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DOI
10.1016/S0042-6989(96)00120-4

Publication date
1997

Published in
Vision Research

Pergamon

PII: S0042-6989(96)00120-4

Vision Res., Vol. 37, No. 2, pp. 249–253, 1997

Printed in Great Britain
0042-6989/97 $17.00 + 0.00

Research Note

Near Infrared Light Absorption in the Human Eye Media

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Received 19 January 1996; in revised form 1 April 1996

Available literature on the spectral transmittance of the eye media in the infrared (IR) is insufficiently accurate to estimate the deposited doses, e.g. in view of light damage risks. Analysis of the data of Boettner and Wolter [*Investigative Ophthalmology and Visual Science, 1*, 776–783 (1962)] for cornea, anterior chamber, lens and vitreous separately, shows that they can be explained on the basis of the pure water content. The transmittance spectrum of Geeraets *et al.* [*Archives of Ophthalmology, 64*, 606–615 (1960)] for all eye media combined is found to be impossible. It is concluded that in the near-IR, light losses in the eye media are best estimated with the absorption coefficient for pure water. A table is given from 700–2500 nm in steps of 10 nm. Copyright © 1996 Elsevier Science Ltd

Absorption   Damage   Infrared (IR)   Media   Lens

INTRODUCTION

Absorption of infrared (IR) light energy in the eye media has repeatedly received interest. At first, the interest was confined to the lens, in order to understand glassworkers cataract. It was concluded that the water content of the lens dominates its IR absorption (Goldmann *et al.*, 1950; Lenoble & Le Grand, 1953). To understand IR cataract theoretically, the temperature distribution in the eye resulting from IR irradiation was modelled (Okuno, 1991). For the IR absorption spectra of cornea, aqueous, lens and vitreous, proportional parts of the spectrum of Geeraets and Berry (1968) for all eye media combined, were taken [originally published in Fig. 5 of Geeraets *et al.* (1960)] up to 1400 nm. Above 1400 nm the absorption of pure water was taken. In a subsequent paper, this was extended to lower wavelengths, without further foundation (Vos & van Norren, 1994).

This subject is of renewed interest because of the introduction of different therapeutic treatments of the eye with IR light such as in diabetic macular edema or choroidal neo-vascularization. Insight to absorbed light doses in the eye media is needed in view of the cataractogenic risks involved. Also, for proper dosage at the target site, energy losses in the eye media must be compensated for in the output power of the delivery instruments. In a recent paper on transpupillary thermotherapy in choroidal melanomas (Oosterhuis *et al.*, 1995), the data of Geeraets and Berry (1968) were used to argue that 810 nm would be a better choice of wavelength because it has 5% eye media absorption, as compared to 35% at 1064 nm. This claim was challenged by Fankhauser who proposed a value of 20% at 1064 nm (private communication). In an attempt to clarify the issue, it was found that the existing literature on IR absorption in the eye media is conflicting, and that no proper comparison with the absorption spectrum for pure water has been made. It is the purpose of the present paper to present this comparison and to propose a more accurate figure for the spectral absorption of IR light energy in the eye media.

METHODS

There are only two original sources of sufficiently detailed literature data on IR absorption spectra in the eye media, both much reproduced: Geeraets *et al.* (1960) and Boettner and Wolter (1962). Their graphs were digitized using the hardware and software, including some laboratory-made routines, of the Vidas 2.1 system for morphometric analysis (Kontron Elektronik GmbH, Eching, Germany): from Geeraets *et al.* (1960) Fig. 5 (curve denoted "OM", for total optical media), and from Boettner and Wolter (1962) Fig. 3 (curve denoted "total", for the cornea), Fig. 4 (for the aqueous humor), Fig. 5 (curve denoted "total", for the lens) and Fig. 6 (curve denoted "total", for the vitreous humor). In the study of Boettner and Wolter (1962) "total" denotes transmittance measured with a large (170 deg) receptance angle, as opposed to "direct" transmittance using a small (1 deg) receptance angle. Geeraets *et al.* (1960) did not specify receptance angle, but it can be estimated as about 20 deg. Note that absorption losses are overestimated because of light losses due to scattering or reflection. Light losses

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TABLE 1. Log [absorption coefficient (m^{-1})] for pure liquid water as a function of wavelength (nm)

