SCOTOMETRY

HISTORY AND TECHNIQUE; WITH A SCOTOMETRIC TANGENT SCREEN AND SCALES*

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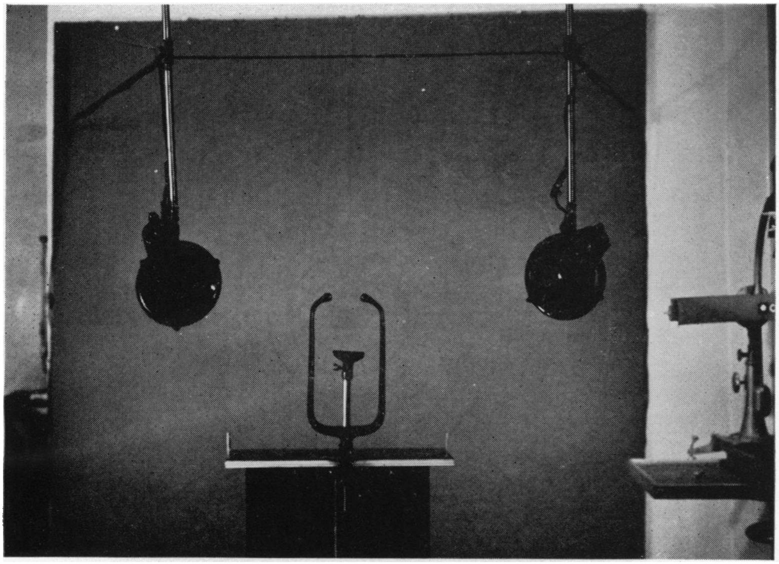
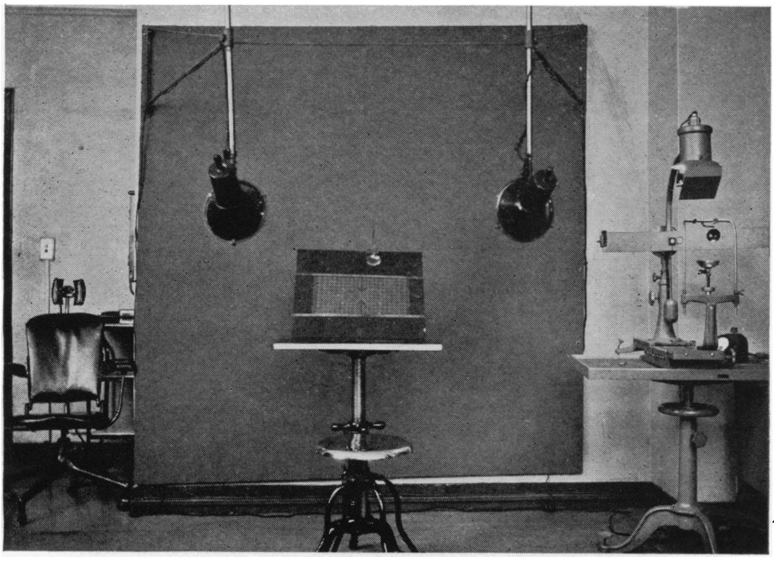
* Candidate's thesis for membership accepted by the Committee on Theses.



THE NEUTRAL GRAY SCREEN



THE SCOTOMETRIC UNIT

The upper plate shows the neutral gray screen with illumination system and head-rest in position. The lamps are just behind the patient's head so that side-shielding is unnecessary. The campimeter attached to the opposite side of the head-rest table is folded down.

The lower plate illustrates the Scotometric Unit—a Ferree-Rand perimeter, a neutral gray tangent screen, and a short range campimeter. The dark area on the screen is due to the shadow of the campimeter. The lamps in position furnish even illumination for the campimeter, which is held up at a convenient angle by brackets on the table. The working distance of the campimeter is 195 mm., and a 55 mm. orthogon lens (+5.25) is held by a brass bar which slides along the top of the campimeter, permitting centering for either eye.

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I. HISTORY

A. SCOTOMAS

The word "scotoma" brings to the mind of an ophthalmologist the concept of an island-like, usually negative, gap in the visual field. A little reflection recalls an increasing number of adjectives, nouns, and verbs applied to modify the concept. I have found over 30 such terms used to indicate variations, and the use of synonyms and eponyms augments this list. From being a purely ophthalmologic term, scotoma has come, in recent years, into adoption by the psycho-analysts, who have verbalized it and greatly extended its meanings. To discover each new variation of meaning and to trace out its evolution would require the abilities of an encyclopedist.

This thesis is concerned only with the ophthalmologic use of the word scotoma, and in the endeavor to locate the earliest records, all the later ramifications of meaning must be discarded and only the most generic sense of the word or its prototype retained. It seems indubitable that our prehistoric ancestors suffered from diseases and injuries which caused scotomas. To discover by what names the condition was then called, and how it was explained, is the object of historical research. In science, the Minerva-birth occurs but rarely. That which we now speak of so familiarly and comprehendingly was in older times a mystery under other names.

Hirschberg traces the history of ophthalmology back to 2770 B. C. or earlier. Magnus[1] quotes the earliest record of ophthalmic surgery (2250 B. C.) found in the code of Hammurabi. It concerns redress for the loss of an eye following an operation for a lacrimal fistula. Winckler,[2] whose translation from the Babylonian Magnus used, has given also other parts of the code, including the, to us, rather alarming pronouncement that a surgeon, treating the cataract of a freeman by certain means and losing the eye, shall have his hands chopped off.

It is somewhat beyond credibility to think that these ancients never suffered from hemianopsias, choroidal or retinal diseases or detachments, yet among the existing fragments of their history no recorded evidence survives. Nor does the next great ancient record, almost a thousand years later, indicate these defects. This is the Ebers Papyrus,[3] 1550 B. C. While parts of it are devoted to gynecology and ophthalmology, neither Joachim, the translator, nor Hirsch (my source) makes reference to visual field defects. Still another thousand years of recorded history must elapse before we reach our first unmistakable descriptions.

The Suśruta Samhitá attributed to Suśruta, a contemporary of Buddha (580–480 B. C.), is rejected by Hirschberg, at least the existent text, as dating from the time of King Kanishka well into the middle of the second century A. D.

Wise's Commentary of the Hindu System of Medicine,[4] which is documented far into the pre-Christian era, has whole parts devoted to ophthalmology, and gives literal translations of early cataract operations (couching), but makes no mention of field defects. It is later, and in the West, that we find the first definite record of this subject.

Hippocrates,[5] 460–380 B. C., mentions half-blindness. To his name has been attributed almost all the medical literature of the fifth and the first half of the fourth centuries B. C. To him also are attributed many writings, including the description of some 30 ocular diseases or symptoms. There are no authentic texts. But it still remains factual that here are our first recorded and preserved records of scotomas. The Hippocratic school knew of half-blindness (hemianopsia?), which occurred in brain diseases, although they left no records of measurements. The reference taken from the Second Book of Diseases, "and when he would glance at something vision fled from his eyes, and he believed he was seeing but the half of a person," is the first reference to half-blindness in scientific medical literature. And not for twenty-three hundred years was there to be the further differentiation between homonymous and crossed hemianopsia.[45] In the forty-seven centuries of ophthalmologic history this sentence stands almost at the noon mark.

The next chapter in the story is touchingly human in its complications. Some day I hope to read an adequate account of the trivia which interlocked so effectually to bar science for fifteen more centuries from one of its prizes. Plato and Hippocrates, says Galen (Graefe-Saemisch Handbuch, xii–2, p. 173), in one of his most celebrated passages, accepted the proposition that a body which is seen must either send some of its substance to us, thereby making it possible for us to recognize it, or wait until a sensory force reached it from us. The first possibility was eliminated because they had no idea of dioptrics; but not until the eleventh century was the second concept relinquished (Alhazen Thesaurus Opticae).

The ancients, therefore, believed that the true seat of sensation of light lay exclusively in the lens. A pure fluid, a pneuma, a light-principle, was conducted thereto by the optic nerve and media, and from the lens it streamed outward, falling upon objects which thereupon became visible.

In the Hippocratic collection (De locis in homine, cap 2, Littré VI, p. 279), says Hirsch,[36] the scotoma was considered to be a result of shrinkage of the tiny vessels which conduct the "purest fluid" into the pupil.

The venerable Aristotle,[6] 384–323 B. C., fathered the idea, not sufficiently robust to survive, that light was a movement—a vibration emanating from a luminous body. But his teaching was ignored until the scientific renascence. This has much to do with scotoma, for if only this hypothesis had been applied by the amazing intellects of the Hellenic era, the scientific fifteenth century might have much more nearly resembled 1931. A bare quarter-century after Aristotle Euclid was to give us our first work on optics. How completely he was misled, and yet with what amazing ingenuity he rationalized his misconceptions! Probably before Euclid the basis of optics was laid; *e. g.*, in the Actinographia of Democritus, although no part of this has survived. Herophilos,[7] 325–280 B. C., had written or was writing the first book on the eye. He coined the names for many of its parts. This work has been lost but it is known that it was more than an anatomic description. It was written near the end of the fourth century B. C., and only the name *περὶ ὀφθαλμῶν* remains. (Hirschberg, in Graefe-Saemisch Handbuch, xii–2, Ed. 2, p. 352.)

Euclid[8] was the author of the first work on optics that has reached us. Heiberg, in 1882, printed the Vienna manuscript, together with Theon's fourth century edition. Hirschberg[9] makes his own translation into German. How completely the ideas suggested by Plato and Hippocrates and enunciated by Aristotle have disappeared! The text of the fundamentals reproduced by Hirschberg[9] with his translation (German) are of such interest that I give them here. For the English translation I am indebted to Professor Kraemer, of New York University.

Ὑποκείσθω τὰς ἀπὸ τοῦ ὄμματος ὄψεις κατ' εὐθείας γραμμὰς φέρεσθαι διάστημά τι ποιούσας ἀπ' ἀλλήλων.	Wir müssen annehmen, dass die vom Auge ausgehenden Sehstrahlen fortziehen in graden Linien, die gewisse Zwischenräume zwischen sich lassen.	Assume: that the rays of sight proceed from the eye in straight lines some distance apart from each other.
Καὶ τὸ μὲν ὑπὸ τῶν ὄψεων περιεχόμενον σχῆμα εἶναι κῶνον τὴν κορυφὴν μὲν ἔχοντα πρὸς τῷ ὄμματι, τὴν δὲ βάσιν πρὸς τοῖς πέρασι τῶν ὀρωμένων.	Die von den Sehstrahlen gebildete Figur ist ein Kegel, dessen Spitze am Auge liegt, die Grundfläche aber auf den Grenzen der sichtbaren Gegenstände.	Furthermore; that the figure outlined by the rays of sight is a cone having its apex at the eye and its base at the edge of the objects viewed.
Καὶ ὀρᾶσθαι μὲν ταῦτα, πρὸς ἃ ἂν αἱ ὄψεις προσπίπτωσιν, μὴ ὀρᾶσθαι δὲ, πρὸς ἃ ἂν μὴ προσπίπτωσιν αἱ ὄψεις.	Wir sehen nur das, worauf Sehstrahlen fallen; wir sehen aber das nicht, worauf keine Sehstrahlen fallen.	Furthermore; that whatever objects have rays of sight impinge upon them are visible, whatever objects do not have rays of sight impinge upon them are invisible.

Euclid believed the outstreaming fluid from each eye had the form of a cone, the apex of which lay in the pupil and the base of which fell on the object fixed. He thought no visible object was seen instantaneously *in toto*. There were empty spaces—interstices—on which the sight rays did not fall. But he explained our belief in seeing the whole object simultaneously by stating that the "sight rays" were quickly shifted over the object, permitting the powerful central ray (axial vision) to cover quickly the entire object. This can hardly be considered a reference to scotomas or to scotomatous areas, as Euclid believed there were interstices between the emanating rays. It is, however, the earliest suggestion of differentiation between central and peripheral visual acuity. He did not specifically mention the fixation point or the size of the visual field.

In the following five centuries more knowledge was accumulated than in either of the adjoining millennia. Demosthenes[11] wrote the most complete work on ophthalmology antedating the Christian era. It has been lost,[9] but parts have been retained in the writings of Aëtius (sixth century) and Paulus Äginetes (seventh century). The Sydenham Society's translations of the works of Paulus may be found in the American Encyclopedia of Ophthalmology.[246] Ptolemy[12] gave the first measurements by instruments, that is, by experiments, of the field of vision. This is the first-known evidence of perimetry. His measurements of the angles of refraction were remarkably accurate and yet he insisted that the width of the visual field was exactly a right angle! His experiments in physiologic optics were numerous and extremely interesting, if we are to believe his commentators, and exciting deductions were made from his limited knowledge. It is difficult accurately to locate and identify his work. Heliodorus of Larissa is quoted by Arago (Astronomy I, p. 145) as crediting Ptolemy with the perimetric measurements described.[56] Foerster,[55] who is credited with the invention of the perimeter, says: "Dass schon Ptolemeus (um 150 n. Chr.) eine Art von Perimeter, mit Winkelgrad-Teilung, hergestellt und zur Messung des Gesichtsfeldes benutzt hat, wusste wohl damals kein Augenarzt, obwohl es in den von 1583 bis 1758 oefters gedrukten Ausgaben der Optik Damianos zu lesen war." Foerster locates Ptolemy at 150 A.D., as do Joseph Priestley[32] and Moeser.[56] The biographical encyclopedia notes: "Claudius Ptolemeus, flourished second century," and Anthon[256] makes that date definite, specifically differentiating from the line of 13 Egyptian Ptolemies which began with Euergetes in the third century B. C. Of this line Ptolemy I and Ptolemy III were both called Euergetes (benefactor), and some have believed that the text referred to above [12] was the work of Heron who lived under Euergetes.

Heliodor of Larissa[13] stated more exactly the suggestions of Euclid; that is, he definitely gave the visual conic base a circular form, and was the first specifically to differentiate between central and peripheral visual acuity (Magnus[10]). This statement has been made by others besides Magnus, although I have had access to nothing earlier than Gale's Opuscula . . . etc., 1671,[257] which contains the Heliodori Larissae Opticae in Greek with a parallel Latin translation. The Greek is in execrable logographic type; the significant Latin passages read: "Visum itaque figura coni esse, his rationibus confirmari potest. Conus autem est rectangulus specie definitus: species enim est infima, ut est rectus angulus. Qui vero obtusis sunt angulis, aut acutis, incerti sunt, nec finiti specie: quoniam tales anguli augeri, minui, specie denique innumerabiles esse possunt. . ." Others credit Damian with this differentiation but the uncertainty of dates leaves a question.

Hirschberg[9, 93] describes Heliodor as a famous surgeon of Rome under Trajan (Juvenal, Sat., VI, 369), and credits him with the authorship of a large volume, Χειρουργὸς μέγας, from which Oribasius has rescued a part (Graefe-Saemisch Handbuch, xii–2, p. 353). Trajan lived from 52 or 53 to 117 A. D., and was emperor from 98 to 117 A. D. Hirschberg places Ptolemy at 150 A. D., and Damian as a son (freed slave?) of Heliodor or possibly a contemporary of Proklos, 450 A. D. Shastid[153] dates the time of Damian as 5th century. Priestley[32] gives the time of Heliodor only as posterior to Tiberius (42 B. C.–37 A. D.), whom he mentions. In any case the misconceptions of all held much in common and their rationalizations were equally erroneous. Heliodor, for example (Liber I, Cap. 1, 2, 3, 13), concludes—"Vision is performed by the emission of light from the eye—in which respect it resembles the sun. The assertions are sufficiently evident from the very form of the eye, which, being protuberant, is by no means formed for the reception of anything, and from the consideration of some animals being able to see in the dark."[32]

Of the works of Damian,[14] there is the translation by Richard Schoene which Hirschberg so much admired. Damian followed Ptolemy, and with exceptionally rigid mathematics (although at times including the errors of his inheritance from Euclid and Archimedes) demonstrated the visual field as a right-angled cone and the visual acuity as standing in inverse proportion to the eccentricity of the conic axis.

Ptolemy, Heliodor, Damian—whatever their actual time relations may have been, their scientific exactitude of statement was in an ascending order.

At the close of the Hellenic era comes Galen,[15] 131–179 A. D. The part of his system dealing with the anatomy of the eye has been lost, but most of the present uncredited references are taken from Hirschberg's authoritative translation of parts of the 83 genuine texts he examined. Baas[109] credits Galen with recording many field defects as well as scotomas, peripheral shrinking, and hemianopsia. Contrasted with the Hippocratic explanation of scotomas (*v. s.*), Galen[36] attributed them to small bodies floating in the aqueous (De symptomatum causis. Lib. I, Cap. II, ed. Kuehn, vii, p. 96). This controversy was to last fifteen centuries, and to be reflected in the analogous viewpoints of Thomas Willis,[232] 1667, and Waldschmidt,[84] 1695. Galen assembled a large group of the most varied field defects; he knew of the central scotomas[85] because he noted specifically that in certain cases the patient saw as through holes (durchloechert—Magnus[10]). Peripheral contraction of the field was known to him and also hemianopic defects.

This seems, and is, a great body of knowledge for those times, and it becomes difficult not to augment it by conclusions which seem so inevitable to us. But in spite of their exciting appearance these observations are not accompanied by any suggestion of clinical application in a diagnostic or prognostic sense. Desire would aid us to believe that the ancients knew the value of these classic observations, but it is a practical certainty that they did not. And the certainty comes from the knowledge of their basic misconceptions. Accepting as they did what might be called the tactile theory of sight, which they probably acquired by their favorite process of analogy (touch, taste, hearing; and from nature study—the antennae of insects, etc.), they were, in the modern psycho-analytic sense, scotomatized in the direction of the truth.

So they believed that as the pneuma streamed from the lens in the visual conic form any interference must of necessity be in or anterior to that body. The aqueous supplied such a possibility. Thickening of the aqueous in the form of a cataractous membrane constricted the cone—if the thickening was peripheral—and hence caused contraction of the visual field. If such a thickening occurred in the center of the pupil, the periphery remaining clear, the powerful central rays were obliterated and what was directly gazed at disappeared (central scotoma). Muscae volitantes were observed and placed (erroneously) in the aqueous, thus interfering with the outflowing pneuma (Hirsch[36]).

"And so it is quite comprehensible that we frequently meet in ancient ophthalmopathology the finest and most superior clinical observations combined with the most fantastic and complicated explanations."[10]

Following Galen is a thousand year hiatus. Physicists and astronomers made the succeeding observations and studies, and, because they were using spherical projections, they concerned themselves less with the size of images than with angular measurements. Arago gives Venturi's findings of the visual field as horizontal 135°, vertical 112°.[109]

Arabian medicine, heavily indebted to the Greek, amplified its inheritance and once more the truth or the partial truth was offered, only to be rejected. Ibn Al-Haiṯam (965–1038 A. D.) vehemently denied the doctrine of outstreaming rays. His viewpoint was, in a modified way, expressed as his own by Roger Bacon (1214–1294), who was familiar with Ibn Al-Haiṯam's writings. Hirschberg seems to believe that both Bacon and Vitello simply copied Ibn Al-Haiṯam. In any case the latter's teachings in this field seem to have been ignored by his contemporaries. Benevenuto Grapheus,[16] twelfth century, gave in his Practica Oculorum names to many of the ocular conditions, mixing Provençal, old French, and old Italian with Latin and Arabic. The names frequently reveal the existence of the misconception we are tracing.

In 1363, the date of Guy von Chauliac's Chirurgia Magna,[17] the ancient error still survived, for here amaurosis or blindness with a clear pupil is called "Gutta Serena." "In cataract one sees a spot in the pupil but in Gutta Serena none is seen—for this reason it is called Gutta Serena. Because of blockage of the optic nerve the seeing force (pneuma) is prevented from getting out." This conception of amaurosis apparently was not original with von Chauliac.

Two hundred years later Fr. Maurolycus[18] at last dethroned the lens as the seat of vision but could not accept the retina, as he was unable to believe the world was seen upside down. Porta (1583), who frequently is credited with having invented the camera obscura, had compared the eye with that instrument, but he supposed that the image was formed on the crystalline lens. Venturi's[251] translation of Leonardo da Vinci contains a pertinent paragraph: "The following experiment shows how objects send their images to intersect on the albiginous humor inside the eye. When the images of illuminated objects enter into a very dark chamber by a small, round aperture, if you receive these images in the interior of the room on a piece of white paper placed at some distance from the aperture, you will notice on the paper all the objects in their proper forms and colors; they will be lessened in size and be reversed, and that in virtue of their intersection already noted." As Leonardo died in 1519, the important parts of Porta's concepts in this direction had been known for at least seventy years.

