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FOUNDATIONS OF MODERN OCULAR VEGETATIVE PHYSIOLOGY

I. REFRACTIVE INDEX OF THE OCULAR MEDIA

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„There is perhaps no part of natural philosphy more interesting, than that which relates to the determination of the physical properties of bodies. An accurate knowledge of these properties is of extensive use in the arts and sciences and has conducted the experimental philosopher to some of the finest investigations and discoveries of which the human mind can boast."
SIR DAVID BREWSTER (1813, p. 240)

The investigation of the physical properties of substances during the eighteenth century has been confined, primarily, to the mechanical and chemical properties of opaque bodies, and it was only at the beginning of the nineteenth century that interest turned towards the study of the *refractive index* (or *„refractive power"*) of transparent media. Admittedly, there were exceptions to this statement, and the instrument maker FRANCIS HAUKSBEE, the Elder, (? – 1713) [1] may perhaps be singled out, as he would appear to have been the first to have attempted to estimate, experimentally, the refractive index of the ocular media. [2] His experiments, inclu-

[1] HAUKSBEE was HOOKE's Successor as Curator of Experiments, at the Royal Society.

[2] Although not related to the ocular media, THOMAS HARRIOTT (1560 – 1621) as early as 1606 used hollow glass prisms, which he filled with liquids such as turpentine, salt water, spirits of wine, and obtained estimates of the refractive indices for middle rays and red rays (thus anticipating NEWTON's experiments on dispersion), See JOHS. LOHNE (1959).

ding his table of refractive indices (powers), appeared in the *Philosophical Transactions*, (1710) [3] and also in his previously published popular *Mechanical Experiments . . .* (1709) [4]. Hauksbee described his experimental apparatus and procedures in the following manner:

> The whole *Apparatus* its fix'd on a Table, parallel to is Surface. On one and the same *Axis* is fix'd a Sextant, of a *Radius* of 4 Feet, and a moving Limb to bear the Object. The Sextant is divided into Degrees and Minutes by a Diagonal, and remains always fixt. The Object, which is plac'd on the moving Limb is seen parallel with the Table when observ'd through the Prism, and at no Degrees on the Sextant; but when any Transparent Liquid is put into the same, the Object must be elevated till it appears to the Eye: Then observing how many Degrees and Minutes the *Index* on the Limb cuts on the Sextant, we note it, and call it the Angle of Observation. Thus for different Liquids you have different Elevations of the Object, as you will find by the following Table. The Sight-Slit (if I may call it so) is composed of two pieces of Box Wood, plan'd parallel to one another: These Pieces are separated only by 3 slender Slips of common Cards; and with that Intervention are screw'd down one upon the other, exactly parallel with the *Axis* of the moving Leg and Sextant. The Prism, thro' which it directs the Sight, is plac'd pretty near it, and consists of an Angle of d.' 44.54, which Angle is fix'd Perpendicular to the Plane of the Table, its upper side being parallel with the same. The Object is a Piece of white Paper, in form of a Cross, pasted on a black board, is fix'd at the end of the moving Limb, which is in length about 7 Feet from the Sight; its Diameter is about 2½ Inches, which just comprehends the Sight through the Slit; so that when the Object is wholly within view, we conclude the Observation to be exact. With this *Apparatus* the Experiments are made as well by Candle-light as Day-light, (the Presence of the Sun beams being no ways necessary) and I think they may be depended on as pretty Accurate. I have taken the Specifick Gravity of the several Liquids, where I could obtain a sufficient quantity, as appears by the Table: So that if any Person should have the Curiosity to repeat these Experiments, he must expect a different Angle of Observation, if the Specifick Gravity agree not with the Table; for sometimes it happens, that Liquids of the same Denomination are not always of an equal goodness, and consequently will have a different Specifick Gravity and Refraction.
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> The Christalline Humour of the Ox Eye I prest into the Angle of the Prism, whereby it received the form of it, and gave the Angle of Observation, as specify'd in the Table. I could not see the common Object thro' it, but was forc'd to make use of a Candle for that purpose; the Flame whereof appeared very broad, at least 5 or 6 Inches, nearly in the form of a Half Moon: But what should occasion such a Change of Figure, I cannot at present determine.