Wavelength	log(a)	Wavelength	log(a)	Wavelength	log(a)	Wavelength	log(a)	Wavelength	log(a)
700	−0.187	1100	1.233	1500	3.262	1900	3.913	2300	3.331
710	−0.079	1110	1.313	1510	3.199	1910	4.002	2310	3.389
720	0.068	1120	1.421	1520	3.157	1920	4.031	2320	3.409
730	0.255	1130	1.593	1530	3.092	1930	4.051	2330	3.447
740	0.377	1140	1.787	1540	3.047	1940	4.051	2340	3.461
750	0.393	1150	1.902	1550	2.993	1950	4.027	2350	3.497
760	0.407	1160	1.969	1560	2.955	1960	3.996	2360	3.537
770	0.400	1170	1.993	1570	2.908	1970	3.957	2370	3.573
780	0.373	1180	2.000	1580	2.881	1980	3.913	2380	3.602
790	0.334	1190	2.009	1590	2.848	1990	3.868	2390	3.620
800	0.316	1200	2.011	1600	2.810	2000	3.830	2400	3.635
810	0.315	1210	2.004	1610	2.790	2010	3.785	2410	3.678
820	0.396	1220	1.993	1620	2.763	2020	3.740	2420	3.705
830	0.490	1230	1.982	1630	2.763	2030	3.698	2430	3.718
840	0.555	1240	1.964	1640	2.743	2040	3.667	2440	3.754
850	0.597	1250	1.946	1650	2.711	2050	3.620	2450	3.776
860	0.642	1260	1.944	1660	2.705	2060	3.586	2460	3.821
870	0.680	1270	1.953	1670	2.720	2070	3.548	2470	3.843
880	0.723	1280	1.969	1680	2.720	2080	3.508	2480	3.877
890	0.776	1290	2.000	1690	2.705	2090	3.474	2490	3.906
900	0.850	1300	2.031	1700	2.716	2100	3.405	2500	3.924
910	0.888	1310	2.092	1710	2.718	2110	3.376		
920	0.933	1320	2.150	1720	2.734	2120	3.367		
930	1.103	1330	2.206	1730	2.752	2130	3.322		
940	1.315	1340	2.306	1740	2.776	2140	3.320		
950	1.521	1350	2.407	1750	2.814	2150	3.284		
960	1.624	1360	2.485	1760	2.841	2160	3.260		
970	1.653	1370	2.582	1770	2.893	2170	3.244		
980	1.629	1380	2.736	1780	2.911	2180	3.242		
990	1.597	1390	2.953	1790	2.911	2190	3.235		
1000	1.559	1400	3.096	1800	2.911	2200	3.210		
1010	1.479	1410	3.266	1810	2.906	2210	3.208		
1020	1.394	1420	3.329	1820	2.913	2220	3.195		
1030	1.266	1430	3.345	1830	2.911	2230	3.213		
1040	1.197	1440	3.389	1840	2.951	2240	3.230		
1050	1.136	1450	3.414	1850	2.991	2250	3.239		
1060	1.110	1460	3.398	1860	3.085	2260	3.262		
1070	1.114	1470	3.369	1870	3.284	2270	3.300		
1080	1.116	1480	3.351	1880	3.510	2280	3.300		
1090	1.179	1490	3.293	1890	3.745	2290	3.302		

due to scattering are more important if smaller receptance angles are used. If these effects are wavelength independent, they can be corrected by taking the ratio with maximal transmittance [see van den Berg & Tan (1994); van den Berg & IJspeert (1995)].

In general, transmittance by a layer of thickness d is related to the (Lambert) absorption coefficient $a(\lambda)$ by:

$$\text{transmittance} = I/I_0 = e^{-a(\lambda)d} \qquad (1)$$

with I transmitted intensity, and I_0 incident intensity. Values of $a(\lambda)$ for pure water were taken from Table 1 of Smith and Baker (1981) <800 nm, and read from Fig. 2 of Curcio and Petty (1951) >800 nm. They are given in Table 1 in steps of 10 nm. For a recent review of the optical properties of water, see Mobley (1995). The transmittance data including the transmittance for a 1 mm layer of pure water are given in Fig. 1. Maximal transmittance of the eye media is <1.0, probably due to reflection or (back) scattering. To correct for this, the subsequent analysis of the eye media transmittances is performed after division by the maximal transmittances, ranging from 0.948 to 0.986.