Finally, in 1604, Johannes Kepler[19] for the first known time expressed the exact statement of the physical act of seeing. Scheiner[20] soon thereafter is said to have proved the retinal imagery in the case of animals by cutting out a scleral window and viewing the image projected on the retina, and in 1625 is said[231] to have performed this experiment on a human eye. Hirschberg (Graefe-Saemisch Handbuch, xiii, p. 309) doubts this but declares Descartes perfected the experiment and published it in his dioptrica in 1636. "With the exception of a few amateurish and wholly impossible propositions that have been put forth in opposition to it, Kepler's theory has received practically universal acceptance from the first. For example, N. Th. Muehlbach and Campbell denied the existence of the retinal image, and Lehot advanced the idea that a three dimensional image is formed within the vitreous humor. Plagge worked on the theory that the eye is a mirror and that the image used in vision is the reflection in the cornea. J. Reade concurred in this opinion and attributed vision to the presence of nerves in the cornea. Mayer opposed Plagge's view, but advanced an equally remarkable one of his own, namely, that the retina acts as a concave mirror. Likewise Andrew Horn imagined the vitreous humor to be the reflector and the resulting image to act upon the optic nerve."[231] Mariotte believed the choroid to be the seat of vision since it was absent from his blind spot.

With one or two exceptions all these explanations and the preceding ones could only retard scotometry, because accurate delineation on their basis was impossible and every real attempt at accurate measurement must have been sadly discouraging. Kepler's great contribution, however, corrected the ancient misconception that had retarded progress for twenty centuries since Aristotle's aborted teachings, and the stage was set for the great rebirth. It was natural—inevitable—that this powerful concept should stimulate the curious to closer observation and lend direction to their deductions; natural, too, that scotomas now should be properly recognized, and that the epochal discovery of the great normal one should soon take place. And, further, natural that this discovery should have aroused the interest and contention that it did and that scotometry as a scientific procedure should be established. Kepler's statement was a solid cornerstone upon which, for the first time, a structure of truth might be built.

To me one of the most interesting chapters in ophthalmologic history is Mariotte's announcement and the subsequent contention regarding the blind spot. It definitely dates the origin of scientific scotometry. The observations of Hippocrates, Euclid, Heliodor, Ptolemy, Damian, and Galen, while certainly indicating measurements of scotomas, were gross statements. But beginning with Mariotte differences as fine as those occasioned by vessel shadows were measured and plotted.[25]

Hirschberg (Graefe-Saemisch Handbuch, xiii, p. 311) states that Mariotte published his discovery of the blind spot in the Mémoires de l'Académie, 1666, and gives the same date in his Zeit Tafel. I have tried to verify this but have failed. Morton[203] gives it as 1616. Ovio[134] gives it as 1868—obviously a misprint, but, astonishingly enough, proceeds to date Mariotte's letter "Dijon, 1868"[134, p. 4] and repeats, in his bibliography, this error. These *lapsus calami* are familiar. Did Morton hang his date on the Shakespeare peg and was Ovio overcome by the bulk of 19th century literature he was reviewing? A score of other writers give the date 1668, but their reference is almost universally the Philosophical Transactions of that year. This citation[21] is an excerpt from the Mariotte-Pecquet correspondence and is titled "A New Discovery Touching Vision." "This is the TITLE of two or three printed sheets of paper, lately sent from PARIS to the PUBLISHER, by the no less obliging than ingenious Monsieur JUSTEL; in which are contained both an Epistle of the Discoverer Monsieur L'ABBÉ MARIOTTE, of DYONS,* to Monsieur PECQUET, and the Answer to it. Of both of which we cannot omit to give the Reader the substance in ENGLISH, as follows," and there follows a translation of part of Mariotte's letter to Pecquet and part of Pecquet's response. Neither letter is complete or dated.

The Histoire de l'Académie Royale des Sciences[233] is catalogued under both Mémoires and Histoire. Tome I of the Histoire (depuis son établissement en 1666 jusqu'à 1686) was published in 1733, and was made from the records of the Society and in part from the Latin History of M. DuHamel.[242] M. De Fontanelle, permanent secretary of the Academy, supervised this history from the origin of the Académie in 1666 until the latter part of 1679. A careful review of the first hundred pages of this volume discloses no reference to Mariotte, but on page 102, under the date of 1669, and the title, "Sur l'organe de la vision," we find: "Monsieur Mariotte avoit fait sur la Vûë une découverte très-étonnante par elle-même, et qu'il étoit encore plus étonnante que personne n'eût faite jusque-là—," which is the first mention of Mariotte's discovery in this history. Later, on page 103, the only reference to dates is made—"Rien n'avoit plus l'air d'une Demonstration Physique: cependant MM. Pecquet et Perrault ne s'y rendirent pas. Leurs objections à M.

* Dyons—so it stands. The letter in all the printings I have seen is dated "à Dijon ce—1668."

Mariotte, et ses réponses ont été imprimées en 1676 avec plusieurs autres ouvrages d'Académiciens. Il faut voir cette dispute dans toute son étenduë, pour la voir dans tout sa beauté." Tome II continues the "Histoire de la même Académie depuis 1686 jusqu'à son renouvellement en 1699," and, for the first time, in Tome III, do we find "*Memoires* pour servir à l'Histoire—etc." The earliest definite date I have been able to uncover regarding Mariotte's discovery occurs in the curious little Journal des Sçavans.[22, 243] This contains the "Lettre de • M. Pecquet sur la nouvelle découverte touchant la Veuë," and is definitely dated Lundi, 17 Septembre, 1668. It is, apparently, an abstract of the second of Hirschberg's references. It reminds one vividly of the continual contentious correspondence that is carried on in our Science weekly.

The complete "Works of Mariotte,"[23] published (à Leide) in 1717, contains copies of the correspondence between Mariotte, Pecquet, and Perrault. Only the first letter, from Mariotte to Pecquet (this is the one partially translated and published in the Philosophical Transactions),[21] is dated. The letter concludes "à Dijon, ce ——— 1668." It refers to "other reasons deducted in a paper" read previously. The letters of Perrault and Mariotte[24] are undated, and Perrault's arguments, abstracted in the Philosophical Transactions,[25] have no date. The Acta Eruditorum[26] reviews the situation and the arguments but does not give the year in which they occurred. The Maitres de la Pensée Scientifique[27] dates the announcement as 1666, but includes only Mariotte's first letter to Pecquet (dated à Dijon, ce ——— 1668). It was published in 1923. Briggs[28] supported Pecquet in his attack on Mariotte's conception of the choroid as the seat of vision. His work was not available to me, and Gradle gives it no date. Mariotte states in his first letter: "This discovery I communicated to my friends—You have made it yourself in his Majesty's library where I showed it to those of your illustrious assembly." This may well have been in the latter half of 1666—the Academy began its séances in June of that year, but the Histoire is curiously silent concerning Mariotte until 1669. That a previous communication had been made is certain from Pecquet's first letter but I have not been able to locate the date. Much space in the Histoire is devoted to the enthusiastic account of the dissection of a fish and a lion by the members of the Academy and possibly Mariotte's demonstration was not deemed sufficiently important to report. It is also possible that Hirschberg was mistaken in regard to the date or that he was misprinted (his reference to the Philosophical Transactions contains such a typographic error—658 for 668).

Mariotte's announcement inevitably stimulated interest in and search for other scotomas. The papilla optici nervi is not the only normally scotomatous area of the retina, but the pathologic scotomas were so much more prominent that they received attention secondary only to blind-spot studies. The great disadvantage of those times lay in the absence of a visual check—except in rare instances—upon the subjective findings. This difficulty was to persist until 1850, when Helmholtz presented his ophthalmoscope.

Pitcairn[230] reported one of the earliest scientific studies of scotoma and scotometry. From his investigations he concluded that the laws of refraction were incompatible with the theory that scotomas were caused by opacities in the media and that the cause, therefore, must lie in the retina itself. Boerhaave[29] is credited with having given the first description of scotomas in which they were referred to as retinal defects (1708).

St. Yves believed scotomas to be due to partial detachment of the retina, which hindered light from reaching the choroid. How similar this is to the very modern viewpoint that enlargement of the blind spot in choked disc is due to peripapillary detachment of the retina! (Reese.)

From now on scotometry becomes progressively more refined and the classification of scotomas more varied. Blind-spot studies become a subject in themselves, while peripheral scotomas lead into the extensive literature of perimetry. Central scotometry develops much later, probably because of the inherent difficulties involved in accurate fixation. The shadow scotomas caused by pre-retinal opacities are treated in physiologic optics. More than passing attention to experiments and findings in their chronological order would extend this discussion beyond practical limits.

Daniel Bernouilli,[30] 1725, was one of the pioneer experimenters with the nerve-head scotoma. He made an interesting endeavor to calculate the size of the blind spot from its projection upon the floor. Using a plumb bob for a line of fixation and a coin as a test-object, he found an elliptic figure for the blind area. He determined its size, its elliptic form, its exact correspondence with the papilla, the direction of its major axis, and its position above the horizontal meridian. His dimensions, due to the lack of adequate optical data, were too large. Wittich[50] later reported that *J.* Bernouilli, with others, believed only the vessel stumps to be involved in the blind spot. This statement brought forth the historical notice of von Zehender,[51] in 1865, correcting the mistake in names and crediting Daniel Bernouilli with a refutation of the vessel-stump theory.

Le Cat[31] included an estimation of the size of the disc in his work, and erred for the same reasons as, but in the opposite direction to, Bernouilli.

Observations over the previous forty years had made it apparent that the fixed scotomas were conditioned by retinal affections but that this explanation was inadequate for the moving spots, and hence the earlier assumption was resumed; *i. e.*, that they were the result of retinal shadows cast by small bodies moving in the ocular fluids; some investigators held them to be in the vitreous, some were of the opinion they were in the aqueous, while others believed they were in the Morgagnian fluid. Richter,[234] in 1778, differentiated between fixed and moving scotomas. He believed that the first were caused either by irritation of the retina, a form of *hysteria oculi*, or by decreased or complete loss of function of single spots of the retina; and that the latter were due to opacities in any of the transparent media, but he showed that only those opacities behind the lens could cause relatively sharp shadows. This view was held by almost all of the later observers, but not without contradiction. Walther,[235] for example, believed muscae volitantes as well as amaurosis to be the result of ciliary disease or dysfunction of the retina similar to muscle cramps elsewhere in the body. Rudolphi[236] accepted this view, and declared myiodesopsia to be always the result of retinal cramp. Donné[237] was sure he had seen with a loupe moving bodies which caused scotomas, not only in the vitreous but also in the aqueous and in the Morgagnian fluid. But Brewster[238] contended that those bodies which caused scotomas were moving in the vitreous, and that the shadows cast were dark in proportion to the proximity of the bodies to the retina. His report to the Royal Society is a classic example of the uses to which an intelligent and curious man may put his own infirmities. Finally, Mackenzie[239] differentiated between myiodesopsia sensitiva (objective scotoma) and myiodesopsia insensitiva (subjective scotoma). Concurrently investigations were being extended in other directions, and one of the first important reports was that of Purkinje in 1825.[34] It is the first statement of peripheral color blindness. Thomas Young[33] gave impetus to the study of peripheral form limits; Griffin[35] years later (1838) introduced the concept of relative scotoma around the blind spot; Fick and DuBois-Reymond[40] and Volkman[41] advanced the theory of associative filling-in of this area, and the latter enunciated the law of retinal identities. Fischer[37] reported perimetric studies in 1846.

Investigations with divergent objectives and varied means of attaining them became numerous. Because these ramifications of scotometry were becoming so extended and interwoven that it is difficult to discern the course of any one thread through the pattern, it becomes simpler to trace out chronologically some of the main lines of application, development, and technique.

1. *Blind Spot*

a. *Cause.*—For a long time following Mariotte's discovery of the blind spot its explanation was in dispute. Mariotte's first and chief opponent was Pecquet. Each mixed error with truth, for if Mariotte was right in insisting the whole area of the optic nerve entrance was blind, he erred in contending that the choroid was thereby proved to be the seat of vision; whereas Pecquet, stoutly combating this error, committed the equally egregious one of insisting that only the vessel entrances were blind. The quotations from the Histoire[233] that "it is necessary to see the full extent of the argument in order to see it in all of its beauty" and that "an extract would omit a host of clever and ingenious ideas, and very fine detail, on which all of the subtlety of the argument hinged" are eminently justified. Pecquet was supported by Perrault,[24, 25] Briggs,[28] and Picard.[243] The storm raged for a time and then subsided. Bernouilli,[30] in 1725, found an elliptic figure in the visual field quite incompatible with Pecquet's explanation (von Zehender[51]), but no great comment ensued. Finally when Weber,[39] in 1852, disproved Pecquet's contention, "still alive in some quarters," the argument broke out anew. Volkman,[41] in 1853, supported Pecquet. He calculated the size of the defective area from the dimensions of the gap in the visual field and the projection distance and found this area corresponded to measurements of the retinal artery. Fick and DuBois-Reymond,[40] in the same year, disproved Pecquet and lent their support, regarding the extent of the defect, to Mariotte, Hannover, and Weber. Listing (Wagner's Handwörterbuch, 1853, iv, p. 492) supported them, as did Budge,[44] who stated definitely: "The artery alone cannot account for the blind spot. The optic nerve itself cannot see." Donders[150] disposed of the argument by flashing a light on both the nerves and the vessels. There was no response—hence more than vessels is blind. The question did not arise again until 1859, when Coccius[48] gave it the final airing. He dealt with vessel scotomas. A few years later Wittich[50] again proved the oval shape of the blind spot and its incompatibility with Pecquet's view, which no one since has seriously supported. In these polemics Bernouilli should be credited with having produced, though not stressed, the significant data regarding the form of the scotomas; Weber and Wittich should be given credit for the repetition and the emphasis of these data; and we are indebted to Donders for the physiologic proof.

The earliest exact scotometry, as indicated, concerned itself with the location and the mensuration of the blind spot.

b. *Location.*—Mariotte, in describing his discovery, locates the projected area "to one side and somewhat lower" than the exact center of the eye. Listing[38] found it 12° 37′ 5″ from the fovea, and Weber, 12° 30′ from the axis. Dobrowolsky[59] and Landolt[60] give it as 3.915 mm. from the macula. Discussing Dobrowolsky's report Knapp characterized it as "unthinkable," and questioned the method used in the determinations. Recent and probably more accurate data are those of van der Hoeve,[149] who gives the distance of the center of the blind spot from the fixed point as 15° 33′ 47″ in a horizontal direction and 1° 40′ 41″ below the point of fixation. Peter[164] locates it 15° 33′ 47″ from, and 1° 40′ 41″ below, the fixation point. Gradle[170] finds its center 16° 33′ 32″ from the macula, and Bissell[176] gives from 13° to 15° for the same measurement. Axenfeld[186] states that the normal blind spot is 12° to 18° temporal; Fuchs[244] places it 15° to 16°

temporal; and Berens[198] calculates it to be 15° 20′ 41″ from the fixed point. Finally Traquair[217] locates it 15° 27′ 36″ from the fixation point and (approximately) 1° 24′ below the horizontal.

c. *Dimensions.*—Mariotte, we may infer from his contentions, made fairly accurate measurements but we do not have the data. In addition, the lack of knowledge of dioptrics in this time precluded exact translations into trigonometric terms. We may roughly convert the measurements taken from his letters into angular terms and arrive at the horizontal diameter as at least 3° 35′. This corresponds to 8 inches at 10 feet and this figure receives historical confirmation in the report that Mariotte's demonstration before the English court of the phenomenon he discovered, resulted in a royal game whereby His Majesty was able to make the head of a member of his entourage disappear by regarding that member eccentrically at a distance of 10 feet. Five degrees at that distance would subtend a tangent of about 10 inches. Mariotte's measurements are thus seen to be smaller than the present accepted sizes, yet too large to be accounted for by the vessel theory.

Picard,[243, 21] who dramatized Mariotte's discovery, reversing the positions of fixation mark and test-object and thereby demonstrating both blind spots at once and making *three* distant spots disappear simultaneously, gives, through Pecquet, data enough only to show that part of the blind area lies at 12° 30′ from the macula. (The calculation is mine.) Griffin[35] gave the horizontal diameter of the blind spot as 7° 31′, and found it to vary within limits inversely as the intensity of the stimulus. We shall return to this qualification later (penumbra, border scotoma). Bernouilli,[30] as noted, overestimated its size, as Le Cat[31] underestimated it. Listing[38] gives the horizontal diameter as 5° 56′, and Weber, to whom he wrote, found the middle two-thirds of the nerve entirely insensitive 12° 30′ from the optic axis. Weber reports measurements of 2.09 mm. and 1.71 mm. as the diameters of the optic nerves at the entrance. These measurements were made on the eyes of a young person who had been dead twenty-four hours. Weber gives the findings of Hannover and Thompson as from 3° 39′ to 9° 47′. Fick and DuBois-Reymond, walking backward and forward, as did Mariotte, instead of moving the test-object, obtained measurements of 1.37 mm. and 1.61 mm. (5° 4′ and 6° 3′). Budge[44] found his blind-spot measurements too large to be compatible with vessel-stump scotomas. Aubert[47] gives the horizontal diameter as 5° 51′, while Wittich[50] found the horizontal diameters for the left and right eye to measure 8° and 7° 30′ respectively. Landolt's[60, 64] measurement of the diameter was 6° 45′ on the radius of the fovea; which is the only example of such a specification I have discovered. Ole Bull (Perimetrie) records the horizontal diameter as 6° 30′; Baas,[109] as 6° 12′; Helmholtz, as 6° 30′ or 1.81 mm.; Sinclair,[128] as 7 inches at 2 meters; and van der Hoeve,[149] as horizontal 5° 42′ 55″, vertical 7° 26′. The more recent dimensions are those of Gradle,[170] horizontal 4° 54′, vertical 7° 45′; Elliot,[199] horizontal 5.48°, vertical 8.15°; Berens,[198] for 3/1000 test-object, horizontal 102 mm., vertical 153 mm.; Traquair,[217] horizontal 5° 7′ 5″, vertical 7° 17′; Rutherford,[245] horizontal 5° 28′, vertical 7° 40′. With the exception of the measurements of Helmholtz and Bull no two sets of these dimensions are identical, and Elliot's minima and maxima (horizontal from 4° to 7°, vertical from 6.25° to 10.5°) are probably representative of normal variations. Fuchs[244] says the blind spot is from 5° to 6° wide and has a vertical diameter of from 7° to 8°, with a penumbra from 1/4° to 3/4° in width.

d. *Penumbra, Border Scotoma.*—It is obvious to anyone who has ever tried to measure a blind spot that its border is not as sharply defined as could be desired. Whether this is due to division of attention, to decreased eccentric visual acuity, to an actual relative scotoma (penumbra) at its borders, or to a real or psychologic distortion of the image on this area, constitutes another historical discussion.

Griffin[35] first advanced the view that a relative scotoma surrounds the normal blind spot. He deduced this from his measurements which showed the diameter to vary, within limits, inversely as the intensity of the stimulus. Weber,[39] using a luminous test-object, verified the existence of this penumbra. Johansson,[81] however, ascribed to the border zone only a relative scotoma for color. Bjerrum[89] supported Griffin, and was in turn supported by Groenouw[100] and Meisling.[120] Johansson's statements were sustained by Ovio,[134] by Polimanti,[147] and by Haycraft[146] who charted the relative limits for the various colors. Sinclair[128] described an amblyopic zone near the upper and the lower poles due to vessels. More recently van der Hoeve[149] made the statement accepted by Fuchs[244] that the blind spot is surrounded by a zone from 1/8° to 1/4° wide relatively blind for white, and by a zone from 1/8° to 3/4° wide amblyopic for colors. Peter[164] dissented from this view, and proclaimed that such a zone (he stated 1° wide) at 16.5 cm. is valuable and conclusive evidence of pathologic change. This assertion was made in 1915. In 1916 Gradle[170] reaffirmed the presence of the penumbra. Ferree and Rand[150] attribute the penumbra to three factors: divided attention, practice (or lack of it), and distortion. They do not believe retinal fatigue plays much part in its demonstration.