Generally speaking, the method of measuring refractive index, was to form a prism of the transparent substance to be examined, and then to estimate the deviation of a solar ray from its original direction, when transmitted through the two surfaces.

Another mid-eighteenth century method, suggested by LEONHARD EULER (1747 – 1758) was to enclose the fluid between two large meniscuses of glass, and then to observe the focal length of the compound lens, as altered by the convex lens formed by the enclosed fluids (the refractive index of the glass and curvatures of the

[3] From HAUKSBEE's ratios, we can calculate that the refractive indices he found for the vitreous and crystalline humour (ox eye) were 1.336 and 1.463, respectively.

[4] The second edition appeared in 1719. An influential work, promoting interest in natural phenomena, it was the first work in the 18th century to provide a detailed account of luminescence, see E. NEWTON HARVEY (1957).

meniscus lenses being pre-determined. This method was in fact adopted by EULER's son (ALBERT) and used for determining the refractive powers of several substances. EULER's method in a way anticipated the principles later employed by BREWSTER, in the modified microscope method to be discussed below.

Early Nineteenth Century: — Refractive Index of Ocular Media

WILLIAM WOLLASTON (1766 – 1829) immediately appreciated the practical utility of establishing the refractive powers of transparent substances, in view of the small quantity of substance required in order to establish its physical properties. By his newly designed method, WOLLASTON (1802, p. 367) found that the refractive power of genuine oil of cloves, was as high as 1.535, ,,*but I have also purchased*", he noted, ,,*oil by this name, which did not exceed 1.498, and which had probably been adulterated by some less refractive oil.*" It was a consideration of such practical aspects, which was one of the prime objects which led WOLLASTON to examine almost a hundred different media. BREWSTER's later experiments included the determination of 130 transparent substances (ranging from marmalade to haddock eye!).

Whatever other advantages were to be gained from the uses of WOLLASTON's new apparatus (prompted by a consideration of NEWTON's work), for estimating refractive index, it is evident that its application to the examination of the ocular media was uppermost in his mind. As WOLLASTON was quick to point out, he would ,,*not so much insist on this advantage, were it not for the opportunity hereby afforded of examining the crystalline lens of the eye, which is not known to be generally more dense in the centre than its surface*". . . (1802, p. 369). WOLLASTON's values for the ocular media have been compiled from his tables, and are shown in Table 1.

Table I. Refractive indices of the ocular media (WOLLASTON).

Centre of cryst. lens (fish) and dry cryst. lens of ox	. . .	. . .	1,530
	. . .	. . .	1,447
Cryst. lens (ox) varies from to	. . .	. . .	1,380
Computed average of cryst. lens (ox)	. . .	. . .	1,430
Vitreous humour of an eye	. . .	. . .	1,336

When discussing his table of indices, Wollaston mentions that not only the ,,*limits*" (ascertained by trial) of refractive power in the crystalline lens of an ox were obtained, but so also were the average values, which he computed from the refractive density of a dried crystalline lens (ox). These values were arrived at by estimating the weights taken „*in the recent state*", and by measuring the quantity of water that was lost by drying (1802, p. 369).

This aspect of WOLLASTON's paper became somewhat neglected, mainly because of the importance that became attached to the end of the paper describing his highly important discovery of the spectral lines. WOLLASTON's method for determining the refractive index, described in 1802, was apparently known to THOMAS YOUNG (1773 – 1829) at least two years before WOLLASTON's publication, as he mentions that „*the method* [was] *suggested to me by Dr. WOLLASTON*". (1807, p. 580). Young further noted, that

„Wollaston has ascertained the refraction out of air, into the centre of the recent crystalline of oxen and sheep to be nearly as 143 to 100 [1.43]; into the centre of the crystalline of fish and into the dried crystalline of sheep as 152 to 100 [1.52] (1807)

YOUNG found the refractive power of the center of the lens (recent state) to water as 21 to 20 (i. e. 1.050 with respect to water, or 1.400 with respect to air). By calculation, based on an equal density crystalline lens, YOUNG (1807) arrived at the ratio 14 to 13, i. e. 1.0769 (to water), and 1.4359 (to air), respectively. Realizing that the crystalline was not of equal density throughout, and hence would necessitate some modification of his calculations, YOUNG (1807) concluded that

„On the whole, it is probably that the refractive power of the centre of the human crystalline, in its living state, is to that of water nearly as 18 to 17 [1.4117, with respect to air]; that the water, imbibed after death, reduces to the ratio of 21 to 20 [i. e. 1.400 with respect to air]; but that, on account of the unequable density of the lens, its effect on „the eye is equivalent to a refraction of 14 to 13 for its whole size."