Qualitatively, the IR band structures in Fig. 1 suggest the spectra to have a common basis in that wavelength region. The first question is how to test whether all spectra can be explained on the basis of one absorbing substance, leading to Eq. (1) for transmittance? This can be tested by performing a log(−ln) operation on Eq. (1) (logarithm with base 10 is "log", with base e is "ln"):

$$\log(-\ln(\text{transmittance})) = \log(a(\lambda)) + \log(d). \qquad (2)$$

So, a plot of log(−ln(transmittance)) should result in curves of identical shapes, but different vertical positions, since d appears only additively as log(d) in Eq. (2). Note that *mutatis mutandis* log(−log) or ln(−log) transformations could also be used. The second question is to what absorbing substance (pure water?) the found shapes would correspond.

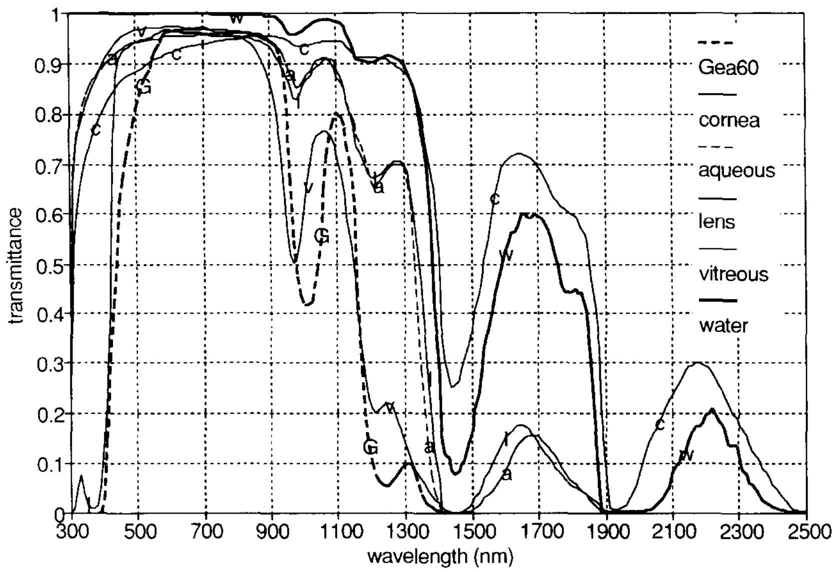

FIGURE 1. Transmittance spectra replotted from literature. Heavy dashed line, Geeraets *et al.* (1960), total eye media. Thin lines, Boettner and Wolter (1962): upper line, cornea; dashed line, aqueous; middle line, lens; and lower line, vitreous. Heavy continuous line, 1 mm of pure liquid water.

RESULTS

Figure 2 shows log(−ln(transmittance), for the set of data presented in Fig. 1. Excluded from the analysis were data with transmittances (after division by maximal transmittance) between 1.000 and 0.990 or 0.010 and 0.000, because they are relatively inaccurate after the log(−ln) transformation. This resulted in gaps in some of the curves. All curves except one [the heavy dashed line of Geeraets *et al.* (1960)] show approximately the same shape, but with different vertical positions. The heavy drawn line is for a 1 mm water layer, the thin lines are for Boettner and Wolter (1962). Figure 3 gives the differences with the curve for 1 mm of water. This corresponds to log(d) with d the thickness of the equivalent water layer in mm. So, average values of the curves in Fig. 3 can serve as estimates for log(d), and consequently d can be estimated as $d = 10^{\log(d)}$ mm. The average values $\pm$SDs for the five lines in Fig. 3 are: (1, heavy dashed line) total eye media from Geeraets *et al.* (1960) log(d) = 1.145 $\pm$ 0.331 (i.e. estimated thickness d = 13.97 mm), and for parts of the eye media from Boettner and Wolter (1962); (2, lower thin line) cornea −0.260 $\pm$ 0.095 (d = 0.555 mm); (3, broken thin line) aqueous humor 0.553 $\pm$ 0.084 (d = 3.58 mm); (4, middle