I believe that, with the proper technique, this zone always can be demonstrated on the normal eye. It is more easily found by the use of small test-objects rather than large ones, by a long range screen rather than a short range campimeter, by colored rather than white test-objects, and on a gray rather than a black background. To these four facilitating factors should be added an important fifth: practice.

e. *Psychologic Representation. Associative Filling-in.*—An interesting offshoot from the border studies concerned the psychology of the totally blind area. The academicians had been astonished that no one had noticed, before Mariotte, these gross vacancies in the visual world. They were satisfied to explain the phenomenon on a basis of eccentricity and overlapping fields. Fifteen decades later Volkman[41] stated that this gap is filled in by association from the background. Fick and DuBois-Reymond[40] in the same year (1853) independently published a study and advanced essentially the same opinion—that the mind fills in the gap. Czermak[42] agreed with these investigators, as did Helmholtz.[218] According to Ferree and Rand,[150] the question had assumed considerable theoretical importance when they began their study. Their report (1912) contradicts the theory of an associative filling-in and substitutes a theory of complete shrinkage with compensatory distortion (magnification) at the borders. The next year Werner[155] described the blind spot as a "nothing"—"ein psychologisches Nichts innerhalb ein Sehkontinuitaet," and in 1921 Nussbaum[193] failed to verify Ferree and Rand's results and believed he had refuted them. The problem remains open.

f. *Medullated Nerve Fibers.*—The nerve-head scotoma may be extended in various directions by different causes. One of these, first reported by von Jaeger,[43] is medullated nerve fibers. Since this report by von Jaeger, in 1855, it has been taken for granted that the presence of these fibers near the disc was projected on to the field as an enlargement of the blind spot. Much evidence that was advanced for and against this contention has been summarized by Gradle,[195] who showed that while in many cases an enlargement is produced, it frequently is not. Nor does the enlargement correspond in size, shape, or completeness with the area of medullation. Gradle's work was substantiated by Goar and Ralston.[205] Nevertheless it still remains a common practice to list medullated nerve fibers as indications for cecal scotometry.

g. *Diseases Affecting the Blind-Spot Scotoma.*—Scotometry of the papillary area had been practised almost two hundred years as an academic pursuit before it found its important place as a clinical procedure. Von Graefe opened wide the new field of applied clinical investigation, and curious minds in all parts of the world were set to work. While von Graefe outlined scotomas, absolute and relative, central, peripheral, annular, and pericecal, and noted many field changes, he did not recognize the diagnostic value of the enlargement of the blind spot which he noted in toxic amblyopia. It remained for Coccius[48] to attach the first clinical diagnostic importance to this sign. In 1859 he described an enlargement of the blind spot toward the periphery, confluent with a temporal defect in the visual field as diagnostic of glaucoma. He reported in addition secondary smaller blind areas which he believed to be pathognomonic of glaucoma. These were vessel shadows. Leber[57] is frequently given credit for this report, but his was published ten years later. About this time Foerster presented his perimeter and the popularity of this instrument diverted, for a while, attention in that direction. With the advent of the Bjerrum technique at the close of the century, the return swing of the pendulum began.

The relationship of all the disease entities to enlargement of the blind spot cannot be considered here but a brief list of the maladies in which this enlargement is to be looked for includes:

Glaucoma: Leber,[57] Coccius,[48] Sinclair,[128] Smith,[133] Bjerrum,[89] Roenne,[143] Seidel,[162] Elliot,[173] Traquair,[217] Peter,[164] Peters,[187] Morax,[194] Berens,[198] Goar and Ralston.[205]

Myopia: Bjerrum,[89] Cantonnet,[124, 132] Gradle,[163] Peter,[164] Duane,[161] Goar and Ralston.[205]

Commotio retinae: Peter.[164]

Toxic amblyopia: Von Graefe,[45] Leber,[57] Foerster,[92] Groenouw,[95] Wilbrand and Saenger,[158] Berens,[198] Goar and Ralston.[205]

Optic neuritis: Peter,[164] Berens,[198] Goar and Ralston.[205]

Medullated nerve fibers: Wilbrand,[113] Peter,[164] Gradle,[195] Goar and Ralston.[205]
Colobomata: Wilbrand,[113] Peter.[164]
Congenital conus: Wilbrand.[113]
Embolism of central artery: Wilbrand.[113]
Sympathetic ophthalmia: Ramsey and Sutherland,[131] Mosso,[144] Holth,[141] Goar and Ralston.[205]
Sinus diseases: Birch-Hirschfeld,[137] Peter,[164] Gradle,[170] Berens,[198] Goar and Ralston.[205]
Eclipse blindness: Speleers,[151] Pergens.[241]
Nephritis: Peter.[164]

2. *Central Scotomas*

These defects, because of their annoying nature, probably were the first to attract attention. We have seen how until after Kepler there could be no accurate measurement of them, and even since von Graefe's time they have challenged the technical ingenuity of investigators. They cause great discomfort for the patient and are extremely difficult to measure, because just where the subject would look or is directed to look blindness or ambylopia exists and the resultant inability to maintain fixation frustrates the scotometry.

Von Graefe[45] did outline central scotomas and by a means very similar to our latest technique. De Wecker[52] also succeeded in plotting them. Others who did so were Foerster,[92] Bjerrum,[89] Groenouw,[95] Sinclair,[128] Holth,[141, 188] Swett,[213] Peter,[214] and Otto and Hans Barkan.[229] De Schweinitz[108, 215] credits Noyes with having been the first American to call attention to the presence of central scotomas in amblyopia ex anopsia. Evans[221] found the condition present in the great majority of tropias. Jackson[110] plotted these scotomas with an extremely simple apparatus, and Ferree and Rand[183] outlined them by a more elaborate means. These citations represent only a minute percentage of the hundreds of recorded reports.

3. *Intermediate and Peripheral Scotomas*

The history and technique of intermediate and of peripheral scotometry are so intimately associated with those aspects of perimetry that they may be discussed more conveniently there. The exception of the "peripheral fatigue" factor is not inconsistent, for it forms an almost detached chapter in the history.

Foerster,[55] in 1869, by making complete transversals of the field with his test-object obtained two figures (the "in" and "out" limits). Simon[58] verified this and noted that they frequently cut each other. Later Wilbrand,[111] measuring the inner limits, found the fields gradually contracting (fatigue?). Schloesser confirmed this fact. These phenomena were not constant and the cause was not known. Anesthesia retinae was offered as one explanation and for some time the belief was held that they were the result of central nervous lesions. Whatever explanation was accepted they were generally considered to be the expression of a pathologic change, but the careful studies of Schmidt-Rimpler,[98] Siemsen,[107] and others demonstrated their occasional occurrence in perfectly normal subjects. They have since been attributed to fatigue. Peters[105] believed these phenomena, as well as the contraction of the field obtained by moving the test-object in compared with that obtained by moving the test-object out, occurred in healthy eyes. The change due to fatigue is not diagnostic of anesthesia retinae.

4. *Color Scotomas*

The pericecal penumbra for colors has been discussed. The numerous reports dealing with central scotomas, especially of the toxic type, have indicated a marked tendency, in this century, to supplement the form studies with color investigations, and it is now established that in the early stages of retinal disease, before an absolute scotoma develops, an amblyopia for colors may be demonstrated. In the intermediate and peripheral zones this condition will be manifest as island scotoma, or in some toxic cases as peripheral defects or concentric contraction. While the retina to its limits may have some degree of sensitivity to extreme colored stimuli, a differentiation of color and of form fields can regularly be made with ordinary test-objects and the difference represents the normal and relative peripheral color scotoma. Purkinje[34] is credited by Baas as having given the first report of this peripheral color blindness (1825). Leber,[57] years later, clinically applied these academic exercises, and was the first to pay exact attention to the color fields as diagnostic phenomena. Clinical application stimulated closer study, and with the advent of qualitative control "normal values" began to have some meaning. Landolt[65] at the Heidelberg Congress reported coextensive limits if sufficiently intensive stimuli were employed, and stated that "no color tests have value unless the intensity of the color as well as the general illumination and state of adaption is given." Hess[87] proved this statement. He attributed variations in the field to difference in the pigment of colors and the brightness of the background, and established support for the Hering color theory with his statement that the sensitivity of pairs of colors, red and green, and blue and yellow, falls off from the center to the periphery in constant ratio. Hegg[96] agreed with this statement, as did Baird,[127] who stated that "the results show that the zone of stable red is coincident with that of stable green and that the zone of stable yellow is coextensive with that of stable blue." These results have been flatly contradicted by Ferree and Rand[179, 180] who find, instead, a "striking absence of uniformity of ratio of sensitivity to the pairs of colors, red and green, and blue and yellow, from the center to the periphery." Hess wrote in 1889, Hegg in 1892, Baird in 1905, and Ferree and Rand in 1919. Meanwhile Landolt's statement made in 1873 has received only confirmation. Wilbrand reaffirmed in 1897 the dependence of the results of color-field examination upon the four factors: saturation and size of the test-object, illumination, and background, and every contribution since has added support to this dictum. Ferree and Rand[182] state that: "By a sufficiently wide variation in the intensity of the stimulus the fields of color sensitivity may be made to have almost any breadth within the field of vision. The conventional clinic rating of limits from widest to narrowest in the order blue, red and green, is, with the exception of green, a function of the relative intensities of the stimuli employed. With high intensities the limits of red, blue and yellow are coincident and coextensive with white." Lauber, Traquair, and Peter[223] in their report to the International Congress of Ophthalmology of 1929 formulated a set of "simplified standards" which included the recommended use of a 5/333 test-object of the Heidelberg series of papers for peripheral color investigations. It should be illuminated by at least 7 f.c. of artificial daylight. These standards, I believe, fall widely short of the ideal, especially in not including a statement of the background against which color judgments are to be made, but in justice to them it must be stated that they represent a very great advance over the inaccurate clinical scotometry generally practised at present.

That there is a normal peripheral *relative* scotoma for colors seems established. This relativity enhances the value of color scotometry, because it permits earlier determinations of fundus change before total loss of retinal functions takes place (absolute scotoma). In the intermediate and central zones the relative color amblyopias or scotomas usually precede the absolute states, so that this form of qualitative scotometry represents an invaluable and irreplaceable refinement.

5. *Other Normal Scotomas*

The papilla nervi optici is not the only normally scotomatous area of the retina. Part of the temporal and inferior retinal limits have been held to be functionless because independently of the position of the eye the nasal and superior fields cannot be made to approach in extent the normal temporal field. The peripheral retina, as has just been stated, is relatively color blind.

Midway between these normal states and the pathologic lie the scotomas of medullated nerve fibers already noted. They are usually classified as anomalous rather than pathologic.

Small vessel shadows comprise a fourth and interesting type of normal scotoma. While these shadows have received much attention recently due to the beautifully refined work of Evans[209] they are by no means recent discoveries. One of Perrault's objections to Mariotte's view that the choroid was the seat of vision was that the overlying retinal vessels would cast shadows. Whereupon Mariotte replied[25] that there *are* defects in vision caused by the blood-vessels, and he proved it by a remarkable as well as new experiment. Many of the older investigators indicated vessel-stump scotomas about the blind spot. Aubert and Foerster[46] definitely discussed these "small blind spots" in 1857, and divided them into real ones, which were constant and could be located from day to day, and those due to fatigue. They did not call them angioscotomas. They credit Heinrich Mueller with having called attention to them. Coccius[48] described separate blind spots—two in particular—which he believed to be pathognomonic of glaucoma. These were no doubt vessel shadows. Another investigator described two or four secondary blind spots which were constantly present and which he attributed to the exit openings of the venae vorticosae. (Schoen[69] believed these vessels explained annular central scotoma.) Basevi[88] referred similar small negative physiologic scotomas to the retinal vessels. Wittich,[50] in 1863, showed illustrations of vessel stumps in his blind-spot drawings. Landolt[64] said that very small physiologic scotomas were discovered by Coccius and by Aubert and Foerster. His reference occurred in Aubert's Physiologie der Netzhaut or was misprinted. I did not find it there. Sinclair[128] mapped out vessel stumps and believed the irregular amblyopic zones at the upper and the lower poles of the blind spot were due to the vessels. Haycraft[146] produced drawings of vessel stumps extending from the nerve head.

I do not believe that anyone has spent as much time or achieved as great success in mapping out these vessel shadows as has Evans.[209] His collection is unique, and is a triumph for his patience and ingenuity and the Lloyd campimeter with which he worked.

B. *Instruments*

1. *The Perimeter*

The tool is designed for the material and when that material is gross the instrument will lack refinement. The ancient concepts of the visual field were grossly in error as we have seen. In repeated efforts to control or eliminate all extraneous factors in an experiment a complexity usually is erected—and with the further knowledge derived from the experiment simplification may be attained. The perimeter is following this program. Ptolemy may have constructed and calibrated a perimeter but the refinements of quantitative and qualitative perimetry were obviously unknown to him. For various purposes a veritable horde of perimeters has been designed and only recently has the tendency to simplification been manifest. This has resulted from an increasing knowledge of the really important factors. Foerster[55] is usually credited with designing the perimeter as we know it, although this statement is misleading in several directions. As we have seen (p. 492), Foerster himself credits Ptolemy with using some sort of an instrument calibrated in degrees for measuring the visual field. Also the Foerster perimeter had as its center the blind spot, and the field was plotted from this point. Landolt[64] first used the fixation point as the center of the arc and thus created the classic method. Finally, it seems, Aubert designed the instrument which Foerster introduced.[86] I do not know the technique of Arago or Venturi. Wittich[50] several years prior to Foerster's perimeter had been using a metal quadrant of 230 mm. radius, and Houdin,[247] in 1867, constructed a portable perimeter. Carter,[61] in 1872, retained the quadrant similar to Houdin's in his "Improved Perimeter" and introduced an important modification by boring a hole through the axis, thus permitting fixation on a distant test-object. Carter says Donders first made a hole in a blackboard to look through but the patient looked into an observer's (assistant's) eye. The same year Scherk[62] presented his hemisphere perimeter, the forerunner of a whole series of this type extending down to 1929.[222] From the very beginning the perimeter's most serious drawback, namely, illumination, was appreciated, and even in his first instrument Scherk had the hemisphere bisected and hinged so that the unused portion might be swung aside. Landolt, as indicated, improved Foerster's perimeter.

Schweigger,[249] in 1872, introduced his perimeter, with which he did much of his work,[72] and, in 1888, presented his hand model.[248] Badal demonstrated a portable perimeter in 1875, which was similar to the one Houdin constructed in 1868. Fixation was through a tube in the side of which was a slit exhibiting the test-object.

In 1882 McHardy's[78] self-registering perimeter appeared and achieved great popularity. It is the prototype of another long line.

Meyer,[86] in 1887, attempted to combine the advantages of perimetry and campimetry with his machine, and another series (Hudson,[174] Ferree and Rand,[183] and Salzer[222]) was begun.

Hess[87] used a large perimeter on the arm of which was mounted a color mixer. It belongs to the purely research type, which are periodically constructed for special work. Gurfinkel's[94] apparatus appeared two years later, in 1891.

Katz[99] devised one of the early luminous object perimeters. The origin of this line I have been unable to locate, but if Katz's instrument was not the prototype, it merits attention for another striking feature—a 4 cm. hemisphere covering the eye. The test-object at 26 cm. was viewed through a slit. Groenouw[100] used the Aubert-Foerster perimeter. Azoulay,[102] in 1893, presented a pocket perimeter, consisting of an arc divided into 10 articulated segments; and Wilbrand,[113] in 1897, introduced a bed perimeter.

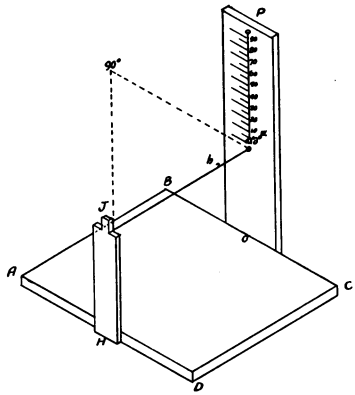


Fig. 1.—Hembold's perimeter.

In this same year (1897) Hembold[114] presented an exceedingly ingenious device designed for the use of the practitioner. It was described as simple and inexpensive, and with modifications it could be made to combine many of the advantages of both the tangent screen and the perimeter. The Hembold apparatus consisted of an upright chin-rest (*HJ*) attached to a baseboard (*A B C D*) (fig. 1). On the opposite side of the baseboard was a tall upright (*OP*). Beginning at the point above the chin-rest and directly under the eye was a string which ran horizontally across to the second upright, through a hole therein and, running upward along the back was again brought forward through a second hole near the top and held taut against the front surface by a small weight (w). At a distance of 30 cm. from the eye a small hook (h) was fastened to the string. The test-object holder gripped this hook. If, now, the test-object is moved in any part of the field of vision, the pull on the string acting through the holes will cause the weight to rise along the graduated scale indicating the exact latitude of the field under investigation.

Gagzow[116] suggested some improvements on the Hembold apparatus. Instead of drawing the string back through the second upright he passed it over a pulley and let it hang behind—out of sight of the patient and in a position where the scale could be run toward the floor thus making the machine less bulky. A groove was placed for the weighted string. Von Zehender[121] improved the perimeter still further by changing the pulley system, painting the exposed parts a matt-black, and hanging a black curtain before the second upright. He added a hinged protractor to determine accurately the meridian being investigated. I constructed one of these perimeters because it appeared to have so many of the single advantages of perimeter and tangent screen. The curtain was neutral gray, supplying the proper total background—a distinct advantage of the tangent screen. The test-object remained at the same distance from the eye and hence the visual angle it subtended remained the same—a distinct advantage of the perimeter. But the handle of the test-object was a positive nuisance—it must be rigid to control the weight suspended, and for small test-objects the necessary size of the handle became obtrusive. A second fault lay in the difficulty of maintaining an accurate control or knowledge of the meridian, and a third in making a record—this practically necessitates the services of an assistant.

Fuchs[139] had a self-illuminated perimeter made which appeared about 1907. "The product of his ingenuity is of considerable interest, as it is the obvious prototype of the large number of similar pieces of apparatus which are now to be found in different parts of the world, bearing the names of various surgeons. Probably the best of these is the De Zeng" (Elliot[199]). Walker[169,171] devised a perimeter with a wide extension arm to increase the uniformity of the field surrounding the test-object, and also the large 1000 mm.-radius umbrella perimeter to utilize the quantitative principles of perimetry which Cushing so strongly advocated. Hudson[174] also designed a long radius perimeter, which, however, was of the arc quadrant type. The radius was one meter. In 1920 Ferree and Rand[183] presented the forerunner of their present instrument, and the same year Holth[188] introduced his "chord perimeter."

This includes practically all the "types" of instruments, although discussion of individual models could be extended indefinitely. Examples of some which have achieved significant popularity are: Aubaret's, Bordeaux's, Spiller's, Galezowski's, and Dana's (all portable), Black's (electric), De Lapersonne's (mechanical), Loew's, Priestley Smith's, Skeel's, Magnus', Albertotti's, Mayerhausen's, Emerson's, and Schiötz' (all self-registering—Schiötz had two models, one in 1885 and one in 1915), Skeel's and von Michel's (electric), Hare's (automatic), Lister's (self-registering with illuminating system), Elliot's and Mackay's (long radius), Bardsley's (spherical section), Ozoulay's, Azoulay's, and Bagot's (pocket perimeters), and Willet's and Schoenberg's (prismatic perimeters). An entirely different type of perimeter which does not concern us here is the Reitsch objective perimeter used for localizing foreign bodies.

The significant trends in the historical development of the perimeter have been: (1) toward conservation of time and labor—this resulted in the great number of "self-registering" perimeters and was probably overdone, in the end defeating its own purposes; (2) control of extraneous factors—this has resulted in the modern, gray instruments with increasingly standardized test-objects, background, and illumination; and (3) the application of quantitative and qualitative principles of technique. The former has been stressed by Cushing in this country; the latter by Ferree and Rand.

Whether or not Traquair's statement,[217] that "the elaborate refinements of the Ferree-Rand instrument have not yet proved to be of value in clinical work, while their utilization involves the serious disadvantage of prolonging the time for the examination," will prove to be justified by continued experience remains to be seen. I do not believe it will, for I am convinced the finer qualitative changes elicited only by more refined methods are destined to become increasingly important in the early diagnosis (and hence treatment and prognosis) of scotomas and their causes. It represents, however, an attitude not infrequently encountered since the appearance of this instrument. On the other hand, prior to these "elaborate refinements" there was a rather widespread pessimism regarding the value of existent perimeters. Peter[172] had said in 1917: "To the writer the arc perimeter in its present form is an obsolete instrument. To those who have given thought and study to perimetry *and who have actually spent much time in its practice*, this will stand as a concise summary of the relative merits of tangent and arc perimeters." Gradle[197] wrote in a similar vein in 1922: "The arc perimeter is no longer regarded as an instrument of great precision by the ophthalmologist who desires accurate knowledge of the visual fields. The knell of this instrument was sounded with publication of Bjerrum's tangent screen perimeter and its grave was deepened by Peter's campimeter so that today the perimeter, that formerly was in daily usage by the scientific ophthalmologist, is accumulating dust together with the many other instruments that have been replaced by newer methods of greater accuracy."

2. *Campimeters*

A campimeter is, strictly speaking, a tangent plane used for measuring the field, and as the latter extends to the temporal side beyond 90° the former, literally, cannot exist without some optical means of compensating for the fact that tan $90° = \infty$. Usage has liberalized the definition to include any plane surface used for testing indirect vision, and in the same manner the various "tangent" planes, screens, and curtains have come to indicate the long-range instruments, while "campimeter," unqualified, indicates a working distance less than the conventional perimeter radius (30 cm.).

Mariotte and his followers used the long-range method, and this was the rule with experimenters up to the time of von Graefe. The versatility of this master was manifested in his instruments—he used anything at hand for his demonstrations, a blackboard, a piece of paper, a table-top. De Wecker[52] began the long list of "specified" instruments. His campimeter was a black-covered surface one meter square (later hexagonal). It gave the field out to 70°. An ingenious method for plotting was described (*v. i.* Test-Objects, Sect. II, part B).