It is interesting to compare YOUNG's theoretical results with the findings of later writers. L. MATTHIESSEN, (1830 – 1906) many years after YOUNG, derived a simple, approximate formula for estimating the refractive index of the crystalline lens. Using this formula, [5] for the values later obtained by BREWSTER and CHOSSAT (to be discussed below), we are able to compare their results. From the results obtained by YOUNG, we see that they are almost the average of the later values obtained by BREWSTER and CHOSSAT. TSCHERNING's value represents the refractive index he used for his schematic eye, and is very close to that of YOUNG's results., A new method of ascertaining the total index, which MARIUS TSCHERNING (1854 – 1939) had arrived at, in collaboration with STADTFELT, indicated that the index should in all probability be lower than 1.4371. A revised value of 1.42 (i. e. the same as BREWSTER's value), was suggested, although STADTFELT's results on his eleven eyes (within thirty-six hours after enucleation), gave a total index of 1.4368, which again is quite close to YOUNG's value.

[5] MATTHIESSEN's Law: $N_{total} = 2n_2 - n_1$ where n_1 represents the central refractive index, and n_2 refers to the peripheral refractive index [C. S.] CHARLES SHEARD (1918).

Essentially, SIR DAVID BREWSTER (1781 – 1868), in claiming that the subject was virtually in its infancy, and that the determination of refractive and dispersive powers, including the confirmation and correction of results of earlier workers would be particularly useful to both experimental philosophers and chemists.

BREWSTER's extensive researches on refractive index followed very shortly after WOLLASTON's investigations. He mentions that although aware of WOLLASTON's instrument for ascertaining refractive power, he had not adopted it. What was of interest to BREWSTER (1813, p. 245) however, was the *enormous difference between many of his* [WOLLASTON's] *results and mine* [BREWSTER's]". BREWSTER was convinced that the discrepancy in results on the basis of YOUNG's assumption, that WOLLASTON's figures belonged to the extreme red rays. BREWSTER, therefore, concluded that all of WOLLASTON's measurements ,,*would need to be increased by half the angle of dispersion, a quantity which cannot be obtained till the index of refraction has been previously determined*". (1813, p. 242) In addition to this objection, BREWSTER suspected that the principle of prismatic reflection was liable to various sources of error *against which Dr. Wollaston has not sufficiently provided*". (1813, p. 245)

BREWSTER's attention had been directed to the subject of refractive power as a result of using an apparatus which he had previously designed, for viewing objects under water. In order that it might be adapted for estimating the refractive power of substances, the apparatus needed considerable modification. A description of BREWSTER's modified apparatus (a compound microscope) and analysis of his results has received a detailed discussion by the author (LEVENE, 1966) elsewhere. BREWSTER's findings (Table 2) for refractive power have been converted to refractive index, using THOMAS YOUNG's formulae (1814 – 1827). ,,*Powers*" to ,,*index*" has been included by the writer as these are more intelligible to the modern reader. Although a consideration of the implications of the values presented in table 2 is not within the scope of the present discussion, it is worth pointing out that BREWSTER's results compare very favorably with modern values.

These were some of the earliest of BREWSTER's experiments relating to the crystalline lens. From an examination of his dozens of papers on optics, during the following forty years, the subject of the crystalline lens occupied much of his thought, particularly with reference to polarization effects (1816, 1813) in the applications of which he was a pioneer.