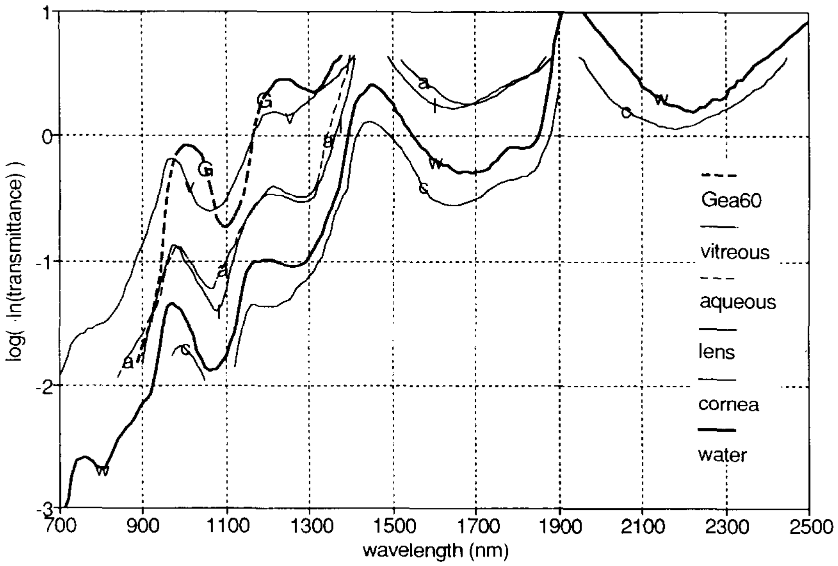

FIGURE 2. The same transmittance spectra of Fig. 1, but after log(−ln) transformation to test correspondence in shape with pure water (1 mm layer, heavy continuous line). Heavy dashed line, Geeraets *et al.* (1960), total eye media. Thin lines, Boettner and Wolter (1962): upper, vitreous; middle, lens; dashed, aqueous; and lower, cornea.

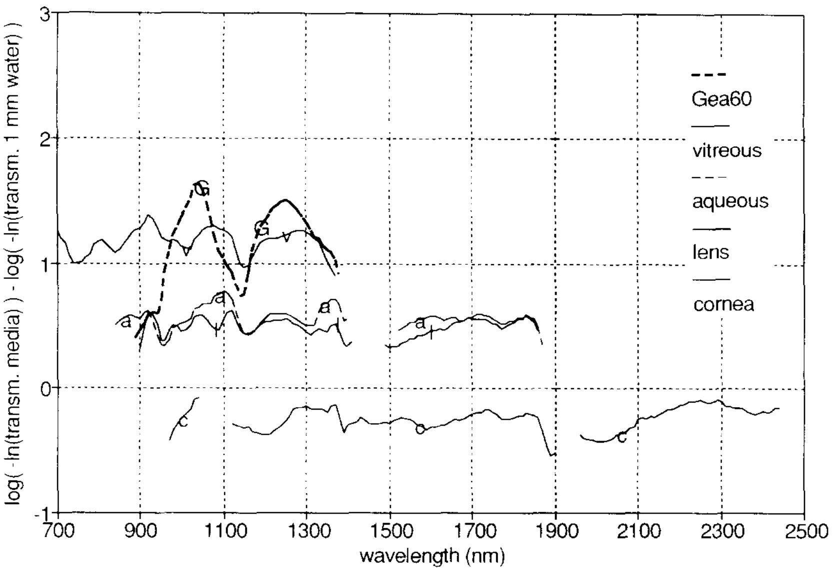

FIGURE 3. The spectra of Fig. 2, with that for 1 mm of pure water subtracted. Heavy dashed line, Geeraets *et al.* (1960), total eye media. Thin lines, Boettner and Wolter (1962): upper, vitreous; middle, lens; dashed, aqueous; and lower, cornea.

thin line) lens 0.487 ± 0.074 ($d = 3.07$ mm); and (5, upper thin line) vitreous 1.182 ± 0.099 ($d = 15.22$ mm). Note the difference in SDs between the data of Geeraets *et al.* (1960) (0.331 log units) and the data of Boettner and Wolter (1962) (0.074–0.099 log units).

DISCUSSION

The results, especially Fig. 3 and the numerical values derived from Fig. 3, suggest the data of Geeraets *et al.* (1960) to be inaccurate. Absorbance corresponding to that of the pure water component, is the lower limit for the absorbance in the eye media. Yet, the data of Geeraets *et al.* (1960) correspond on average to an equivalent water layer of 13.97 mm, considerably lower as compared to the 22 mm of water in front of the retina (22 mm = 15.5 + 3.0 + 3.0 + 0.5 mm approximately for vitreous + lens + aqueous + cornea, respectively). Speculatively, we might assume that the geometries of the eyes used were not normal, especially since an opening in the posterior pole had been made, as needed for the transmittance measurements. The data of Boettner and Wolter (1962) correspond much better to the respective water layers, in average as well as standard deviation, taking into account that the above value for the lens (3.07 mm) must be corrected for the low water content of the lens. An essential improvement might have been that Boettner and Wolter (1962) used special holders for the eye components, defining accurate optical pathlengths through the respective media.

