stimulate the search for more sensitive and reliable signs of early injury. In early or moderate damage, we found that OAG causes selectively greater loss of larger-diameter RGCs with larger axon diameters projecting to the magnocellular lateral geniculate body. The anatomic facts supporting this finding have been confirmed in other laboratories in rats, cats, and monkeys with experimental glaucoma, as well as in human OAG. If we accept that there is selective death of larger RGCs, its pathophysiological basis deserves further investigation.

As stated by Robert Shaffer, OAG patients don’t care what their eye pressure is, they care if they can see. It has been of great interest to us to test how visual field damage (the ophthalmologist’s view of OAG injury) affects persons with the disease. Quality-of-life questionnaires describe how persons report the effects of OAG on their functionality. Alternatively, one can test the actual tasks such as reading, face recognition, mobility, and automobile driving. We know little about whether it is functionally better to have one normal eye and one severely damaged eye, or, to have two moderately damaged eyes. More studies are needed on the functional effects of OAG.

**THE MICROCOSM**

**Who Dies in OAG Damage?**

It was formerly common to see debates pitting simplistic “mechanical” or “vascular” theories of OAG against one another. With present sophistication, we realize that many factors can be contributory and that both biomechanics and vascular nutrition are contributing issues in damage. But, newer, basic knowledge of neuronal death processes has touched OAG research. While a study of secondary glaucoma offered evidence for photoreceptor loss, we found that photoreceptors and other retinal layers are generally intact in primary human OAG and only RGCs die. What do we know about RGC death and what is the next step in research?

**How Do RGCs Die?**

Clearly, one site of injury is the RGC axon at the level of the nerve head where orthograde and retrograde axonal transport are blocked. In 1994, we found that apoptotic RGC death occurs in experimental monkey and human OAG, as well as in other optic neuropathies (a line of research suggested by Robert Nickells [Quigley et al.] and Don Zack [Kerrigan et al.]). While many disorders have been reported to be somehow associated with apoptosis, in OAG a logical theory that links known events and apoptotic cell death suggested itself. RGCs receive protein signals (neurotrophins) from target neurons in the brain that support their survival. In embryologic life, RGCs that grow an axon to the proper target receive brain-derived neurotrophic factor (BDNF) and live, while mistargeted RGCs die by turning on their apoptotic, pro-
grammed death genetic sequence. This parsimonious system prunes two of three early RGCs that would represent excess retinal baggage.

**Gene Therapy for RGCs**

If BDNF dependence continues during adult life, the blockade of axonal transport in OAG would cut off the supply coming from the brain, possibly reactivating the cell death program. In this scenario, pathology recapitulates ontogeny. Mary Ellen Pease, who has headed our laboratory efforts so capably, showed that BDNF is blocked from entry into the eye by experimental glaucoma (Quigley et al.95), as is the transport molecule on which it travels.34 To prove this theory directly, Hani Levkovitch-Verbin97 generated a reproducible model of IOP elevation in the rat, to allow large-scale, therapeutic studies. Keith Martin96 produced an adeno-associated viral vector that expressed the human BDNF gene in the inner retina. Replacement of BDNF in the rat glaucoma model salvaged nearly 40% of RGC that would otherwise have died.

The hypothesis that neurotrophin withdrawal leads to RGC death suggests that cell death follows by pathways of intracellular alteration that have been delineated in other cell types. Stuart McKinnon97 found that cysteine proteases were activated in the rat glaucoma model. This pathway leads to cell death by digestion of nuclear DNA. This idea led to another successful gene therapy experiment that preserved RGC in rat glaucoma by blocking the activation of caspase enzymes.98