At about the same time as BREWSTER's experiments (1818), a most detailed study had been independently conducted in France by CHOSSAT. CHOSSAT's investigations included the refractive index of the ocular media in man, bear, ox, pig, elephant, turkey, and carp (Bull Soc., 1818, p. 94; Bib, 1818, pp. 26 – 31). [6]

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[6] This reference probably refers to JEAN FRANÇOIS GABRIEL DE CHOSSAT DE SAINT SULPICE (1755 – 1841).

Table II. The refractive powers of ocular media (from BREWSTER), and their conversion to refractive index (YOUNG).

Ocular Media Examined	Refractive Power (BREWSTER)	Refractive Index (YOUNG)
Outer coat, crystalline lens (lamb)	2.541	1.386
Central portion, crystalline lens (lamb)	2.829	1.436
Middle coat, crystalline lens (lamb)	2.780	1.428
Fluid from above lens, after puncturing capsule	2.473	—
Vitreous humour (lamb)	2.346	1.345
Outer coat, crystalline lens (old haddock)	2.670	1.439
Outer coat, crystalline lens (young haddock)	2.843	1.410
Fluid between crystalline lens and capsule (young haddock above)	2.491	—
Aqueous humour (haddock)	2.326	1.341
Vitreous humour (pigeon)	2.380	1.353
Crystalline lens (pigeon)	2.650	1.406
Cornea (lamb)	2.541	1.386
Vitreous humour (haddock)	2.326	1.340

Details were given of the progressive increase in index, proceeding from the outer coat of the lens to the nucleus. Although in Table 3 only two values for the lens in each case have been given, these values representing the maximum change from the outer coat to nucleus, CHOSSAT's actual study gave as many as nine readings for any one crystalline lens. Comparing the results of BREWSTER and CHOSSAT (Table 4), it will be seen that CHOSSAT's mean for his three lens averages, compares with BREWSTER's results for the ,,whole'' lens.

BREWSTER claimed his own results as the more accurate, based on the view of the improbability of the outer coat of the lens (given by CHOSSAT as 1.338) being inferior to that of the vitreous (BREWSTER and GORDON, 1819) (CHOSSAT's value being 1.339). This represented a difference, incidentally, of 0.001! As supporting evidence BREWSTER stated that his results for the central portion of the lens nucleus (1.339), coincided almost exactly with those of YOUNG's earlier finding

(1.4025), a difference of 0.0635. As the human eye used by BREWSTER was from a female, BREWSTER suggested that a possible cause of the difference in results might be a sex difference. Even so, BREWSTER's finding differed only by 0.0175 from CHOSSAT's. Compared with modern (average) values for the aqueous (1.336) and other ocular media, BREWSTER was a little closer than CHOSSAT. BREWSTER's value of 1.3394 for the vitreous would seem a little surprising, as prior to his observations, it had been generally assumed, quite correctly, that the values refractive indices for water, the aqueous and vitreous, were all the same, i. e., 1.3358. It had occurred to BREWSTER however, that this was highly improbable in view of the fact that the aqueous and vitreous were known to contain albumen (recognized as having a higher refractive index than water). This accounted for his difference in values for the aqueous and vitreous.

Table III. Refractive Indices. (CHOSSAT, 1818)

	man	bear	pig	elephant	ox	turkey	carp
crys. lens from periphery to center	1.338 to 1.420	1.383 1.460	1.386 1.424	1.369 1.450	1.375 1.440	1.383 1.403	1.374 1.450
capsule (lens)	1.359	1.369		1.349	1.357	1.354	
vitreous	1.339	1.349	1.339	1.340	1.338	1.338	1.349
aqueous	1.338	1.349	1.338	1.338	1.338	1.344	1.349
cornea	1.33	1.35		1.34	1.34	1.35	1.35

Table IV. Refractive indices of the human eye according to BREWSTER (1818) and CHOSSAT (1818)

	BREWSTER	CHOSSAT
Refractive power of water	1.3358	1.3358
aqueous	1.3366	1.338
vitreous	1.3394	1.339
crys. lens (outer coat)	1.3767	1.338
ditto (middle coat)	1.3786	1.395
ditto (nucleus)	1.3990	1.420
,,whole'' crys. lens	1.3839	—
,,mean'' crys. lens	—	1.384

It will be appreciated that of the hundreds of refractive indices obtained by WOLLASTON, BREWSTER, CAVALLO, and others, some of the most important were those for the ocular media. However, in view of the fact that certain oils were probably compounds of two distinct substances, the question of refractive index lost much of its significance for many substances. This had been appreciated very early by SIR JOHN F. W. HERSCHEL (1792 – 1871, see HERSCHEL, 1830).