Aubert[47] introduced studied variety and control. His paper is a model of the scientific spirit. Donders[49] attached a blue paper to the wall and made his records directly.[69] Mauthner,[74] twenty years later, was using the same means with a black paper. Jeffries,[53] in 1868, utilized a 3′ by 4′ blackboard. This method continues to be popular. In the same year Heymann[54] presented the first of the many mechanical instruments. This consisted of two attached plates, the rear one having a radial slit one mm. wide and the other a spiral row of openings. He was thus able to take rotary fields at any tangent. Six years later Schroeter[68] added to this a third plate bearing different colors. Schenkl[67] is credited with a campimeter similar to De Wecker's. I have not been able to verify this. Schweigger[72] supplemented his perimetric work with campimetry at 10 inches.

Gazepy,[80] in 1884, produced the first portable campimeter. This consisted of a fixation-object and a test-object connected by a ribbon on a spring roller and was not, in our sense, a campimeter at all. A somewhat similar pocket campimeter was designed by Aubaret.[91] Mello's[82] campimeter appeared in 1885, and two years later the line of combination perimeter-campimeters began with the instrument designed by Meyer (see p. 517). Piton's[97] campimeter belongs to the group utilizing protractors for measuring the angles of projections.

In 1904 Haitz,[125, 126] following the Hirschberger-Schloesser technique, produced his stereoscopic charts for campimetry. They were improved upon by Bissell,[176] and led to the excellent stereocampimeter of Lloyd[175, 191, 211] and the phoroptometer adaptations of Wells.[177] Priestley Smith gave real impetus to scotometry with his rotary campimeter,[133] the forerunner of Elliot's scotometer.[173]

In 1910 Ferree[145] devised a rotary campimeter, in an endeavor to add to the vertical campimeter the rotary features of the perimeter. It was the subject of criticism by Seashore,[157] and in the discussion which ensued Ferree[154] has admirably stated the case for the campimeter. Five years later Peter[166] produced his hand campimeter, which has received enthusiastic approval and has been extensively used. In response to a request from the American Ophthalmological Society to work out a better standardization of illumination, Ferree and Rand, in 1920, presented their campperimeter,[183] the forerunner of the present Ferree-Rand perimeter with its campimeter attachment. Berens,[198] in 1922, described a modification of the Peter hand campimeter; a year later Downey[202] presented a self-registering, circular campimeter; and, in 1930, Birch-Hirschfeld[226] published a description of his "Black Cloth Campimeter." As the working distance of this instrument is 50 cm., I should classify it as a tangent screen.

As with perimeters, the evolutionary trend of the campimeter has been toward the control of involved factors and the elimination of external ones. Various means for facilitating fixation and for relieving fatigue have permitted the use of more sensitive tests. Steady fixation has been aided by the binocular technique, by stereopsis, by fusion patterns and various parallactic controls; fatigue has been reduced by improving illumination, controlling the background, and relieving accommodative and muscular strains. Quantitative effects have been attained by the tremendous reduction in the size of the test-object; and qualitative scotometry is directing attention to the reflection factors of test-object and background.

3. *Tangent Screens*

The tangent screen of Mariotte was "an obscure wall." We may assume Pecquet, Perrault, and Briggs used the same instrument. The wall, now "well-lighted, bright and gray," continued to serve Fick and DuBois-Reymond as well as Volkman for their experiments in 1853,[40, 41] and thirty years later, with circular inscriptions of the calculated tangential values, it is Hirschberg's Gesichtsfeldmesser.[75] The campimeter of Mello[82] (1885) had one disc calibrated in tangential values for 10 cm., another for two M. Meyer (1887) plotted his fields out to 40° by a tangent screen and completed them with the perimeter attachment.[86]

But the great date in the history of the tangent screen was 1890, when Bjerrum made his epochal report at the Berlin Congress. Since that time the screen has received the honor really due his technique, for it was the quantitative method that was new and not the instrument, which was simply a matt-black hanging covering the entire wall of the room. The essentials of the technique were the small test-object and the long range at which he worked (quantitative scotometry). As a result of the amazing and beautiful results he achieved the tangent screen continues to this day to be more intimately associated with his name than any other. Another late result of this work was to divert a great deal of attention from the perimetric to the campimetric method and to incalculably refine both.

While Meisling,[120] Sinclair,[128] and others continued to follow and elaborate Bjerrum's technique, experiments with variations of this method were made and, in 1906, Duane[129] added his name to those indissolubly united with this instrument. He published in this year a description of the tangent plane he had found "vastly superior to the ordinary perimeter in plotting scotomata," and in 1914, after eight years of use, still retained his original enthusiasm. "Its value is such that I should scarcely know what to do without it."[160, 161]

Four months after Duane's original public demonstration, Sym and Sinclair[130] reported their model. Roenne,[143] in 1909, continued to use the Bjerrum technique, as did Mosso,[144] Seidel,[162] and others.

In 1915 Gradle[163] presented a new model tangent screen with a white celluloid surface. The test-objects were blue steel balls moved by electromagnets acting from behind the screen. Elliot[173] attempted to combine the advantages of Priestley Smith's scotometer with those of the tangent screen, and, in 1918, submitted his description of the rotary tangent screen and a sign elicited by its use. Morton[178] about this time returned to the old blackboard.

In 1920 Marx[185] described his modification of the tangent screen. It was made of black cloth, had the diagram on the back, was used at 40 inches, and was perforated by 8 to 10 peek-holes to permit observation of the patient as he reported on the movements of steel balls magnetically propelled about the front surface. Lyster,[201] in 1922, added three new principles to the Bjerrum type of screen: (1) The use of prisms to obtain stereoscopic fusion, (2) the use of a translucent screen, and (3) the photographic record. A year later Downey[202] added a pantograph device to make the instrument self-registering, and Goldman,[210] in 1926, attached a stereoscope to a tangent screen to be used at 50 cm. The next year Holloway and Cowan[216] presented an apparatus with two new features: (1) An attached illuminating system (daylight values) and (2) a series of screens calibrated for various distances and held between horizontal rollers. Since that time Traquair[217] has indicated his return to the plain, ungraduated square of black velvet stretched upon a frame, and Birch-Hirschfeld[226] has supplied an instrument of this design.

The total evolutionary result (objectively) has been a circle beginning with Bjerrum (1890) and returning to him with Birch-Hirschfeld(1930). Of all the tangent screens devised, the only two to receive much literary attention are those of Bjerrum and Duane. Both of these are black, and are excellent for quantitative work, yet I firmly believe they will prove inadequate for future scotometry. The dicta of Ferree and Rand, given as academic studies, will find clinical application, and the important elements of quality and amount of illumination and reflection and proper background cannot be ignored if full advantage is to be taken of the refinements of qualitative scotometry.

4. *Scotometers*

Various instruments not falling in the preceding three classifications have appeared from time to time but few have attained importance in the field of scotometry. The Bardsley scotometer[140] may be classified as a central field rotary perimeter. It is part of a spherical section with a radial slit for setting the test-object at any meridian. The whole field may then be rotated about the line of fixation. Holth's scotometer,[141] which was presented the same year (1908), consisted of three red-headed matches held in the end of a match box. This primitive instrument was later refined and incorporated into an inlaid rule. Tomlinson[142] devised a cone within which was hinged a mirror used to reflect the image of the fixation-object upon various parts of the retina. It was described in 1909. The next year Haycraft[146] constructed his self-registering scotometer, similar in many ways to the one of

Priestley Smith already described as a campimeter and to the Elliot scotometer,[199] which was designed later for quantitative work. Downey's[202] scotometer, which appeared in 1923, may be classed as both campimeter and tangent screen. Many others have been invented (the Bouchard fan, De Wecker's, Thompson-Henderson's, etc.—also a large list of central color tests), but, excepting this list, too extensive to discuss here, nothing of significance affecting scotometry has been produced.

A critical review of the merits and defects of the scotometric instruments cannot fairly be undertaken here. This study was begun eight years ago, and has concerned itself primarily with the tangent screen, so that, while perimetry has entered extensively into the ramified investigations, it has not received a proportionate share of attention.

With this limitation in mind, however, it might prove interesting to list the expressed claims and preferences of the authors in the appended references.

5. *Advantages and Defects of the Various Types of Instruments*

For peripheral studies the perimeter is the instrument of choice. No tangent screen or campimeter can be used for peripheral scotometry without introducing awkward and inefficient modifications (eccentric fixation, right-angled extensions, mirrors, etc.). Dor[66] acknowledged the better principles of the perimeter but preferred to do his work on the campimeter because of the ease and rapidity of operation. Groenouw[100] introduced quantitative perimetry with the perimeter in 1893. He preferred the Aubert-Foerster type of instrument. Ferree[154] agreed that the variation in lengths of the two lines, first, of fixation and, second, of indirect sight, is one of the fundamental advantages of the perimeter and one which cannot be overcome by any tangent screen apparatus. He discussed the question of whether this variation, by disturbing accommodation, might influence the results obtained on the campimeter; he made experiments (with negative results) to test for such influence, and concluded that if any were produced it was of insignificant magnitude. He condemns the hemispherical perimeter desired by Seashore[157] as totally impractical for daylight work, unless it could be made translucent. Walker,[169, 171] among many others (Elliot, Hudson, Mackay, Reber), attempted to combine the advantages of the perimeter with those of the tangent screen by constructing a giant perimeter. This type has never gained wide usage.

Faith,[196] in discussing Gradle's paper, pleaded for the retention of the arc perimeter. He felt that assistants learned more readily to use this instrument. Elliot[199] advises a double examination in all cases where glaucoma is suspected: (1) a $\frac{2.6 \text{ to } 2.8}{330}$ perimetric test and (2) a tangent screen investigation. Peter,[204] abandoning his earlier pessimism,[172] is captivated by the Ferree-Rand perimeter, but reserves central field studies for the short-range campimeter. Swett[213] prefers the ordinary self-registering perimeter for the routine rapid examination, reserving the more precise instruments for special study. Traquair[217] advises using the perimeter for peripheral work only, and Lauber, Traquair, and Peter[223] recommended to the International Congress of Ophthalmology of 1929 the double examination, the field beyond 25° being investigated by means of a 333 mm. perimeter.

That the most modern of our perimeters is not more extensively used is probably due to two factors: (1) Cost, many ophthalmologists feel that they are acquiring all the significant data of perimetry through much less expensive instruments (this is debatable), and (2) time. An accurate, efficient perimetrist spends more than half an hour in taking a fairly well-controlled field. This time would be increased for the ophthalmologist who only infrequently plots the field himself, and as, for him, any facility acquired by frequent repetition connotes a larger practice and hence more demands upon attention, the situation is not improved. The addition of a salaried perimetrist to the office staff is not usually considered justified.

An attitude frequently encountered is that, as perimetry is a physiologic test and valid refinements in instruments and technique are limited by the ability of the subject to cooperate on their level, no high degree of precision is possible or even desirable. Hence any ordinary perimeter is quite sufficient. While in many cases, especially in the clinics, this is true, there is to be derived from the not infrequent combination of intelligent patient and precise instrument a pleasure which totally invalidates this attitude.

Lloyd,[175] in 1918, stated that: "The most modern of the perimeters differs from the ideal in several ways. The distance from the eye to the test-object is short by about one inch. The arc is not true and the calibrations are in error. The error accumulates with each 10° so, while the machine records 90°, it is actually about 95°." This last statement remains true today although I see no valid reason why it should be so. An examination of six perimeters (specimens of the three most modern types) showed four of them to suffer from exactly the defects and to almost the degree Lloyd specified. In several the 90° mark should have read 95°—in others the 94° mark was really at 90°. This indicates that two charts made on different perimeters (even if made on the same type of instrument) cannot be expected to agree unless the perimeters have been recalibrated. To my mind this is the most serious and unjustifiable defect of the modern perimeter.

The campimeter was usually used by investigators prior to Bjerrum. With him there began the great trend to apply quantitative measurements by the long-range screen.

Priestley Smith[133] used a campimeter at 35 cm. Ferree[145] devised a campimeter in 1912, and for his present work continues to use one.[154, 183, 228] Peter,[166, 164, 172, 189, 190, 204] after presenting his admirable hand campimeter, found it increasingly useful. In 1917 he believed the advantages of the campimeter to be so overwhelming that for him "the arc perimeter in its present form is an obsolete instrument."[172] In the past few years, however, the Ferree-Rand perimeter has won his support.[204] He still holds the campimeter to be the instrument of choice for central field studies, listing its advantages as: sharp definition, purity of color tone, and ease of maintaining fixation; and as its only admitted disadvantage (as compared with the tangent screen) he cites the magnification of errors. Lloyd[175, 191, 211] prefers his campimeter, listing its advantages as ease of maintaining fixation by means of the stereoscopic method and less fatigue of accommodation. Preceding Lloyd in this line were Bissell[176] and Haitz.[125] Following Lloyd and refining his technique to a quantitative degree came Evans,[209] who has used the campimeter (Lloyd's and one of his own devising) for scotometric work as accurate and precise as anyone has been able to accomplish with any instrument. Seashore, as noted, criticized the campimetric technique. Berens[198] felt that the radius of the Peter campimeter was too short and inflexible. He increased it from 165 to 270 mm., and added an adjustment to permit achieving this range in every case. He still finds this modification of value for bedside use, but prefers the tangent screen for office and clinic practice. Swett[213] believes the campimeter ranges are too short to detect the finer changes, and advises the Bjerrum technique for central fields. Goar and Ralston,[205] in their studies of the blind spot, compared four methods: (1) Tangent screen at one M., (2) phoroptometer at 27 cm., (3) Lloyd's stereocampimeter at 19 cm., and (4) Peter's campimeter at 16.5 cm. They finally adopted the first method as the simplest and most accurate.

The strain put upon accommodation, especially in presbyopes, and the lack of magnification of the defective areas are generally held to be the disadvantages of the extremely short range campimeter. Elliot says: "Whatever may be the verdict of other surgeons, nothing would shake the author's conviction that the magnification of scotomas, whether these be physiologic or pathologic, makes the patient's task enormously more easy, and the surgeon's results much more accurate. We cannot, therefore, afford to give up the Bjerrum method. To do so would be a retrograde step."[199]

From the time of Bjerrum, the tangent screen has held, or has shared with the campimeter, the preference of the great majority of ophthalmologists for central field study. It is the original and unsurpassed method of obtaining quantitative effects, and I believe it is to be applied qualitatively with increasing frequency. Peter's prophecy that after 1920 perimetry would be largely practised on a tangent plane is being fulfilled. The tangent screen cannot take the place of the perimeter for peripheral investigations, but he says, "central field study including the 40° circle is a special function of one of the various types of tangent screen."[190]

Among those who have expressed preference for this method and followed the Bjerrum technique are: McBride,[115] Meisling,[120] Sinclair,[128] Sym,[130] Holth,[141] Roenne,[143] Mosso,[144] van der Hoeve,[149] Seidel,[162] Walker,[171] A. Peters,[187] Rossler,[192] Nussbaum,[193] Morax,[194] Elliot,[199] Goar and Ralston,[205] Thomasson,[212, 219] Swett,[213] and Traquair.[217] Duane,[129, 161] as indicated, ascribed to the tangent plane accuracy, simplicity, thoroughness, and rapidity, and vast superiority over the perimeter for outlining scotomas. After eight years of use he reiterated his conclusions. Gradle has consistently used the tangent screen, first at 50 cm., then at 60 cm., and now at 1 meter. Elliot's scotometer[173] was a special tangent screen, as were those of Marx,[185] Lyster,[201] Goldman,[210] and Birch-

Hirschfeld.[226] Among the special advantages claimed for the method are: Reduction in the visual angle by the most simple and positive means, speed, decrease in the error at the borders of the scotoma, more careful analysis, increased sensitivity, ease of operation, more accurate fixation under adverse circumstances (Traquair), and, hence, decrease in error due to unsteadiness of fixation (Traquair). This latter statement is not accepted by Peter,[214] who believes that, "what was gained (in long distance scotometry) by reduction in the size of the test-object was lost by poor fixation and inadequate standards of illumination."

The disadvantages of the tangent screen method include the varying apparent size of the test-object with increasing eccentricity, the practically inevitable inequalities in length of the lines of fixation and indirect vision (noted above), and the difficulty of achieving uniform illumination. The first two defects it shares with the campimeter, the last with the perimeter. The first can be eliminated by special means now being developed (Best[227] has made the first report), the second, according to Ferree's experiments,[154] was without influence (at least upon accommodation), and the third has been practically eliminated both in the perimeter and in the tangent screen.

II. TECHNIQUE

A great part of the technique of scotometry has been, by necessity or convenience, included in the preceding historical discussion. This is especially true of that element relating to distance, radius or range, and it will be treated here in a brief, tabular form. Many details of the personal technique of various individuals cannot be given space for discussion, and hundreds, of course, remain unknown to me. Below are indicated what I consider the important practical elements of technique and the attitudes, so far as I have been able to ascertain, of those who have stressed or practised them.

A. WORKING DISTANCE

The working distances used in scotometry have varied from 150 mm. (Badal[70]) up to 4800 mm. (Roenne[217]). This does not include those of only historic interest—Mariotte's 10 feet (3000 mm.) and the early perimetric examination made by carrying a lighted taper about in a darkened room.

1. *Perimeters*

Badal's perimeter[70] was but one of the shortest range type. Salzer used 200 mm. as the working distance for his perimeter; Wittich, 220 mm., and Azoulay, 280 mm.

Since Foerster most instruments have been used at a range of 300 mm. or further. Dobrowolsky, Landolt, Groenouw, Holden, and Schloesser used the Foerster type of perimeter; Hembold, Gagzow, von Zehender, and Baird worked at the same distance (300 mm.) as did Foerster with his instrument. Carter and Scherk worked at 305 mm. and McHardy and Lang at 330 mm. The latter has become the presumed radius of an unspecified perimeter. It is the radius of the Ferree-Rand, Elliot, and Traquair instruments. Walker, Hudson, and Mackay used 1000 mm. as the working distance. Any present report on field limits should specifically note the type and radius of the perimeter if the data are to have value for comparative purposes.

2. *Campimeters*

The working distance of campimeters is less standardized than that of perimeters. The distances which have been enumerated show the following variations:

150 mm. Aubaret[91]
160 mm. De Wecker,[52] Dor,[66] Gazepy,[80] Mello[82]
165 mm. Peter,[164] Reber[165]
166 mm. Holloway and Cowan[216]
170 mm. Wells,[177] Downey[202]
190 mm. Haitz,[125, 126] Lloyd,[175] Evans,[209] Barkan,[229] Bissell[176]

200 mm. Aubert[47]
250 mm. Jeffries,[53] Schweigger,[72] Ferree[145]
270 mm. Berens[198]
300 mm. Mauthner,[74] Meyer[86]
305 mm. von Graefe[45]
330 mm. Ferree, Rand and Monroe[228]
350 mm. Smith[133]

3. *Tangent Screens*

There has been more tendency toward standardization of the working distance of the tangent screen than has been the case with either the perimeter or the campimeter. The latter is especially variable, whereas the perimetric radii have shown a trend toward two values, 250 mm. for the hand instruments and 330 mm. for the standards. Unless specified, it is usually assumed that the tangent screen is used at one meter. The following distances have been employed:

500 mm.	Piton,[97] Gradle,[170] Goldman,[210] Birch-Hirschfeld[226]
510 mm.	Downey[202]
650 mm.	Lyster[201]
750 mm.	Duane,[129] Berens[198]
1000 mm.	Hirschberg[75] (1880—ten years before Bjerrum)
1000 mm. to 2000 mm.	Bjerrum,[89] and his followers. McBride,[115] Meisling,[120] Holth,[141] Roenne,[143] Mosso,[144] Sym,[156] Seidel,[162] Morax,[194] Thomasson,[212] Traquair,[217] Sinclair,[128] Marx,[185] Elliot,[173] Nussbaum[193]
2000 mm.	Sym and Sinclair,[130] van der Hoeve[149]
1000 mm. to 2500 mm.	Walker[171]
1150 mm.	A. Peters,[187] Rossler[192]
1000 mm.	Gradle[197]
1000 mm.	Goar and Ralston[205]
1200 mm.	Swett[213]
4800 mm.	Roenne[217]

Two variants only have been widely used. Duane employed his screen at 750 mm. because at that distance he could plot fields of diplopia and monocular fixation. If the field of vision were contracted it might be outlined at 750 mm. For scotometry he used the 1500 mm. range. The 1150 mm. screen was chosen because at that distance 2 cm. was said to represent 1°; the 1200 mm. range was elected for the same reason. This apparent advantage is fictitious, since equal linear spaces do not represent corresponding tangential increments as we depart from the point of fixation. It is just as easy, therefore, to calibrate the screen or tangent scale for a standardized distance of one meter as for any variant.