**Upstream Inhibition of Injury**

While these experiments suggest new therapeutic avenues for OAG, we should be asking how the earliest injury to RGC might be avoided. If we wait until RGCs are in extremis, it is more difficult to avoid ultimate neuronal death than if we stopped the process “upstream.” Since change in lamina cribrosa connective tissues is the keystone of clinical glaucoma detection and since regional laminar architecture is the explanation of typical field loss pattern, we infer that change in connective tissue is important in OAG injury. The lamina is heavily invested with elastin that helps it stand up to 85 years of ocular pulsation without irreversible stretching. In the OAG nerve head studies, the number of elastin molecules is unchanged (as reported by Erica Quigley), but their appearance suggests that they are disconnected from the remainder of the extracellular matrix.99–102 Burgoyne102 found a loss of elastic compliance of the nerve head in acute and chronic IOP elevation experiments in monkeys. The elastin gene or those of associated extracellular fibrils would be fine choices as candidate OAG genes.

How do RGC axons sense that their environment has changed, leading to blocked axonal transport? There are pressure-sensitive channels in axonal membranes that may respond to deformation caused by lamina cribrosa strain. These TRAAK channels are linked to intracellular actin and microtubular networks. External compression and/or disturbed energy metabolism could block transport by affecting key motor proteins, kinesin in the direction toward the brain (orthograde for RGCs) and dynein for transport toward the RGCs (retrograde). We have found that experimental glaucoma alters dynein, perhaps affecting neurotrophin transport toward the cell body along tubulin tracks using ATP power. Protection of this transport system may represent an important new therapeutic direction for OAG.

Dynein-mediated transport runs on ATP energy, and so poor autoregulation of nutritional blood flow may participate in ultimate RGC death at this site. In our studies of nerve head blood flow in chronic monkey glaucoma, axons died without any detectable decrease in flow or loss of capillary structure.104–107 This shows that RGCs can be injured in normal monkeys without altering blood vessels or flow (i.e., other factors are sufficient). The monkey experiments do not negate the high likelihood that poor autoregulation of flow may be a contributing feature of OAG damage in some elderly humans.

**Other Factors Implicated in Damage to RGCs**

A variety of other mechanisms have been implicated in OAG damage. How some of these relate to other risk factors for glaucoma is, as yet, unclear. For example, glutamate neurotoxicity has been proposed as a mechanism in OAG injury. We detected disequilibrium responses in the number of glutamate transporters in experimental glaucoma,108 others report possible therapeutic success in blocking glutamate excitotoxicity experimentally,109 and human clinical trials are now ongoing. But, it is unclear why excess glutamate would be present to injure RGCs in OAG. Perhaps it results from the same neurotrophin signal failure and is a midlevel step in damage. If it results from already ongoing damage or death of RGCs, then it would be a secondary degeneration event. It may be more useful to augment glutamate transport (sequestration) than to block its receptors.

Oxidative free radicals are implicated in many neuronal disorders, and there are several reports of possible involvement in OAG. Typically, oxidative damage occurs in the penumbra of major vascular injury as a secondary feature. Recent study of gene expression patterns with microarray analysis by Ron Farkas et al.110 have shown that experimental glaucoma and human OAG are associated with increased expression of iron-regulating genes that are intended to block free radical damage. Again, this mechanism may play a role in secondary damage, but how it becomes activated by the early events of OAG is unknown at this time.

The 2002 Friedenwald awardee Michal Schwartz111 suggested that immune-mediated phenomena may play a role in causing or preventing optic nerve damage. The beneficial effects of Copaxone immune therapy show promise, but it also may block only secondary damage events. To study secondary degeneration in isolation, we devised a model of partial transection of the optic nerve.112,113 Primary injury to upper retinal RGCs is caused by transection, while injury in the inferior retina occurs only if secondary excitotoxic or immune-mediated events are the basis for RGC death. We hope to use this model to dissect in greater detail the events of primary compared to secondary RGC injury.

**Acknowledgments**

The names of many colleagues, teachers, and friends have appeared here to highlight who truly did the work involved. Two of my coworkers were my children, David and Erica, others are my surrogate children, and all comprise a research family that has hopefully had fun in the objective enterprise of generating a few new facts about a complex disease that is rapidly opening its petals to our poking. Thanks to Cristina for her love and support and to ARVO for this high honor.

**References**