The correspondence has limited precision though: the logarithmic standard deviations in Fig. 3 are between 0.099 and 0.074 and the values for eye media thickness that follow from Fig. 3 seem a bit high as compared to the respective geometrical values used by Boettner and Wolter (1962): aqueous 3.58 mm compared to 3.0 mm; lens 3.07 mm compared to 3.2 mm, but 3.2 mm must be lowered because the lens contains only about 70% of water; vitreous 15.22 mm compared to 15.0 mm. For the cornea the present value was 0.555 mm, but Boettner and Wolter (1962) only specified using a cell "to flatten the cornea without compressing it" (its thickness would have to be lowered because of the limited water content of the cornea).

If it were to be concluded that the values found for the equivalent water layer are somewhat larger than the true water layer, then it should also be concluded that a small part of the IR absorbance results from non-water substances in the eye media. If one were interested in light damage mechanisms, it might be considered that the dosage received by these non-water substances might be damaging to these substances, considering that the amounts of these substances would be relatively low.

On the other hand, if one were interested in total light energy losses in the eye media, it might be accurate enough to consider only the water component. One can then profit from the fact that the literature data on pure water absorbance are more accurate than the data on the eye media. Log(absorption coefficient $a(\lambda)$ (m^{-1})) for water is tabulated in Table 1 since in published tables the wavelength resolution is inadequate. As examples, values are calculated for the 810 nm diode laser and for the 1064 nm Nd:Yag laser: from Table 1 log(absorption coefficients $a(\lambda)$ (m^{-1})) can be read as respectively 0.315 and 1.1116. Assuming in total 22 mm of pre-retinal water, light losses would be 4.5% and 25%, respectively.

REFERENCES

van den Berg, T. J. T. P. & IJspeert, J. K. (1995). Light scattering by donor lenses. *Vision Research, 35*, 169–177.

van den Berg, T. J. T. P. & Tan, K. E. W. P. (1994). Light transmittance of the human cornea from 320 to 700 nm for different ages. *Vision Research, 33*, 1453–1456.

Boettner, E. A. & Wolter, J. R. (1962). Transmission of the ocular media. *Investigative Ophthalmology and Visual Science, 1*, 776–783.

Curcio, J. A. & Petty, C. C. (1951). The near infrared absorption spectrum of liquid water. *Journal of the Optical Society of America, 41*, 302–304.

Geeraets, W. J. & Berry, E. R. (1968). Ocular spectral characteristics as related to hazards from lasers and other light sources. *American Journal of Ophthalmology, 64*, 15–20.

Geeraets, W. J., Williams, R. C., Chan, G., Ham, W. T., Guerry, D. & Schmidt, F. H. (1960). The loss of light energy in retina and choroid. *Archives of Ophthamology, 64*, 606–615.

Goldmann, H., König, H. & Mäder, F. (1950). Die Durchlässigkeit der Augenlinse für Infrarot. *Ophthalmolgica, 120*, 198–205.

Lenoble, J. & Le Grand, Y. (1953). L'absorption du cristallin dans l'infrarouge. *Revue d'Optique, 32*, 641–648.

Mobley, C. D. (1995). The optical properties of water. In Bass, M. (Ed.), *Handbook of optics* (pp. 43.1–56). New York: McGraw-Hill.

Okuno, T. (1991). Thermal effect of infra-red radiation on the eye: A study based on a model. *Annals of Occupational Hygiene, 35*, 1–12.

Oosterhuis, J. A., Journée-de Korver, H. G., Kakebeeke-Kemme, H. M. & Bleeker, J. C. (1995). Transpupillary thermotherapy in choroidal melanomas. *Archives of Ophthalmology, 113*, 315–321.

Smith, R. C. & Baker, K. S. (1981). Optical properties of the clearest natural waters (200–800 nm). *Applied Optics, 20*, 177–184.

Vos, J. J. & van Norren, D. (1994). Weighing the relative significance of three heat dissipation mechanisms to produce cataract. *Lasers and Light in Ophthalmology, 6*, 107–117.

Acknowledgements—Appreciation is due to Dr Oosterhuis for copies of his correspondence with Dr Fankhauser and to Dr de Ruiter for the laboratory-made Vidas 2.1 software.