B. TEST-OBJECTS

Test-objects of almost every conceivable material, color, size, and shape have been used in scotometry. Von Graefe used a piece of chalk, as did Jeffries, Mauthner, and others. Aubert recommended test-objects beginning with one sq. mm. and quadrupling each successive area in a series proceeding to 1,024 sq. mm. Wittich[50] used a $\frac{2}{220}$ white test-object. De Wecker,[52] ingeniously, had white ivory balls strung on radial wires. The spheres were blackened on one side so that after bringing them radially into the field of vision, a half-revolution on the wire, while leaving the sphere *in situ*, turned the dark surface toward the patient. The field or scotoma limits were thus built up along successive radii. Foerster[55] used "small" square test-objects. Schweigger[72] plotted hemianopsias (it would be surprising if he could have plotted finer changes!) on a campimeter at 25 cm., using 10 mm. white spheres as test-objects. Meyer[86] used white or colored, square test-objects "or a letter from the alphabet"! Bjerrum's technique is well known. Groenouw[100, 101] introduced the quantitative method into perimetry, employing 0.25, 0.5, 1, 2, and 4 mm. test-objects, and this technique was adopted by Holden.[104] Drott[103] showed that the field was widened temporally 10° by increasing the size of the test-object from 2 to 20 mm. At that time, and for a considerable period later, $\frac{10\text{–}20}{300}$ test-objects were in general use (Schloesser, 1899; Lang, 1925). Hummelsheim[122] and Waldeck,[123] in 1902, investigated fields with test-objects ranging in size from 0.5 to 200 mm., and concluded that nasally the absolute limit of the field was reached with a 15 mm. square test-object, but that temporally the field expanded continuously with the increasing size of the test-object. This is not the experience of more modern investigators, who have reached the limit temporally with much smaller targets. The conventionally accepted limits are given by Roemer[181] and Axenfeld.[186] Dobrowolsky[63] believed many of these "limits" were fictitious, due to failure to recognize the lids as part of the "surrounding facial structure." Smith[133] used a $\frac{2}{350}$ test-object in his rotary campimeter. Ball[159] believed the 2° to 4° test-objects, covering thousands of retinal elements, were too large, and advised the Bjerrum technique. This has been the point of view of an increasing number of observers who use both perimeter and tangent screen. Peter,[166] in 1915, on his campimeter used 2 and 5 mm. test-objects at 165 mm., and Reber[165] followed this technique. Tingley[167] and Calhoun,[168] in 1915, presented luminous test-objects for perimetry and campimetry. These were for manual control on the screen. Many "self-lit" perimeters had been devised previously. Walker[169] believed the field examination was not complete unless a variety of test-objects (1.7° to 8°) were used. He considered that the 1 mm. discs had the widest range.[171] Gradle[170] and Marx[185] used steel balls, propelled by a magnet. Marx's balls were white and colored, $\frac{2\text{–}3\text{–}5\text{–}7\text{–}10}{1000}$. A. Peters[187] plotted the Bjerrum sign with 5 mm. square test-objects at 1150 mm.

The lack of details in specifying perimetric technique prior to 1920 was commented upon by Peter,[190] who understood that perimetry was generally performed with $\frac{5}{330}$ test-objects. He believed that the $\frac{8.75}{1000}$ test-object was the smallest that would give uniform results. This would be the equivalent of a 1.5 mm. test-object on his campimeter. He advocated a 2° test-object for peripheral studies.

Gradle's[197] tangent screen of 1922 was usually used with $\frac{10}{500}$ test-objects. The colors were taken from the Heidelberg series of papers.

Elliot[199] stated that at any distance a full normal field for white can be obtained from a healthy eye if a 1/2° test-object is used. This would mean a 2.6 to 2.8 mm. diameter on the 330 mm. perimeter. Larger test-objects he held to be disadvantageous, since they did not increase the size of the field and served to lessen the accuracy. The use of a $\frac{1}{1000}$ target in the normal eye gives a practically circular field at 26°, and from such a field knowledge of great value may be gained.

Behr,[200] in 1922, advocated graded test-objects, each size one-half the area of the next larger and ranging from 40 sq. mm. down to 5 sq. mm. In 1915 large-object perimetry was still being supported by some investigators. Lang[208] states that if a 4° white test-object (McHardy perimeter) gives an approximately normal field, further observations are unnecessary.

Evans applied quantitative methods to short range instruments and his test-objects for mapping angioscotomas[209] are exceedingly minute. They are small spheres made by fusing the end of a fine wire. The relative sizes of campimeter test-objects are given by Peter[214] as:

	Ferree-Rand Radius, 333 mm.	Lloyd Radius, 225 mm.	Peters Radius, 165 mm.
5′ T.-O.	.5 mm.	.35 mm.	.23 mm.
10′ T.-O.	.96 mm.	.85 mm.	.48 mm.
20′ T.-O.	1.43 mm.	1.30 mm.	.86 mm.

Peter is of the opinion that the small-object, short-range campimeter is the best method, whereas Traquair[217] believes that the long range examination of the $\frac{5}{330}$ and $\frac{1}{330}$ isopters "is in every way much more efficient and satisfactory than the examination of central defects at a short radius." Traquair's tabulation of the extent of the field in degrees obtained by 22 variations of relationship in size of test-object to distance (range of $\frac{1}{4000}$ to $\frac{80}{1000}$ or from 0.86′ to 275′) is the most complete I have seen. Ferree, Rand, and Monroe[228] used a 0.17° stimulus for their preliminary work on a diagnostic scale for form fields, and contended it was of little value to reduce the size of the test-object below this point.

Those who have followed the Bjerrum method include McBride,[115] Meisling,[120] Sinclair,[128] Sym,[130] Holth,[141] Roenne,[143] Mosso,[144] van der Hoeve,[149] Sym,[156] Seidel,[162] A. Peters,[187] Nussbaum,[193] Morax,[194] Goar and Ralston,[205] Thomasson,[212, 219] and Traquair.[217] The committee on standards of the Concilium Ophthalmologicum, 1929, recommended: (1) Form field examination with $\frac{1}{333}$ and $\frac{3}{333}$ white test-objects and $\frac{5}{333}$ colored objects (Heidelberg papers), and (2) the central field examination on a tangent screen at a minimum distance of 1000 mm. (Peter dissenting in favor of campimeter, preferably short range.)

Unusual test-objects, aside from those mentioned, have been Reid's,[83] a distant source of light, the image of which was revolved about the fixation point by means of a prism; Willets',[112] a flint hexagon to project images on to the retina; Tomlinson's,[142] a mirror hinged within a cone—the image of the fixation mark was used as a test image; and Schoenberg's,[225] which accomplished the same effect by means of a prism the base of which bisected the pupil.

C. Colored Test-Objects

A note should be made on the use of colored test-objects, as these have been employed so indiscriminately as to invalidate entirely much otherwise excellent work. The early investigators (Purkinje, Aubert, and Leber) had no real control of illumination except by choosing the day and hour of work. Later artificial illumination was used extensively both for reflection and transmission. As early as 1873 Landolt[65] stated that no color tests have value unless the intensity of the color, as well as the general illumination and state of adaptation of the eye, is given. Nevertheless, these factors have been consistently ignored by most reporters up to very recent times. For many years pieces of colored glass were used (Schroetter, Gazepy, Katz, *et al.*), later "self-lit" perimeters were in vogue, and finally colored scotometers were introduced. These consisted usually of a small electric bulb situated behind a colored glass and supplied by a variable voltage. Neither the bulb, filter, nor voltage was standardized. Meyer[86] used squares or letters made of colored paper, Marx[185] employed steel balls painted various colors, and Holth[188] filled depressions in his scotometer with colored sealing wax. Pink pills (actually veracolate tablets) have in more than one instance served modern medicine in an unintended way.

An improvement, but too impractical for clinical work, was introduced by Hess[87] and used by Ferree.[145] These investigators employed a color mixer mounted on the perimeter or campimeter. Later Ferree and Rand[179] used spectral light of 670, 581, 522, and 468 m.mu for, respectively, red, yellow, green, and blue stimuli. This, too, was a purely research procedure.

Gradle's report[197] included specification of the Heidelberg series of papers. This was a long step forward, as these papers represent fairly accurate standardization, they are not difficult to obtain, and their use entails no complicating factors. Berens,[198] for his studies, used the Hering series of papers. In 1929 the committee chosen to establish standards reported to the Holland International Congress its recommendation of the Heidelberg papers for colored test-objects.

This move toward standardization is a great advance, and should receive universal clinical support until more accurate and valuable methods are demonstrated. This qualification is not intended to indicate half-hearted support; rather a recognition of the serious drawbacks inherent in any practical test-object so far devised.

The Heidelberg papers are saturated with a pigment that extends theoretically through the entire thickness of the paper, but any attempt to erase or remove the spots resulting from use inevitably blurs and degrades the color. It is impossible to keep them—or any others so far produced—clean and accurate over a prolonged period of use, and the expense of frequent renewal has not efficiently been met.

With the rapid advances of very recent times in the fields of material production and accurate spectrophotometry and photo-electric colorimetry, it is not unreasonable to expect new and accurate standardization of other colored material which will greatly improve our present standards.

D. Fixation

Accurate control of fixation is one of the most important elements of scotometry and one of the most difficult to achieve. It is desirable for the ophthalmologist to have visual control of this factor wherever possible, and the lack of opportunity to keep the eye being investigated under close surveillance is a serious drawback to several otherwise excellent instruments. In the special cases of suspected malingering or hysteria it is, of course, an absolute essential, but even in the type of patient ordinarily encountered there exists an almost uncontrollable tendency to reassure himself by quick shifts in the direction of the test-object.

The perfect fixation device has not been achieved, but many exceedingly ingenious methods have been evolved for assuring fairly steady control even in cases of central scotoma, the *bête noir* of the scotometrist.

Prior to De Wecker[52] a small piece of paper or a cross marked in pencil or crayon had served as a point of fixed vision. He supplied a rest for the chin and a small cross for the fixation object. Carter[61] drilled a hole through the axis of his perimeter and let the patient fixate a distant light through this hole—thus relieving accommodation. Reid adopted this principle.[83] The McHardy perimeter[78] was supplied with a 5 mm. ivory disc to serve as a fixation mark. Hess[87] used a second side light viewed by means of a mirror. This principle has been applied by Peter also.[224] Willets[112] used a light as his test-object in the prismatic perimeter. It is worth noting that in the instruments of Reid, Willets, Tomlinson, and Schoenberg there is produced an optical means of moving the test image without significantly inequalizing the lengths of the lines of fixation and indirect vision.

Michel[117] used a transparent glass plate 80 by 100 cm. as an aid in controlling fixation. Priestley Smith[133] approached the parallax method with his ring placed near the eye under study. In 1907 Irma Herczogh[136] demonstrated the von Szily method of fixation, utilizing a funnel over the good eye. Walker also has devised a somewhat similar macular selector to assist in steady fixation. In the presence of poor fixation due to amblyopia or scars or central scotoma most ophthalmologists simply increase the size of the fixation target by attaching to it a circle of paper of sufficient diameter to furnish adequate stimulus. The methods and technique of outlining scotomas and a description of the Joseph Pigeon maneuver are given by Evans.[148]

A real contribution to the control of fixation has evolved from the line begun by Hirschberger,[90] using binocular fixation with a complementary colored glass before the eye not under investigation. This technique, naturally, could not be used for white test-objects. The method was improved by Schloesser,[118] and led through Haitz and Bissell to the present excellent Lloyd stereocampimeter, which probably gives a maximum of stimulus to subserve fusion and steady binocular fixation. If the latter could be visually checked by the ophthalmologist it would be a great satisfaction. Ferree and Rand facilitate fixation for the myope by bringing the fixation target closer to the eye, and by an extension in the opposite direction, they relieve presbyopic patients of the strain of accommodation. These investigators supply also a device consisting of four radial arms to each of which is attached a sliding target. Fixation should be facilitated when the various targets, so set as to be situated just on the borders of the central scotoma, are all kept continuously in view. I find it difficult to manage. Ferree (Campperimeter, 1920) also recommended facilitating fixation by employing a mirror on the fixation line—thus permitting the eye under investigation to observe itself, and the use of a stationary stimulus, which in his hands showed less tendency to induce shifts in its direction.

Lyster[201] and Goldman[210] have applied the stereoscopic method to tangent screen scotometry. Marx[185] keeps check on the patient by means of 8 to 10 peek-holes in the screen, behind which he moves a magnet.

I believe relief from accommodative strain aids materially in maintaining prolonged fixation. This relief may be accomplished either by using a lens of focal length equal to the working distance or by increasing the distance. Using at a distance of 195 mm. a campimeter which I constructed (imitating that of Evans), I found increased comfort, with the ability to prolong fixation, when a +5.25 lens was employed. This point has been emphasized by others, who have also indicated that the effort of bringing the test-object from the not visible to the visible fields aids in maintaing fixation.

Another factor which aids fixation to an extent not usually appreciated is the effect of the background. Distracting, especially glinting, objects should not be present and the general tone should be a neutral gray. With a gray background of the brightness of the test-object used, marked sharpness in disappearance zones for colors is obtained, and the confusion which acts as a stimulus to "peek" is reduced. This will be discussed more fully later.

E. MOVEMENT OF TEST-OBJECT

It is not difficult to see that by a sufficiently rapid movement of the test-object—without adequate signaling mechanisms—the limits of the field or of a scotoma might be made to agree with any figure. It is but a step further to state that *any* movement of the test-object introduces error. Some scotometrists take that position.

Mariotte, Pecquet, Perrault, Picard, and others of that time experimented with a stationary test-object, although this phrase is not applicable in the modern sense. They observed two fixed objects, one directly and the other indirectly, and by approach or recession varied the relative retinal positions of the images.

"Stationary" as now used applies only to the duration of exposure of the object, which is usually moved under a preexposure shield during the interim between observations.

The movement of De Wecker's test-objects was limited to the excursion along the radial wires, whereas the test-object of Heymann[54] moved in a circular path about the fixation point. Neither could conveniently be given oscillatory movements. Landolt[64] cautioned against too slow movement of the test-object, stating that it induces fatigue; but he likewise warns that too rapid movement extends the borders in the direction of the motion and tends to miss fine defects. Bjerrum and his followers (with one or two exceptions) have manually controlled the test-object, whereas in a great number of the older—and even in the modern—perimeters this is done mechanically.

Hegg,[96] Wilbrand,[113] and others advised imparting oscillatory motions to the test-object. This continues to be generally practised, although subject to criticism and objections. No doubt the procedure gives a wider field. It seems the equivalent of using a larger test-object and the field for motion is involved. Smith,[133] Bardsley,[140] and Elliot[173] used the same motion as that of Heymann, that is, their machines were designed for circular motion about the fixation line. Haycraft's test-object moved in two directions at right angles to each other.

In Ferree's rotary campimeter[145] the test-object was not moved. After proper pre-exposure had taken place the test-object was exposed for three seconds. This stationary-stimulus technique continues to receive the approval of this investigator and is part of the method advised with the Ferree-Rand perimeter. Peter[190] advocates moving the stimulus with a slightly trembling motion from the not visible to the visible areas. Gradle,[197] on the black tangent screen, oscillates the test-object when outlining form. The white celluloid screen was used with steel ball test-objects moved about by a magnet. Berens[198] oscillates the test-object but slightly and takes the average of the NV—V and V—NV readings. Others prefer to take only the NV—V readings and thus avoid prolonging the examination and inducing fatigue. A greater number of readings during a given period of time may be made by this latter technique, and many observers have reported that moving the test-object from a not visible to a visible zone contributes definitely to the maintenance of steady fixation. Traquair[217] states that the object should be moved at a rate of less than one foot per second with little excursions at right angles to its line of progress. This is the only specific recommendation as to rate of motion I have seen and while accurate enough is apt to be misleading. A test-object moving at the rate of one foot per second will certainly fail to reveal many small scotomas. However it is not possible to make a general rule for rate of motion, as this rate must be conditioned to a very great extent by the working distance. The shorter the working range the slower must be the rate of motion of the test-object to pick up fine changes. Working at a short range and plotting angioscotomas, the test-object barely moves; working at two meters and plotting the blind spot, a rate of six inches per second may not be too much. I believe the optimum rate of motion on the tangent screen at 1,000 mm. to be in the neighborhood of two inches per second. The report of Lauber, Traquair, and Peter to the International Congress advises manual control of the test-objects.

The use of a stationary stimulus with proper pre-exposure seems very desirable from a scientific viewpoint. From the practical side it prolongs the examination, with resultant fatigue (if rests are frequently given, the prolongation of time is increased). The stationary stimulus is difficult to apply to campimetry and tangent screen scotometry, although it has been nicely incorporated into perimetry. The objection to having a moving object in the field is not eliminated, if a pre-exposure card is to be used.

F. Illumination

However controversial may be the relative merits and faults of the various scotometric instruments, they all suffer from one defect: illumination. This has never been brought under satisfactory control. Quality and intensity in any given ratio are not difficult to achieve, but a practical means of varying the intensity—in scotometric work—without affecting the quality has presented additional problems. As illumination is the subject of a current study too extensive to be included here, only historical notes and a brief review of some devices will be given.

As noted above, original investigators, from practical necessity, used daylight. Later, as artificial illumination was improved, it was almost as rapidly adapted to the needs of scotometry. Fick and DuBois-Reymond, Volkman, and von Graefe all used "brightly lighted" surfaces for their work. Aubert,[47] in 1857, admirably defined (considering the date) the light he used as daylight, north, clear sky, always the same window and same time of day. Modern scientific specification seldom goes beyond this, and then rarely more than by adding latitude, altitude, and season(or apparent color temperature). Landolt recognized the limitations imposed by the artificial light of his time (1873) and advised daylight, stating that color tests had no value unless the general illumination was known.[64, 65] McHardy (1882) used his perimeter with a gas mantle placed directly above the patient's head,[78] and Priestley Smith's "A Mode of Illuminating the Perimeter,"[79] which appeared the following year, outlined a method which consisted of reflecting the light of the gas mantle backward upon a white wall, thus achieving a more uniform and diffuse illumination.

With the advent of the electric lamp many "self-lit" perimeters, or, rather, test-objects, came into extensive usage. Some of them still remain. As the incandescent filament was perfected it was with increasing frequency applied as a field illuminant, but only since the production of high-temperature, gas-filled lamps and suitable filters has it been possible to get the quality of light desired. In the meantime the list of those who have advocated "daylight" illumination (sometimes specified as "good daylight"—Groenouw[100] or "free from direct sunshine"—Traquair[217]) has stretched over the years from Meyer, in 1887, to Salzer, in 1929.

In 1907 Nelson M. Black[138] questioned the value of such specifications—he was not the first to do so—and quoted the findings of Basquin[135] in support of his contention. Basquin, the year previously, had shown that the variation in light from a clear sky was from 1,050 candles per square foot in August to 140 candles in December of the same year, also that the mean of the monthly readings varied from 2,200 candles per square foot in June to 270 in December. The mean monthly readings taken at 4.30 P. M. varied from 520 candles per square foot in August to 5 in December. From this he concluded that "natural daylight" was unreliable.

Black was interested in illuminating test-type charts, and quoted Bell's statement[252] that a low intensity of proper illumination was quite sufficient for the normal sensitivity of the eye. Black advised artificial light of adjusted color value. This type of light has since been advocated for almost every purpose, including eye-strain therapy in ophthalmology and production increase in industry. Lancaster,[152] in 1913, doubted that the color of the light was an important factor in the production of eye-strain.

Ferree,[154] in 1913, stated that an investigation of the comparative sensitivity of the retina to different colors should be made in daylight illumination. At that time a satisfactory source of artificial daylight was not available, but by 1920 this investigator had acquired filters suitable to convert the light from a Mazda C-type bulb into approximate daylight value. Somewhat similar filters have been incorporated into the Ferree-Rand perimeter.

Modern illuminating engineers can produce light of almost any intensity or quality required, and ophthalmologic reports of the last ten years indicate an increasing desire to take advantage of this fact.

Marx,[185] in 1920, used a "frosted electric lamp" placed behind the patient; Gradle,[197] in 1922, employed an arc of gas-pipe carrying five 50-watt frosted daylight Mazdas. Berens[198] utilized the Macbeth JLS 17 (a 150-watt Mazda C behind a Corning glass filter). Peter,[204] in 1923, illuminated his tangent screen with two banks of daylight filters, behind each of which were two 125 c.p. globes. The next year

Goar and Ralston were using two 50 c.p. daylight lamps above and behind the patient. In 1924 Smith[206] advised the use of the National X-ray Reflector Company flood lamps (two 150-watt); in 1926 Evans[209] and Lloyd[211] stressed the importance of artificial daylight. Holloway and Cowan,[216] in 1927, used four Macbeth JLS 17 daylight lamps for their tangent screen, and the next year Deichler[220] utilized three banks of reflectors, one on each side and one above the patient's head. Each contained two 50-watt daylight lamps. The simplified standards of the Holland Congress Committee specified artificial daylight illumination for color scotometry. They advised 7 f.c. intensity. As a type of illumination the committee recommended that incorporated into the Ferree-Rand perimeter.