The study of refractive index led in turn to a consideration of the related subject of dispersive power. This was of particular significance, not only to the study of the mechanism of the eye, with respect to chromatic aberration, but also to the further development of the telescope, and the improvement of various other optical instruments, not within the scope of the present paper.

Summary

An account is given of the historical development of theoretical and practical methods for determining the refractive index of the ocular media. Reference is made of the writings of Francis Hauksbee, the Elder, William Wollaston (1766 – 1829), Jean François Gabriel de Chossat de Saint Sulpice (1755 – 1841), Thomas Young (1773 – 1829), Sir David Brewster (1781 – 1868). Values for the refractive indices of the ocular media in man and animals including bear, ox, pig, elephant and carp are discussed. Particular consideration is given to the significance of the crystalline lens and the subsequent considerations of dispersion, the mechanism of the eye, chromatic aberration and the indirect relationship to the development of the telescope.

Part I

References

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LEVENE, J. R. – Die Grundlagen der modernen vegetativen Physiologie des Auges. I. Der Brechungsindex der brechenden Medien.

Zusammenfassung:

Die Arbeit bringt eine Zusammenstellung der historischen Entwicklung theoretischer und praktischer Methoden zur Bestimmung des Brechungsindex der brechenden Medien des Auges. Dabei wird besonders auf die Schriften von Francis Hauksbee dem Älteren, William Wollaston (1766–1829), Jean François Gabriel de Chossat de Saint Sulpice (1755–1841), Thomas Young (1773–1829) und Sir David Brewster (1781–1868) hingewiesen. Die Ergebnisse von Bestimmungen der Brechungsindices der Medien bei Mensch und Tier werden diskutiert, darunter Werte für Bär, Ochse, Schwein, Elefant und Karpfen. Besondere Beachtung wird der Bedeutung der Kristall-Linse geschenkt, sowie den sich hieraus ergebenden Konsequenzen für die Streuung, den Sehmechanismus, die chromatische Aberration und die indirekten Beziehungen zur Entwicklung des Fernrohres.

LEVENE, J. R. – Fondements de la physiologie végétative oculaire moderne I. Indice de refraction des milieux oculaires

Resumé

L'auteur rapporte l'histoire des méthodes théoriques et pratiques pour la détermination de l'indice de réfraction des milieux oculaires. Il se réfère aux écrits de Francis Hauksbee père, William Wollaston (1766 – 1829), Jean François Gabriel de Chossat de Saint Sulpice (1755 – 1841), Thomas Young (1773 – 1829), Sir David Brewster (1781 – 1868). Il discute les valeurs des indices de réfraction des milieux oculaires chez l'homme et les animaux (l'ours, le boeuf, le cochon, l'éléphant et la carpe). Il attache une considération particulière à la signification du cristallin et au mécanisme de l'oeil, à la dispersion et à l'aberration chromatique, qui ont contribué indirectement au développement du télescope.

LEVENE, J. R. – Fundamentos de la Fisiologia Vegetativa ocular moderna. I. Indice de Refracción de los medios oculares

Resumen

El autor relata la historia de los métodos teóricos y prácticos para la determinación del índice de refracción de los medios oculares. Se refiere a los escritos de Francis Hauksbee padre, William Wollaston (1766 – 1829), Jean François Gabriel Chossat de Saint Sulpice (1755 – 1841), Thomas Young (1773 – 1829), Sir David Brewster (1781 – 1868). Discute los valores de los indices de refracción de los medios oculares en el hombre y en los animales (el oso, el buey, el cerdo, el elefante y la carpa). Se interesa particularmente a la signifacación del cristalino y al mecanismo del ojo, a la dispersión y a la aberración cromática, que han contribuido indirectamente al desarrollo del telescópio.

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