Just as Basquin, among others, demonstrated the inadequacy of specifying "natural daylight," so have the researches of illuminating engineers shown the phrase "daylight lamps" to be practically meaningless. In the reports of the preceding paragraph, as in many others, the phrase "daylight lamp" is frequently used to specify a type of electric light bulb, frosted, dyed, or made of blue glass. It is commonly called "dalite," "daylite," or "daylike." This is often grossly misrepresentative and frequently misleading. In justice to the authors it must be said that they have only used the labels attached to these lamps and under which they are sold. The fault lies in the unrestrained imagination of the catalog writers and the cupidity of the manufacturers. There is, so far as I know, no such thing as a "daylight lamp" in the sense of an electric light bulb which gives illumination even remotely resembling that of natural sky light of a given luminosity curve or apparent color temperature. The only type of artificial illumination which may fairly be said to have daylight quality is that produced by passing artificial light through a filter. The Corning "daylite" glass filter, 4.5 to 6.5 mm., used on the Macbeth daylight lamp is a satisfactory example of such a filter. The filter used on the Ferree-Rand perimeter modifies light in a manner acceptable to the Holland Congress Committee. The blue bulb lamps, commonly called "daylight," are, so far as quality of light is concerned, but a short step toward daylight from the clear bulb Mazda light. If average daylight can be assumed to have a color temperature between 6,000° K. and 7,000° K., these blue bulbs are well below the 4,000° K. point, with the clear bulb lamps around 2,800° K. in gas-filled and 2,600° K. in vacuum lamps—the latter being in all sizes below 60 watt.

The spectral quality difference between Mazda light and daylight shows an excess radiation in red, orange, yellow, and green of over 80 per cent; the blue bulb absorption figure given by the manufacturers[253] is 35 per cent., an appreciable amount below the necessary minimum absorption of 80 per cent.[254] Further discussion of the physical factors involved in the production and the control of satisfactory artificial daylight cannot be included here, as these factors involve too wide a variety of valuable but conflicting opinions. This is due to the present lack of universally, or even widely, accepted standards of "artificial daylight." In the textile and paper industries the apparent color temperature has come, by usage, to approach a standard. The International Commission on Illumination, which met in London in September, 1931, held one meeting devoted to daylight. "Artificial daylight" was not specifically defined. It would be a great service if the American Ophthalmological Society would formulate, or have formulated, a scientific definition of this factor because this would make possible, for the first time, the substitution of a phrase which means something for the loose, vague, unspecific, and unscientific phrases now in vogue. Those interested in the subject of illumination can find in the bibliography prepared by Troland[255] (complete up to 1924) a wide variety of contributions (over 9,000 references); and in the papers of Priest, Ives, and Macbeth are reported the nearest approaches to accepted standards.

The illumination should be evenly distributed over the perimeter arm or over the surface of the campimeter or the screen. Its intensity, if we are to accept the advice of the Committee reporting to the Holland Congress, should be 7 foot-candles. Reduction in this amount may be used as means of sensitizing tests, and increasing the illumination facilitates them.

Much has been written concerning the quality and intensity of the illumination used in scotometry, but all that has been written has not by any means been proved. I do think it is advisable to incorporate into our work those practical refinements recommended by sound theory and careful research, and for this reason I am strongly in favor of using artificial daylight of an intensity at or near that recommended by the Congress Committee. This may be obtained without much variation on the arc of the perimeter. It is somewhat more difficult to get a perfectly even distribution of luminous flux on the surface of a campimeter, but this difficulty is not insuperable and for all practical purposes does not exist. The combination of instruments, however, presents a radically different illumination problem and one not so easily met. On such a perimeter-campimeter bearing an illumination unit which nominally delivered 7 foot-candles on the test-object at 1.27 amperes, I measured variations from 4.6 to 6.2 foot-candles along the perimeter arc. Control measurements by an illuminating engineer gave variations from 5.0 to 6.4 foot-candles. This is not a serious defect, but when the campimeter was properly adjusted variations within the 30° circle of from 4.3 to 22.1 foot-candles were encountered. This indicates the difficulty of adequately controlling the light used.

Difficulty in illuminating the tangent screen is said by some investigators to be its main drawback; however, with the screen to be described later, using but two daylight units, the illuminometer revealed variations extending only from 5.0 to 6.6 foot-candles. These variations were checked by independent measurements, so that this particular difficulty can be said to have been practically eliminated in so far as evenness of light is concerned. The ability to vary the intensity by a simple, practical means without affecting the quality still remains the chief problem.

G. BACKGROUND

As early as 1853 Fick and DuBois-Reymond[40] specified a "well-lighted, bright, gray wall" as the background in their blind spot investigations. Aubert[47] experimented with black and with white backgrounds for use with his north skylight illumination and colored test-objects. Hegg[96] used a gray background for part of his color perimetry. When Groenouw[100] introduced quantitative methods with the perimeter he added the use of black test-objects on a gray background and gray test-objects on a white background, which Holden[104] says give the same result. The latter investigator employed a neutral gray background. Senn[106] insisted on a neutral gray background for functional tests of the peripheral retina, and Wilbrand[113] emphasized the importance of this factor because of simultaneous contrast. These various procedures were all advocated in the nineteenth century.

With Ferree's first description of the rotary campimeter, in 1912, came the statement: "In all tests of the relative and absolute sensitivity of the retina this screen (background) should be made of gray of the brightness of the color to be used. No departure from this rule should be permitted unless it is for the purpose of determining the effect of different screens on the sensitivity of the retina or of using this effect as a means of varying sensitivity."[145] Ferree used a background of neutral gray made of No. 7 of the Hering series, and a footnote dictum repeats and emphasizes the caution given above. Lloyd[211] has his charts printed in subdued colors to avoid Troxler's phenomenon. Berens[198] has consistently advocated the neutral gray screen.

Very few other investigators have departed from the time-honored technique of using instruments (perimeters, campimeters, or curtains) which supplied a black background, and the question frequently arises, "What difference does it make?" The answer depends entirely upon the aim of the scotometrist.

If the fields for form or motion are to be studied, using a white test-object, or the sharp borders of an absolute scotoma or the blind spot are to be outlined by the same means, then the black background, which supplies a maximum of contrast, is to be preferred. If, however, one is dealing with observations which require color judgments, such as outlining the color fields, sensitizing the tests for blind spot borders, or searching for a relative scotoma, a gray background of the same brightness as the colored test-object used is of much greater value. It increases the sensitivity of the test and greatly facilitates the patient's judgments, because the color values and visibility of the test-objects show sharp drops without the confusing effects of physiologic induction or contrast. In the words of Ferree and Rand: "A further advantage is gained by making the background of the same brightness as the color. That is, when the color and background are of the same brightness, the stimulus disappears completely when the limit of sensitivity to that color is reached, instead of turning into a gray concerning the colorlessness of which the patient is apt to be in doubt."[183, 240] This effect is not so great as that due to pre-exposure but is in the same direction. In tangent screen scotometry the pre-exposure and the surrounding field are supplied by the same material—the curtain against which the test-object is moved.

The choice thus becomes fairly well defined, depending upon the relative importance the individual ophthalmologist attaches to these facts. One must either have two tangent screens, or forego the advantages of one type. As I have indicated, I believe the trends in scotometry are toward the application of qualitative principles, and for this reason, if but one screen is to be used, I would choose to compromise on a neutral gray of relatively dark shade, by this means hoping to retain some of the advantages of the gray background without sacrificing all the merits of the black.

What is "neutral gray"? The grays are an infinite series of mixtures of black and white extending between those limits (black and white). "Neutral" means without color tone. Because "brightness"* involves a more complicated definition and in practice no surface obeys exactly the cosine law of emission or reflection (hence the brightness of a surface generally is not uniform but varies with the angle at which it is viewed), this specification usually is omitted, and the reflection factor substituted for it. The reflection factor of a body is the ratio of the flux reflected by the body to the flux incident upon it. This reflection is usually a combination of regular and diffuse. Therefore a neutral gray screen should indicate a screen with no (or minimal) color tone which reflects an amount of light expressed by its reflection factor. The black screens reflect from 1 to 3 per cent. if made of velvet; the compositions used in most campimeters run nearer 5 per cent.; the light gray screens reflect from 25 to 40 per cent. The Heidelberg series of colored papers for the Bausch and Lomb test-objects should maintain a reflection factor of 11.4 per cent. for the red and blue and 39.5 per cent. for the green.[250] They are usually found not to be so bright. Photometric tests on new materials showed:

* The International Commission on Illumination defines brightness as: "The Brightness in a given direction of a surface emitting light is the quotient of the luminous intensity measured in that direction by the area of this surface projected on a plane perpendicular to the direction considered."[258]

red 9 per cent., blue less than 9 per cent., green 38 per cent. Therefore a dark gray screen with a reflection factor of 10 per cent. will be of almost equal brightness to the red and blue test-objects, and still be useful for quantitative work with the white test-objects. As the reflection factor of the latter is 82.5 per cent., contrast is not greatly affected by using a background with 10 per cent. reflection factor instead of from 3 to 5 per cent.

H. RECORDING

It is impossible to make an accurate representation of a sphere or a hemisphere upon a plane surface so that direct or proportionate linear measurements can be made. Many systems have been devised to overcome this difficulty, but none has been entirely successful. This is unfortunate, as it robs perimetry of the services of what would have been an extremely valuable tool—the planimeter. The campimeter and the tangent screen do not share this difficulty with the arc perimeter, as with them the system of tangential projections utilized is true to and representative of the area projected.

If we assume a plane surface tangent to the arc of the perimeter at the fixation point and an eye in the ordinary position at the center of the perimeter arc, it is easily seen that the perimeter readings up to 50° to 60° can with relative convenience be projected upon the tangent surface and there recorded. (Fig. 2.) A duplicate of this projection on a reduced scale suitable for office records would fulfill all practical requirements for accuracy and truth. This is the system of tangential projections and is perfectly valid as far as we have gone. Beyond 60°, however, the extension along the screen of the succeeding tangent values mounts with increasing rapidity, so that when 90° is reached a screen infinite in extent would be required for the projection ($\tan 90° = \infty$).

As the eye, still sighting along the 90° mark on the perimeter, is moved away from the fixation point (where the screen touches the arc), the projected line would meet a screen of finite extent, and when the distance from eye to fixation point is doubled the intervals on the screen between the projected 10°, 20°, 30° to 90° marks on the perimeter arm are fairly equal (the 80° to 90° interval is still longer than the 10° to 20° interval). (Fig. 3.) This is a type of polar projection. One might hope that, by receding still further, a point would be reached where these projected in-

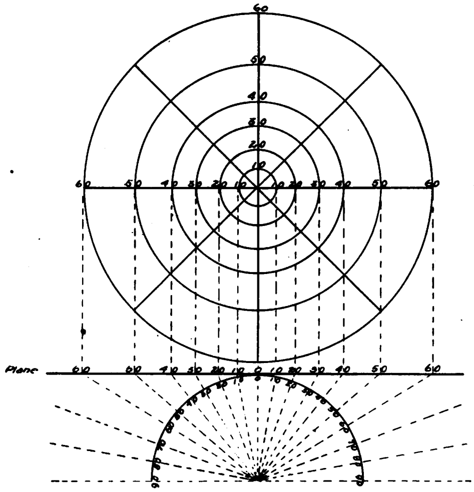


Fig. 2.—Tangential projections.

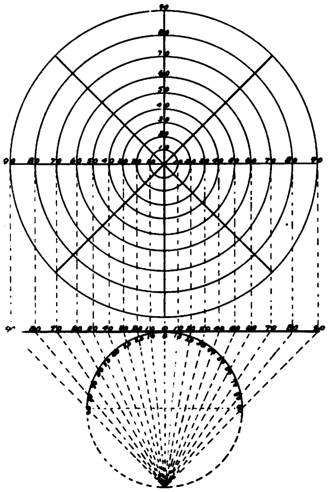


Fig. 3.—Polar projection.

tervals were exactly equalized, but this, unfortunately, is not the case. They approach equality when the distance from the center of the perimeter arc (where the eye was originally located) is 1.7 times the radius of the arc, that is, when the distance from the eye to the fixation point has been increased from one time the radius of the perimeter to 2.7 times the radius of the perimeter. (Fig. 4.) This system was introduced by Foerster and is called "equidistant polar projection." It is now in practically universal usage, the mathematical inequalities having been ignored, and equidistant concentric circles used to indicate the different degrees of eccentricity from the line of fixation.

If we continue to recede, the opposite type of inequality ensues—that is, the space between the 10° to 20° circles becomes larger than that between the 80° to 90° circles, and when the eye reaches an infinite distance from the arc (that is, when the projection lines become parallel) we have a pattern which is the simple projection of a sphere—or a hemi-

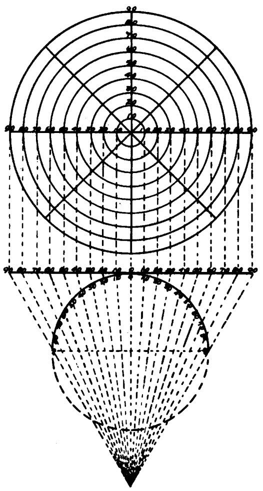


Fig. 4.—Equidistant polar projection.

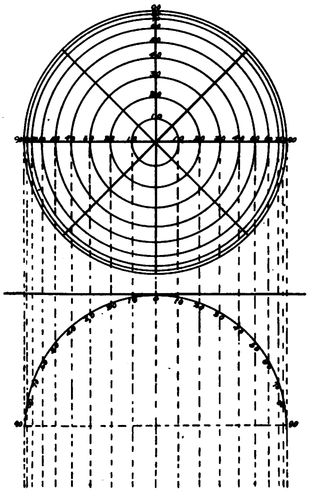


Fig. 5.—Orthogonal projection.

sphere—upon a plane. (Fig. 5.) This is the "orthogonal projection" of Hirschberg.[71]

Because no system of recording perimetric findings has proved adequate to meet the problems involved, the committee of the Holland Congress advised for peripheral field studies the use of the purely diagrammatic charts, consisting of equidistant concentric circles with properly marked meridians.

Tangent screen and campimeter charts are capable of recording more accurately scotomatous areas. They represent true projections of diseased areas upon a plane, and are simply small scale reproductions of those projections. In some campimeters (Peter's, Lloyd's) the record is the original projection, in others (Lyster's[201]) it is a photographic reproduction. It must not be forgotten, however, that this does not permit the application of direct linear measurements or the multiplication of such measurements to give surfaces. They are *tangent* values and as such change with increasing rapidity as we depart from the fixation point.

Measurements taken from a tangent screen or campimeter are valid if expressed in terms of degrees, but are absolutely invalid if expressed in millimeters or inches, unless sufficient supplementary data are given to permit translating them into degrees or retinal equivalents. This fact is not infrequently ignored by reporters who use the tangent screen as a scotometer.

It is possible, by using some standardized assumptions, to calibrate the tangent surface directly in terms of millimeters for linear or areal measurements of retinal defects or to calibrate scales for this purpose. This has been done and will be discussed later.

Some idea of the progress that has been made in the technique of recording scotomas will be gained by reviewing the work of Donders,[49] who designed charts as well as made records directly upon papers affixed to the wall (Schoen[69]). Jeffries[53] mapped scotomas on a blackboard with chalk and then placed over them a frame strung with white threads at three-inch intervals, thus dividing the board temporarily into squares. Landolt[64] and Landolt and De Wecker[73] give a complete review of the methods of recording scotomas up to 1878. Landolt in particular carefully worked out the mathematical projections of the different systems. Hirschberg[71] devised and reported the system of orthogonal projections. Critchett[76] submitted a chart for measuring the field of vision, and Priestley Smith[79] made the suggestion, in the interests of efficiency and economy, of recording the field by a group of numbers indicating the limits on different meridians, thus:

55	55	70
55	R	90
58	65	80

Jackson[110] approved of this suggestion when costs were to be avoided. Wilbrand[113] discussed the inadequacy of perimetric charts to portray the three dimensional figures.

In this century Gradle[170] has reported his method of recording fields, which consists of marking the screen in one cm. square areas and the record cards in one mm. square areas, thus securing a direct 10:1 reduction. Hudson[174] used a system of pulley reductions on his large perimeter in order to give self-registration. Of course, the "self-registering" perimeters were all direct mechanical reductions. Wells,[177] in reporting the adaptability of the phoro-optometer stereoscope to the Haitz and Bissell charts, includes the statement of Prentice that "a discrepancy between the scale and the fundus will ever be present through the use of a stereoscope."

In 1920 Cowan[184] suggested the use of ruled parallel lines at 4° intervals superimposed on the ordinary perimetric charts—the ruled lines remaining parallel and straight throughout the field. This suggestion was accepted by Berens,[198] who transferred the markings to his tangent screen and used them as a scotometric scale, accepting the 4° intervals as the equivalent of one mm. retinal dimensions. This application has been made by others who have seemed to forget that, accepting the primary assumption, such a scheme can be valid only upon the two oblique meridians. Elliot[199] used the equidistant concentric circle charts, and Downey[202] applied a pantograph device to permit direct registration of the screen findings on a chart. Traquair[217] advises the use of a chart with a full circle for each eye and devoid of normal limit or blind spot markings. This renders the chart available for either eye and, he believes, encourages the production of an independent and unbiassed record. Roenne,[207] in 1924, published a critical review of some of the systems used for recording perimetric findings.

III. A Tangent Screen Scotometer With Scales

The scotometric tangent screen and scales here presented are the results of a study begun eight years ago through interest in, and work with, the tangent screen described by Berens[198] in his thesis for this Society. Following the assumption, which is valid optical practice, that 4° in the central retinal area represent approximately one mm., he had the tangential values of 4° intervals at 75 cm. (his working distance) inscribed on the screen as parallel straight lines. The screen was then considered to be scotometric in the sense that the actual retinal dimensions of a diseased area were indicated. This is an error which the Cowan charts—being simply equidistant parallel lines on a chart and not tangential projections—did not share. The error has been duplicated, however, by a number of other charts which use the tangent intervals as parallel lines, and is more simply illustrated by the diagram. (Fig. 6.)

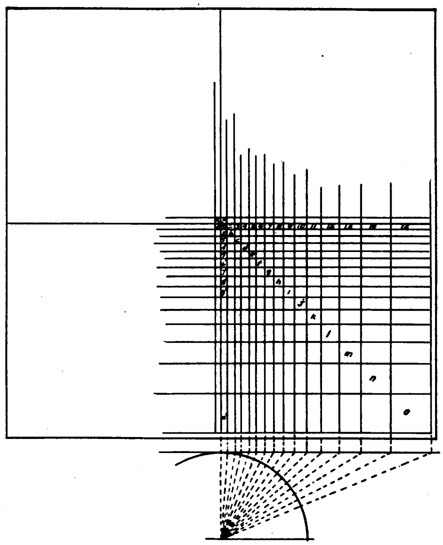


Fig. 6.—Tangential projections. Distortion produced by parallel lines.

In the figure, which represents a quadrant of such a chart or screen, parallel lines have been inscribed at right angles to the horizontal and vertical axes beginning at the fixation point ⊕. The intervals between these parallel horizontal lines represent 4° intervals on the central vertical axis; and the same intervals have been measured along the horizontal axis to locate the positions of the parallel vertical lines. Thus the four central squares (*a, a, a, a,*) surrounding the fixation point ⊕ are all equilateral and represent the tangential values of 4°. As such they may, without serious error, be said to represent areas 1 mm.² on the retina. The same statement, though with less assurance, may be applied to the oblique row of squares *b, c, d, e. . . . o,* but not by any means to any of the others, all of which are in error to a degree proportional to their distance from this oblique line. The "squares" 2, 3, 4, 5. . . .15 all have one dimension, the horizontal, which is correct, and the other dimension, the vertical, is increasingly wrong. If the horizontal dimension of "square" 15, for instance, represents a line 1 mm. in length on the retina, the vertical dimension of the same "square" obviously cannot. The vertical row of "squares" 2′, 3′, 4′. . . .15′ suffers from the same distortion on the opposite axis.

Problem

My aim was to correct this fault and supply a design which, with the fewest assumptions and with reasonable accuracy, might be used as an effective scotometer. It was obvious that no system of straight parallel lines could accomplish this. Two procedures were considered: (1) To retain the 4° assumption, endeavoring to accomplish the projections by this simple means; and (2) to reject it and make independent calculations.

It was relatively easy to plot out the tangent values of 4° intervals, using them as the radii of concentric circles and to subdivide roughly the spaces between these circles into areas of arc values equal to tan 4°. But these spaces, or, rather, the mean circumferences of two adjacent circles, were never exactly divisible by this factor. As a result, one had to choose between leaving the remnants exposed (an annoying sight) or compromising on the nearest whole number and accepting the inaccuracy. Neither choice was satisfactory.

In the end a solution was found which dispensed with these difficulties completely, permitting exact and accurate division of every circular area into a whole number of equal segments and, at the same time, avoiding the assumption that a 4° image, on any part of the retina, is going to represent one mm.

Physiologic Optics

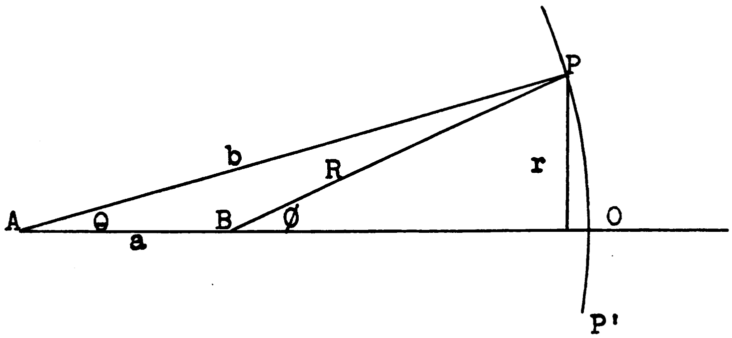
The solution is the result of independent calculation for every increment in the radii of concentric circles surrounding the macula. These increments were approximately one mm., and a secondary calculation involved mathematically adjusting them so that the circles should be exactly divisible by a whole number which represented unit areas of one sq. mm. Knowing these values in terms of angular measurements they may be projected upon any plane surface, which then serves as a scotometer. A third series of calculations converted these data into linear and angular measurements for the various distances used in tangent screen scotometry, and a fourth series provided chord measurements for inscribing the data on screens.

The necessary assumptions for the calculation were finally reduced to two data, both taken from the English translation of the revised edition of Helmholtz.[231] They are: (1) The average measurements of the perpendicular and diagonal inner diameters of the eye gave $R = 11.025$ mm. where R is the radius of the globe, and (2) the distance from the second nodal point to the retina (a+R) is 17.055 mm. (Gullstrand's figure for the complete system of the eye). These are the only two measurements assumed, but the projections, of course, involve optical principles, universally accepted in practice, which postulate sufficient similarity in human eyes to make valid comparisons. They do not take into consideration either the primary or secondary linear projection co-efficients or magnification-ratios, or caustics. In any particular case the retinal margins of a scotoma in a given eye could be correlated and accurately projected, but this could be attained only by the use of a screen tremendously distorted in three dimensions and totally impractical as an instrument. There enters here no question of focus of the oblique pencils of light—any more than with the perimeter—and such a focus is not at all essential. Helmholtz[231] (Gullstrand) stated that: "Point to point correspondence of object and image occurs in a very narrow region in the vicinity of the axis of the optical system; and the structure of the retina corresponds to this fact in the most perfect manner, since it is adapted for distinct imagery only in a very small part of it. Hence, the excellence of *the peripheral imagery in the eye* is a matter of secondary importance. If, as a first approximation, the optical system is considered as a centered system of revolution, the two image-surfaces are surfaces of revolution concave toward the forward side, the first of which, whereon are focused the image lines of parallel circles, is nearer the optical apparatus than the second, on which the radial or meridian lines are reproduced. Since Young's[33] time various investigators have endeavored to construct these image-surfaces by calculation or to compute the astigmatism for the peripheral imagery, generally obtaining results in which the retina is close to the image-surfaces or between them. . . ." Compare with Druault.[119]

One factor in projections has been stressed by Wells[177] and overlooked by several other investigators who have designed or applied scotometers. It is that measurements should be made from the nodal point. In long range instruments this is of little importance, but in short range campimeters the nodal point may be so large as to significantly change the values of calculated retinal images. Helmholtz's[231] statement is here applicable: "If, as often happens, we know in advance that the image is focused on the retina, and all we wish to do is to find the position of the image of a given point, the nodal points are sufficient for the purpose; and if it is permissible to regard the nodal points as coincident as in the reduced eye, the position of the image may be located by drawing a straight line from the luminous point to the nodal point and prolonging it to meet the retina."

Solution

The problem of making these scotometric projections was solved in the following manner, the values of R and (a+R) being taken from Helmholtz-Gullstrand, as noted above:



Let POP′ be a section of the retina, assumed to be spherical. Let OA be the optic axis, R, the radius of sphere, B, its center, A, the nodal point. Let AP = b, be any ray, and a, the distance AB. Let r be the vertical distance from the optic axis to P.

Find the area cut out of the sphere by the cone of revolution generated by line AP in terms of a, R, and Θ.

The circumference of the circle of radius r is $2\pi r$. A small element of arc is $Rd\phi$. Hence an elemental area (dS) is,

$$dS = 2\pi rRd\phi \qquad (1)$$

Therefore the area (S) between $\Theta = 0$ and $\Theta = \Theta$, or, the same thing, between $\phi = 0$ and $\phi = \phi$, is

$$S = 2\pi R \int_0^{\phi} rd\phi \qquad (2)$$

But $r = R \sin \phi$, hence (2) becomes

$$S = 2\pi R^2 \int_0^{\phi} \sin \phi d\phi \qquad (3)$$

Integrating (3)

$$S = 2\pi R^2 (1 - \cos\phi) \qquad (4)$$

From the figure

$$\left.\begin{array}{l} b \cos \Theta = a + R \cos \phi \\ \text{and} \quad b \sin \Theta = R \sin \phi \end{array}\right\} \qquad (5)$$

Eliminating b from equations (5)

$$\text{Tan } \Theta = \frac{R \sin \phi}{a + R \cos \phi} \qquad (6)$$

Substituting cos ϕ and sin ϕ derived from (4) in (6) gives

$$\text{Tan } \Theta = \frac{\sqrt{S (4\pi R^2 - S}}{2\pi R (a+R) - S} \qquad (7)$$

Now if we assign integral values of unit areas to S in (7) and calculate the corresponding tan Θ, the cone determined by tan Θ will cut out S unit areas on the retina. The sum of these areas will be exactly $S(mm.)^2$ and their projection on the screen will outline an S number of corresponding (but not equal) units (the tangential projections).

Measure a and R in mm., and S in $(mm.)^2$. Assign arbitrary values to S and find the corresponding values of tan Θ. Multiply tan Θ by the distance from the eye to the tangent screen; e. g., by 1,000 in the case of a 1 M. screen, to find the radius of the circle on the screen (in mm.) for a given value of S.

The first value of S is 1(mm.).[2] The second is (1+7) (mm.)[2] (if there are to be 7 equal areas in the ring just outside the central circle). The next value of S is $(1+7+X_3)$ (mm.),[2] etc., X_3 being the desired number of segments in the third ring.

If the number of divisions in the rings are X_1, X_2, X_3, $X_4 \ldots\ldots\ldots X_n$, the nth value of S, or $S_n, = (X_1+X_2+X_3+ \ldots\ldots\ldots\ldots X_n)$ (mm.).[2] $X_1=1$, and the other values of X are chosen so as to give approximate squares.

The problem now involves calculating the values of tan Θ and the values of X so as to fulfil two conditions:

(1) The distances between the concentric circles of radial values $\tan \Theta_1$, $\tan \Theta_2$, $\tan \Theta_3 \ldots\ldots\ldots\ldots \tan \Theta_n$ must be approximately equal to the corresponding mean arcs of the X_1, X_2, $X_3 \ldots\ldots\ldots\ldots X_n$ segments—thus forming approximate squares, and,

(2) These approximately square areas must represent the projections of unit (mm.)[2] areas on the retina.

These values correspond closely to the assumption generally made that tan 4° represents one linear mm. on the central area of the retina.

In the following formulas unit distance is understood; e. g., 1 meter.

1. $\tan \Theta_{n+1} - \tan \Theta_n$ is the radial distance between the nth and the (n+1)th rings.
2. $\frac{\tan \Theta_{n+1} + \tan \Theta_n}{2}$ is the mean radius of these rings.
3. $\pi(\tan \Theta_{n+1} + \tan \Theta_n)$ is the circumference of the mean ring.
4. $\frac{\pi(\tan \Theta_{n+1} + \tan \Theta_n)}{X_{n+1}}$ is the length of each of the X_{n+1}

arcs in the mean ring, when the area between the rings is divided into X_{n+1} equal sectors.

In order to make the sectors nearly square Θ_{n+1}, i. e., S_{n+1}, and X_{n+1}, should be chosen, so that

$$\tan \Theta_{n+1} - \tan \Theta_n = \frac{\pi(\tan \Theta_{n+1} + \tan \Theta_n)}{X_{n+1}} \ldots\ldots\ldots\ldots (8)$$

Θ_n is known. Integral values of S_{n+1} and X_{n+1} are to be determined. That is, Θ_{n+1} will be adjusted to the nearest whole number value for X_{n+1} (and hence S_{n+1}). This avoids any error involved in the assumption that each tangent of 4° is constantly going to subtend an arc of one mm. on the retina.

Calculation

Tan Θ_1 is obtained by substituting unity for S in (7).

Tan Θ_2 is obtained by successive approximation assigning reasonable values for the number of segments in the second ring, retaining that value which most nearly satisfies equation (8).

This (tan Θ_2) will give the radius of a circle to be inscribed concentric with tan Θ_1, and the interval between these circles will be divisible by a whole number (X_2) representing the unit area $(\text{mm.})^2$ projections from the retina.

Tan Θ_3 is obtained by finding the value of X_3 which, when added to X_1 and X_2 and substituted in formula (7), most nearly satisfies equation (8). This gives the means of finding the third circle.

This process is continued to the limits of the screen.

The empirical determination of X_{n+1} involves much less labor (with no loss of accuracy) than its mathematically rigid evolution (if possible). Something like a sixth order equation would be required to get (7) into (8) and solve for X_n.

An example of the detailed method of calculating the first two rings might usefully serve as an illustration.

Equations:

$$(7) \quad \text{Tan } \Theta_n = \frac{\sqrt{S_n(4\pi R^2 - S_n)}}{2\pi R(a+R) - S_n}$$

$$(8) \quad \text{Tan } \Theta_{n+1} - \tan \Theta_n = \frac{\pi(\tan \Theta_{n+1} + \tan \Theta_n)}{X_{n+1}}$$

(1) Tan Θ_1.

The radius of the first ring is easily obtained by substituting 1 for S in equation (7). This is because we want the area of the central ring to equal one sq. mm.

Therefore

$$\text{Tan } \Theta_1 = \frac{\sqrt{1\ (4\pi R^2-1)}}{2\pi R(a+R)-1} \text{ and as R and } (a+R) \text{ are}$$

known,

$$= \frac{\sqrt{1(1527.45-1)}}{1181.44}$$

$$= .033098 \text{ meter or } 33.098 \text{ mm.}$$

Here $X_1 = S_1 = 1$.

(2) Tan Θ_2.

We assign "reasonable values" to X_2. Inspection would indicate that the closest value would probably be 5, 6, or 7. We try 6, then $X_2 = 6$ and $S_2 = (X_1 + X_2) = 1 + 6 = 7$, and,

$$\text{Tan } \Theta_2 = \frac{\sqrt{7(1527.45-7)}}{1181.44-7}$$

$$= .08784$$

Now to check the "squareness" of this value, that is, to determine whether the length of the mean arc between the first and second circles is equal to the difference in their radii, we substitute this value of tan Θ_2 in equation (8). If 6 is to be the best value for the number of segments (unit areas) in the second circle, the value of Tan Θ_2 derived by using this will most nearly satisfy this equation:

$$\underset{\text{(radial increase)}}{\text{Tan } \Theta_2 - \tan \Theta_1} = \underset{\text{(arc increase)}}{\frac{\pi(\tan \Theta_2 + \tan \Theta_1)}{6}}$$

or

$$.0547 = .0633$$

This indicates that if we divide the second circle into 6 segments, the radial dimension of each segment (.0547) will be less than the arc dimension (.0633) by .0086 M. Now, obviously, if we divide the space between the rings into more units, we will decrease the length of each of the arcs, and if, in so doing, we continue to hold rigidly to the requirement that each segment *must* represent one sq. mm., this can only be done by an adjustment (increase) in the radial dimension ($\tan \Theta_2$).

We therefore try the value

$$X_2 = 7$$

Then, $S_2 = (X_1 + X_2) = 1 + 7 = 8$

and, $$\text{Tan } \Theta_2 = \frac{\sqrt{8(1527.45-8)}}{1181.44-8} = .09396$$

Repeating the check for "squareness"; i. e., comparing the relative values of radial and arc dimensions under these conditions, we get from equation (8)

$$\tan \Theta_2 - \tan \Theta_1 = \frac{\pi(\tan \Theta_2 + \tan \Theta_1)}{7}$$

$$\text{or} \qquad .0608 = .05700$$

The radial increase (.0608) is now larger than the arc increase (.05700) by .0038 M., but they are more nearly equal than in the first trial, which resulted in a difference of .0086 M., and as the difference is now in the opposite direction, the nearest value $X_2 = 7$ is retained.

It is to be noted that this empirical adjustment of values is for the sole purpose of attaining the closest approach to equality in the dimensions of the individual projected segments, and does not in any way influence their areas *which remain constantly the projection of unit square millimeters.*

This procedure was repeated with the individual circles out to the 16th ring, always calculating two values, sometimes three, and once four, in order to be sure that the nearest approach to uniformity was attained. The calculation in every case included values above and below the optimum.

A third series of calculations involved transferring the data found into values suitable for screens used at various working distances (500, 750, 1,000 and 2,000 mm.). These values were supplemented with values for the radii of the circles subtending five-degree intervals up to the limits at varying distances of a screen two meters on edge; and a fourth series of data were calculated to indicate the chord values in laying off the arcs on the various screens. These will be found of value to anyone marking a screen without the use of a large and accurate protractor. The chord values have been derived for both the scotometric and the ordinary designs to be used on screens at the distances noted above. They represent the linear measurements indicated in the following diagram (Fig. 7): If the chord of the arc of each of X segments in the (n+1)th ring is equal in length to Y and Y is divided into two equal parts (y and y) and the angle subtended by each of the segments in the (n+1)th ring is X, then

$$\frac{y}{Z} = \sin \tfrac{1}{2}X$$

where Z is the radius of the outer ring ($\tan \Theta_{n+1}$).
From this,

$$y = Z \sin \tfrac{1}{2}X$$
$$\text{and,} \quad 2y = 2Z \sin \tfrac{1}{2}X$$
$$= 2 \tan \Theta_{n+1} \sin \tfrac{1}{2} X_{n+1}$$

The results of these calculations will be found in the appended tables, and in viewing them one fact should not be forgotten: The data there, running to five and six decimal places on a meter standard and to seconds of arc, should in no way be taken as representing possible accuracy in practice or even probable error in theory. It seems unnecessary to reiterate that in scientific work it is quite useless, if not actually misleading, to calculate certain factors to the fourth or fifth decimal place when other factors introduce a probable error of 2 or 3 per cent., and I believe that if this degree of reliability were uniformly attained in scotometry, it would represent a great advance.

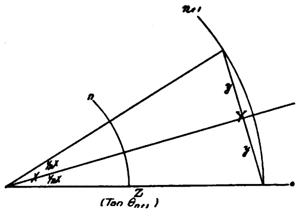


Fig. 7.—Calculation of chords. $Y=2y=$chord of arc of each of X segments in $(n+1)^{st}$ ring; $\frac{y}{Z}=\sin\frac{1}{2}X$; $y=Z\sin\frac{1}{2}X$; $2y=2Z\sin\frac{1}{2}X$ $=2\operatorname{Tan}\Theta_{n+1}\operatorname{Sin}\frac{1}{2}X_{n+1}$.

The calculations were extended to the places indicated not from any false sense of accuracies but from a practical necessity. This arose in several places. In the calculations carried out in detail above it was not possible to get a close adjustment to "squareness" of the areas because they were segments of circles of short radius. But when the fourth circle was reached the difference in the two dimensions was .00028, the fifth showed .00094, the eighth, .0005, the ninth, .00004, the twelfth, .00005, and in the fifteenth calculation to eight places showed no difference in the two dimensions.

Again, in the calculation of the chords it was necessary to work well beyond practical accuracy because, as there were 56 segments in the outer rings, any error introduced into the chord dimension would be multiplied by this factor in stepping off the segments around the circle.

The Scotometric Tangent Screen

The scotometer illustrated is one of several I have built in the past few years.

It consists of a wooden portrait frame of the wedge-joint type used by artists for stretching canvases. It is two meters on edge and has one vertical and one horizontal cross bar. The sides are bevelled inward so that the enclosed edge of the frame is thinner than the outside edge. This permits attaching a backing for the gray cloth without interfering with smooth stretching of the latter. The backing is a thick layer of "silence cloth," obtainable in most department stores, which is usually used as a protective covering for dining tables. It has several advantages over felt, as it is much less expensive and is supplied with many rows of stitches paralleling one another at intervals of about one inch. This cloth is stretched tightly and is tacked to the front surface of the frame on the bevelled area. The top of the screen is so chosen that the stitches run vertically and thus serve to support the backing and prevent sagging. The gray cloth is stretched over this backing, and the edges of the cloth are carried over the edge of the framework and

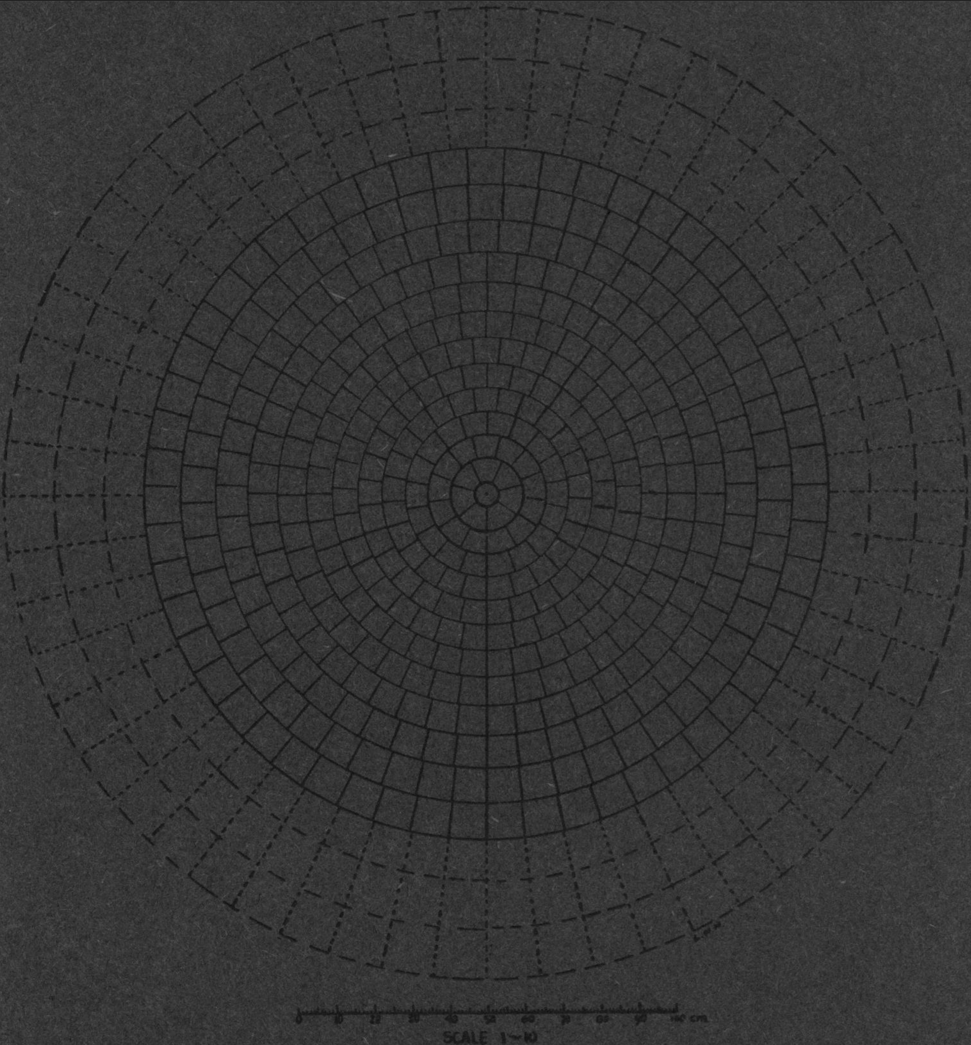


Fig. 8.—Diagram of scotometric tangent screen.

See description at bottom of opposite page.

tacked (after tucking) to the sides. Tacks should be inserted both in the backing and in the covering at one-half to three-quarter inch intervals.

The acquisition of a proper cloth for this surface is not always easy, and it should not be purchased until a variety of samples have been examined and tested. I have found a good quality serge without pattern to be satisfactory. It should be free from color tone and, as stated above, a reflection factor of 10 per cent. represents my opinion of a compromise. The reflection factor of the background illustrated is between 8 and 10 per cent. (Fig. 8.)

As soon as the gray cloth is fastened in position the wedges in the joints at the back of the frame may be tightened by a light blow with a hammer. It will be found easier to mark the screen while it is hanging from the molding, but before it is attached to the wall. This attachment, when made, should be accomplished by means of screws which hold the screen firmly in position. The height should be about six inches above the floor, depending to some extent upon the office furniture used, but both stool and head-rest should be adjustable.

With the screen in position, a mark is placed at its center to serve as a fixation point. This may be a one to two mm. brad head, painted white, or, preferably, a fastener knob similar to that used for automobile or boat coverings. The knob has the appearance of a brass tack with a collar surmounted by a spherical head. The top of the head should be filed flat and painted white. Upon such a device may be clipped larger fixation objects to be used in central scotomas,

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Fig. 8.—Reduced scale markings of scotometric tangent screen. The scale beneath the facing illustration represents one meter. Each individual area represents 1 $mm.^2$ on the retina. The dotted lines indicate extensions possible at 750 mm. This diagram is printed on paper with a reflection factor of 8 to 10% viewed at 45°. The tone is not exactly neutral, but it represents an approximation to that of the tangent screen.

a minute lamp socket to hold a light for the same purpose, or the ends of tangential scales for taking readings.

The screen may be marked according to preference. I do not believe subdued markings interfere in any way with the examination, but some surgeons prefer the blank screen. The style of marking usually encountered is the inscription of tangential values for 5° or 10° intervals and the meridian markings at 15° intervals. If it is desired, the scotometric projections illustrated may be used. Circular inscriptions should be made by means of a beam compass and not a piece of string or other extensible material. I have tried ordinary ink, India ink, and mixtures of each with gum arabic, but have never been satisfied with the result. A brown or dark yellow, hard, crayon pencil kept finely pointed serves well for marking, and these marks may be renewed from time to time or stitched in with dark gray thread. This stitching should be done from the back, having the needle emerge on the front surface, only to take a one mm. step and return. A certain pride will result from carefully spacing these stitches at 1° intervals. Another method of applying marks which leaves them almost imperceptible to the patient is to use a needle attached to a coarse thread with several rough knots tied into it. The needle is passed forward from the back of the screen, and may be drawn through a loose cotton ball before reaching the screen. As the thread and knots emerge they drag with them fine tufts of the white backing. If too long, these tufts may be trimmed off with scissors. Neatness and accuracy with this method produce an admirable result.

Distance is maintained by means of a head-rest affixed to a table. It should be checked at every examination, and as the nodal point lies about seven mm. behind the cornea, and the lid adds one or two mm. to this distance, a rod 99 cm. long is sufficient for practical accuracy. Excellent work is done by some ophthalmologists who dispense with the head-rest and use simply a shield attached to the fixation object by a cord of suitable length. This serves to maintain the proper distance, as the shield is held over the eye not being studied.

The illumination on the unit here presented is supplied by two Macbeth JLS 17 daylight lamps. These give a diffuse light of a quality similar to that from uniform overcast skies, and an apparent color temperature of from 6,000° to 7,000° K. The intensity at the center of the screen and at various points on the 30° circle in foot-candles is:

5.2	5.3	5.8
5.3	6.6	6.3
5.0	5.1	5.6

The illumination may be intensified at the sacrifice of extent and some uniformity by detaching the rod which holds the lamps the proper distance apart and swinging both lamps in toward the screen, re-directing the beams as necessary. The brackets are of home construction, made from standard brass fittings turned down on a lathe. The horizontal bars are 6 feet 2 inches from the floor, so that one may pass beneath them.

A short range campimeter—made after seeing that of Evans, is attached to the chin-rest table by a hinge. The campimeter consists of a Monel metal plate painted dark and bearing a slider on its upper edge. To this slider is attached a 55 mm. orthogon lens of +5.25 strength, which is held at a distance of 195 mm. from the screen. It has been used mainly for comparative studies of screen and campimeter values.

B. Scotometric and Tangential Scales

In the preceding pages I have tried to outline the historical and technical developments in scotometry. I have indicated a problem as it has appeared to me and my solution of it. This has involved the conception and production of a scotometer which has proved valuable to me. But, in Elliot's words: "The medical man is ever an individualist and it is in the last degree unlikely that the methods of perimetry will ever be really standardized. What is really important to realize is that—any intelligent and painstaking surgeon can evolve a system which will in his own work yield strictly comparable and practically consistent results." The value of the unit here described extends beyond the scotometric feature—which can be applied to any tangent screen to include adaptation to qualitative principles while sacrificing a minimum of sensitivity for quantitative work. I, with others, have proved its efficiency in quantitative and qualitative scotometry. But the entirely laudable individuality of ophthalmologists will always lead to the use of various screens and of various distances dictated by their personal preferences. In order to extend the usefulness of the scotometric projections, I have devised scales applicable to a variety of screens. (Figs. 9, 10, 11.) These scales include one or more segments from each of the circles out to the limits of the screen, and by merely clipping them on to the fixation mark or holding the zero point over that mark and extending the scale in any given direction, the size and area of a scotoma may be estimated, if not accurately measured.

The scale is made by drawing the design, taken from the data in the tables, on the surface of a plate glass, from which direct prints are made on a sensitized plate, and from this plate copies by contact printing are made on heavy film. These are converted by a special process into white lines on a clear background. On each scale, opposite the scotometric calibration, is a tangential scale indicating degrees of eccentricity from the line of fixation for various distances. This serves to replace the concentric circles at 5° to 10° intervals usually inscribed on tangent screens. I hope the scale and the screen it was originally designed for will find useful application in the service of scotometry.

IV. TANGENT SCREEN DATA TABLES

TABLE I.—TANGENT SCREEN DATA

1,000 Millimeters. Scotometric

θ	Tan θ	Angle θ			S	X	Angle X			$\frac{X}{2}$			Y Chord (2 Tan θ sin ½ X)
	meters	°	′	″			°	′	″	°	′	″	meters
θ_1	.0331	1	53	44	1	1	360	00	00	..	..	..	..
θ_2	.0940	5	22	04	8	7	51	25	48	25	42	54	.081528
θ_3	.1533	8	42	50	21	13	27	41	31	13	50	45	.073362
θ_4	.2137	12	03	50	40	19	18	56	49	9	28	25	.070346
θ_5	.2762	15	26	20	65	25	14	24	00	7	12	00	.069226
θ_6	.3395	18	45	20	95	30	12	00	00	6	00	00	.070983
θ_7	.4054	22	04	00	130	35	10	17	10	5	08	35	.072678
θ_8	.4750	25	24	20	170	40	9	00	00	4	30	00	.074529
θ_9	.5480	28	43	20	214	44	8	10	52	4	05	26	.078179
θ_{10}	.6262	32	03	20	262	48	7	30	00	3	45	00	.081916
θ_{11}	.7099	35	22	20	313	51	7	03	32	3	31	46	.087407
θ_{12}	.7995	38	38	40	366	53	6	47	31	3	23	46	.094727
θ_{13}	.8975	41	54	30	421	55	6	32	42	3	16	21	.102470
θ_{14}	1.0037	45	06	20	477	56	6	25	41	3	12	50	.112530
θ_{15}	1.1230	48	18	35	533	56	6	25	41	3	12	50	.125900
θ_{16}	1.2549	51	27	00	589	56	6	25	41	3	12	50	.140710

TABLE II.—TANGENT SCREEN DATA

NORMAL TANGENT AND CHORD VALUES

1,000 Millimeters. Tangent Values at 5° Intervals. Chord Values at 15° Meridians

θ	Angle θ	Tan θ	X	Sin $\frac{X}{2}$	Y Chord (2 Tan θ sin ½ X)
	°	meters	°		meters
θ_1	5	.08749	15	.13053	.02284
θ_2	10	.17633	15	.13053	.04603
θ_3	15	.26795	15	.13053	.06995
θ_4	20	.36397	15	.13053	.09502
θ_5	25	.46631	15	.13053	.12133
θ_6	30	.57735	15	.13053	.15092
θ_7	35	.70021	15	.13053	.18279
θ_8	40	.83910	15	.13053	.21905
θ_9	45	1.00000	15	.13053	.26106

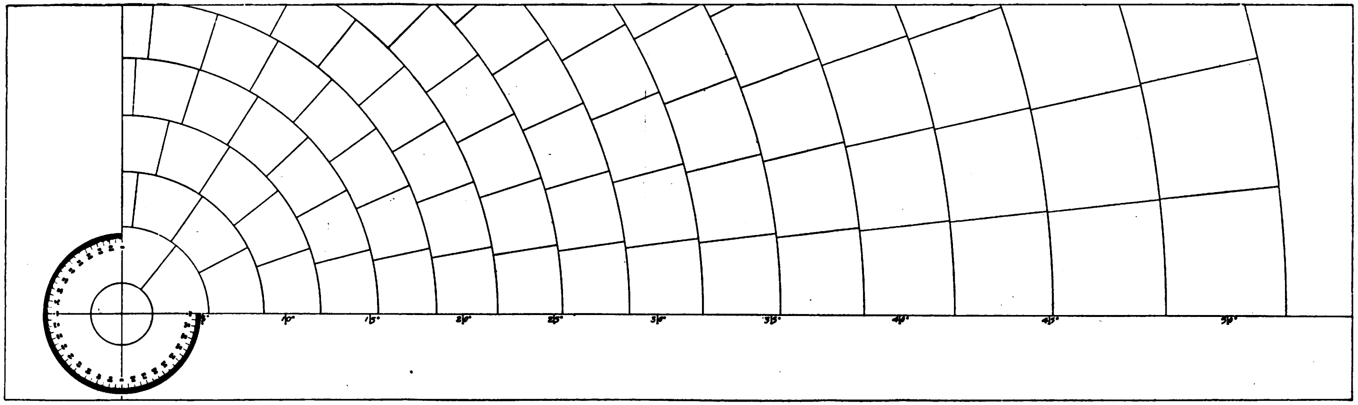

Fig. 9.—Scotometric tangent scale. For use at 750 millimeters. Each area of scale represents one square millimeter on the retina; lower scale indicates degrees from fixation point; protractor indicates meridian.

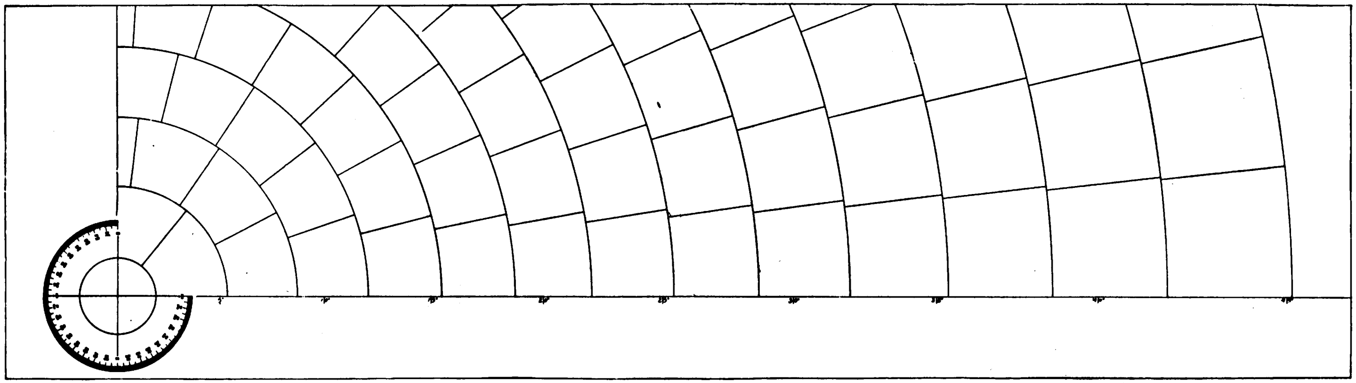

Fig. 10.—Scotometric tangent scale. For use at 1,000 millimeters. Each area of scale represents one square millimeter on the retina lower scale indicates degrees from fixation point; protractor indicates meridian.

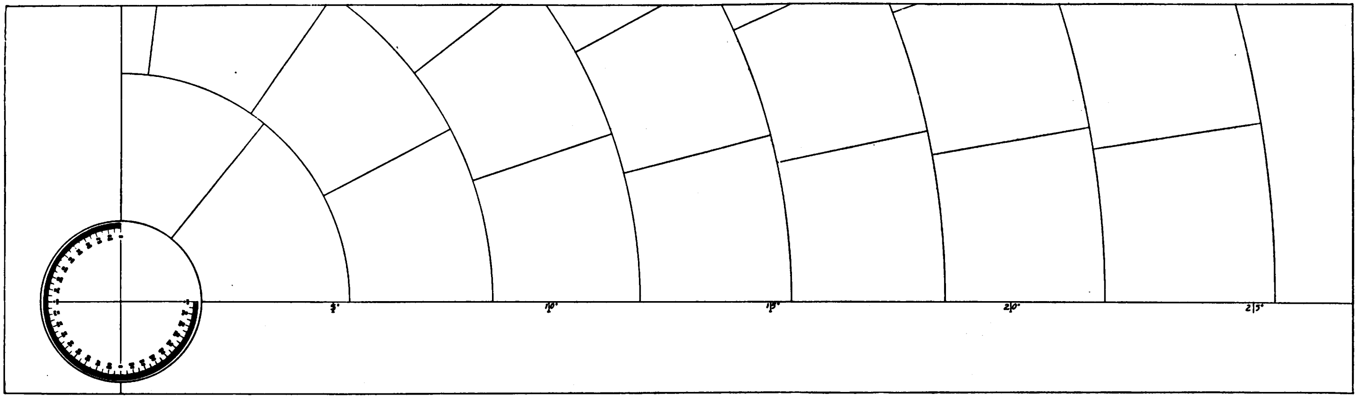

Fig. 11.—Scotometric tangent scale. For use at 2,000 millimeters. Each area of scale represents one square millimeter on the retina; lower scale indicates degrees from fixation point; protractor indicates meridian.

In Figs. 9, 10, and 11 are represented the scotometric tangent scales for use at 750, 1,000, and 2,000 mm. respectively. After the scotoma has been outlined on a tangent screen at the distance chosen, the corresponding scale is placed over the screen with its zero point (at the center of the protractor) on the fixation mark. The scale is then rotated into the area of the scotoma. The protractor gives the exact meridian on which the scotoma lies, the lower scale the distance in degrees from the macula, and from the unit areas overlying the outlines its area can be accurately estimated. The scales are approximately 40 by 120 cm.

TABLE III.—TANGENT SCREEN DATA

750 Millimeters. Scotometric

θ	Tan θ	Angle θ			S	X	X Incr. (X_{n+1} less X_n)	Angle X			$\frac{X}{2}$			Sin $\frac{X}{2}$	Y 2y (2 Tan θ_{n+1} sin ½ X_{n+1})
	meters	°	′	″				°	′	″	°	′	″		meters
θ_1	.0248	1	53	44	1	1	..	360	00	00	..	..	..	..	..
θ_1	.0705	5	22	04	8	7	6	51	25	48	25	42	54	.43389	.06118
θ_3	.1149	8	42	50	21	13	6	27	41	31	13	50	45	.23931	.05499
θ_4	.1603	12	03	50	40	19	6	18	56	49	9	28	25	.16459	.05276
θ_5	.2071	15	26	20	65	25	6	14	24	00	7	12	00	.12533	.05191
θ_6	.2546	18	45	20	95	30	5	12	00	00	6	00	00	.10453	.05323
θ_7	.3040	22	04	00	130	35	5	10	17	10	5	08	35	.08964	.05451
θ_8	.3562	25	24	20	170	40	5	9	00	00	4	30	00	.07846	.05589
θ_9	.4110	28	43	20	214	44	4	8	10	52	4	05	26	.07133	.05863
θ_{10}	.4696	32	03	20	262	48	4	7	30	00	3	45	00	.06540	.06141
θ_{11}	.5324	35	22	20	313	51	3	7	03	32	3	31	46	.06155	.06550
θ_{12}	.5996	38	38	40	366	53	2	6	47	31	3	23	46	.05923	.07105
θ_{13}	.6731	41	54	30	421	55	2	6	32	42	3	16	21	.05708	.07685
θ_{14}	.7527	45	06	20	477	56	1	6	25	41	3	12	50	.05606	.08439
θ_{15}	.8436	48	18	35	533	56	0	6	25	41	3	12	50	.05606	.09418
θ_{16}	.9412	51	27	00	589	56	0	6	25	41	3	12	50	.05606	.10553

TABLE IV.—TANGENT SCREEN DATA

NORMAL TANGENT AND CHORD VALUES

750 Millimeters. Tangent Values at 5° Intervals. Chord Values at 15° Meridians

θ	Angle θ	Tan θ	X	Sin $\frac{X}{2}$	Y Chord (2 Tan θ sin ½ X)
	°	meters	°		meters
θ_1	5	.06561	15	.13053	.01712
θ_2	10	.13224	15	.13053	.03452
θ_3	15	.20096	15	.13053	.05246
θ_4	20	.27547	15	.13053	.07126
θ_5	25	.34976	15	.13053	.09129
θ_6	30	.43301	15	.13053	.11319
θ_7	35	.52516	15	.13053	.13709
θ_8	40	.62932	15	.13053	.16429
θ_9	45	.75000	15	.13053	.19579
θ_{10}	50	.89385	15	.13053	.23334
θ_{11}	55	1.07107	15	.13053	.27971

TABLE V.—TANGENT SCREEN DATA

2,000 Millimeters. Scotometric

Θ	Tan Θ	Angle Θ			S	X	Angle X			$\frac{X}{2}$			Y (2 Tan Θ_{n+1} sin ½ X_{n+1})
	meters	°	′	″			°	′	″	°	′	″	meters
Θ_1	.0662	1	53	44	1	1	360	00	00	..	..	..	..
Θ_2	.1879	5	22	04	8	7	51	25	48	25	42	54	.16306
Θ_3	.3066	8	42	50	21	13	27	41	31	13	50	45	.14672
Θ_4	.4274	12	03	50	40	19	18	56	49	9	28	25	.14069
Θ_5	.5524	15	26	20	65	25	14	24	00	7	12	00	.13845
Θ_6	.6790	18	45	20	95	30	12	00	00	6	00	00	.14197
Θ_7	.8108	22	04	00	130	35	10	17	10	5	08	35	.14536
Θ_8	.9500	25	24	20	170	40	9	00	00	4	30	00	.14906
Θ_9	1.0960	28	43	20	214	44	8	10	52	4	05	26	.15636

TABLE VI.—TANGENT SCREEN DATA

NORMAL TANGENT AND CHORD VALUES

2,000 Millimeters. Tangent Values at 5° Intervals. Chord Values at 15° Meridians

Θ	Angle Θ	Tan Θ	X	Sin $\frac{X}{2}$	Y Chord (2 Tan Θ sin ½ X)
	°	meters	°		meters
Θ_1	5	.17498	15	.13053	.04568
Θ_2	10	.35266	15	.13053	.09206
Θ_3	15	.53590	15	.13053	.13990
Θ_4	20	.72794	15	.13053	.19004
Θ_5	25	.93262	15	.13053	.24346
Θ_6*	30	1.15470	15	.13053	.30144
Θ_7*	35	1.40042	15	.13053	.36558
Θ_8*	40	1.67820	15	.13053	.43810
Θ_9*	45	2.00000	15	.13053	.52210

* Extension for larger screen.

TABLE VII.—TANGENT SCREEN DATA

500 Millimeters. Scotometric.

θ	Tan θ	Angle θ			S	X	Angle X			X/2			Y 2y (2 Tan θ_{n+1} sin ½ X_{n+1})
	meters	°	′	″			°	′	″	°	′	″	meters
θ_1	.01650	1	53	44	1	1	360	00	00	..	..	..	..
θ_2	.04698	5	22	04	8	7	51	25	48	25	42	54	.04076
θ_3	.07665	8	42	50	21	13	27	41	31	13	50	45	.03668
θ_4	.10685	12	03	50	40	19	18	56	49	9	28	25	.03517
θ_5	.13810	15	26	20	65	25	14	24	00	7	12	00	.03461
θ_6	.16975	18	45	20	95	30	12	00	00	6	00	00	.03549
θ_7	.20270	22	04	00	130	35	10	17	10	5	08	35	.03634
θ_8	.23750	25	24	20	170	40	9	00	00	4	30	00	.03726
θ_9	.27400	28	43	20	214	44	8	10	52	4	05	26	.03909
θ_{10}	.31310	32	03	20	262	48	7	30	00	3	45	00	.04095
θ_{11}	.35495	35	22	20	313	51	7	03	32	3	31	46	.04370
θ_{12}	.39975	38	38	40	366	53	6	47	31	3	23	46	.04736
θ_{13}	.44875	41	54	30	421	55	6	32	42	3	16	21	.05124
θ_{14}	.50185	45	06	20	477	56	6	25	44	3	12	50	.05626
θ_{15}	.56150	48	18	35	533	56	6	25	44	3	12	50	.06295
θ_{16}	.62745	51	27	00	589	56	6	25	44	3	12	50	.07035

TABLE VIII.—TANGENT SCREEN DATA

NORMAL TANGENT AND CHORD VALUES

500 Millimeters. Tangent Values at 5° Intervals. Chord Values at 15° Meridians

θ	Angle θ	Tan θ	X	Sin X/2	Y Chord (2 Tan θ sin ½ X)
	°	meters	°		meters
θ_1	5	.04374	15	.13053	.01142
θ_2	10	.08816	15	.13053	.02301
θ_3	15	.13397	15	.13053	.03487
θ_4	20	.18198	15	.13053	.04721
θ_5	25	.23315	15	.13053	.06066
θ_6	30	.28867	15	.13053	.07546
θ_7	35	.35010	15	.13053	.09139
θ_8	40	.41955	15	.13053	.10952
θ_9	45	.50000	15	.13053	.13053
θ_{10}	50	.59590	15	.13053	.15557
θ_{11}	55	.71405	15	.13053	.18641
θ_{12}	60	.86605	15	.13053	.22609
θ_{13}	65	1.07225	15	.13053	.27992

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Note: An effort has been made to consult all the original material in the following list. In a few cases insufficient knowledge of the language or inaccessibility of the material has aborted this effort. Such references are marked n. v. (not verified) and/or the source of the quotation is indicated in parentheses.

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