The Perception of Haidinger's Brushes and Macular Degeneration

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Haidinger's brushes are an entoptical effect of the human visual system which enables us to detect linearly polarized light. The perception of the brushes is related to the macula which acts essentially like a radial polarizer. In addition, the perception of the brushes varies individually with the birefringence of the cornea. We simulated this optical system of the eye experimentally and calculated the light transmission through a system where the macula polarizes only partially. The brush pattern forming in this case may indicate macular degeneration.

1 Introduction

The mineralogist Wilhelm Haidinger (1844) discovered that linearly polarized sky light can generate the impression of a faint yellow brush pattern on the bluish background of the sky. Helmholtz (1866) explained this perception by the concentric alignment of the dichroic pigment molecules around the fovea. This area is called macula. It behaves similar to a radial analyzer, which absorbs blue, linearly polarized light along the molecular chains. Thus, it generates the perception of a pair of faint, yellow brushes, which resembles the figure of a bowtie or hourglass. The brushes are easily seen when looking through a polarizer into the darker blue light from a computer monitor. The impression will disappear after a couple of seconds. Blinking or rotating the polarizer is needed for this phenomenon to last. In the later case the brush pattern generally seems to rotate with the same speed as the polarizer. However, it has been shown[1] that the phase shift which is introduced by the cornea leads to a non linear relationship between the rotational speed of the polarizer and the rotational speed of the brushes. For a high birefringence of the cornea this nonlinearity is very pronounced and a switching or a jumping brush pattern is perceived instead of one that rotates smoothly. The variability of the birefringent values in human corneas thus influences not only the intensity[2] but also the behavior of Haidinger's brushes, and thereby can explain individual perceptions. We also quantified another possible mechanism for individual differences of the percept. In our calculations we varied the absorptive strength of the radial analyzer, thereby simulating varying densities of the macular pigment. The density of the macular pigment has been correlated to Age related Macular Degeneration (AMD) with decreasing densities correlated to the onset or propensity to develop AMD[3]. The form and intensity of these calculated AMD-related brushes is compared to the brushes of the healthy eye.

2 Theory and Experiment

We investigated the behavior and form of Haidinger's brushes by simulating various principal optical components of the eye. In the Jones matrix formalism the behavior of the human cornea can be represented as a flat retarder[2] and is therefore represented by the matrix

$$C = \begin{pmatrix} \exp(i\Delta) & 0 \\ 0 & 1 \end{pmatrix} \qquad (1)$$

assuming that the slow axis coincides with the x-axis of the laboratory system. The phase shift Δ can vary between 0 and π/4. The macula is approximately a 3-5mm diameter circular region surrounding the fovea centralis and behaves like a dichroic material[2]. It was modeled to act as a radial analyzer. This element consists of radially aligned linearly polarizing angular segments which are oriented at an angle φ to the x-axis of the laboratory system where φ changes continuously between $0 < \varphi < 360^\circ$. As a Jones matrix element it is written as a linear polarizer rotated by an angle φ. In the case of macular degeneration the macula polarizes only partially. And the components of the partial polarizer are then given by the transmission coefficients for the electric field, $\sqrt{k_1}$ and $\sqrt{k_2}$. Each segment of the partially polarizing macula can thus be described by the matrix

$$M(\varphi) = \qquad (2)$$

$$\begin{pmatrix} \sqrt{k_2}\cos^2\varphi + \sqrt{k_1}\sin^2\varphi & \left(\sqrt{k_1} - \sqrt{k_2}\right)\cos\varphi\sin\varphi \\ \left(\sqrt{k_1} - \sqrt{k_2}\right)\cos\varphi\sin\varphi & \sqrt{k_2}\cos^2\varphi + \sqrt{k_1}\sin^2\varphi \end{pmatrix}$$

When linearly polarized light

$$E_{in}(\theta_0) = \begin{pmatrix} \cos\theta_0 \\ \sin\theta_0 \end{pmatrix} \qquad (3)$$

enters the eye the angular dependence of the electric field vector after the macula is given by

$$E_{out}(\varphi) = M(\varphi)\, C\, E_{in}(\theta_0) \qquad (4)$$

The intensity distribution behind the macula can be calculated by

$$I(\varphi) = E^*_{out}(\varphi) E_{out}(\varphi) = \qquad (5)$$

$$= k_1 - (k_1 - k_2)\cos^2\theta_0 - (k_1 - k_2)\cos^2\varphi +$$
$$+ 2(k_1 - k_2)\cos^2\varphi\,\cos^2\theta_0 +$$
$$+ 2(k_1 - k_2)\cos\varphi\,\cos\theta_0\,\sin\varphi\,\sin\theta_0\,\cos\Delta$$

For a perfectly polarising macula, i.e. $k_1 = 1$ and $k_2 = 0$, it can be seen that an eye with a corneal birefringence of Δ=0 produces the brush pattern with the highest contrast because the linearly polarised light entering the eye does not change its polarisation in the cornea and is therefore fully absorbed or transmitted in the macula. The same is true for a linear polarisation which passes the cornea through the slow or the fast axis.

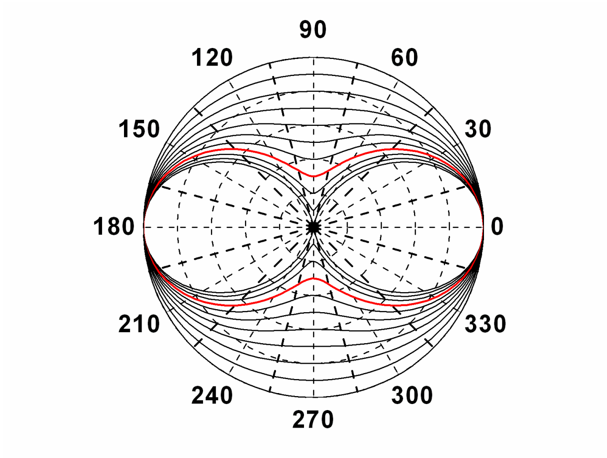

Abb. 1 *Angular intensity distribution. Setting $k_1 = 1$, the contrast between the dark and the bright red areas diminishes already to 0.54, if the pigment molecules in the macula transmit 30% of the blue light (red curve).*

How will this perception change if the transmission coefficients k_2 increase because the density of the pigments decreases? In this case equation (5) simplifies to

$$I(\varphi) = k_2 + (k_1 - k_2)\cos^2\varphi \;. \qquad (6)$$

Figure 1 shows brush patterns for transmission coefficients $k_2 = 0.1, 0.2, ..., 0.9, 1$. In the healthy eye these coefficients are by a factor 0.87 – 0.97 lower than k_1 anyway[4]. But if the transmission increases the waist of the brush pattern widens even more relatively to the healthy eye, so the contrast diminishes.

We physically simulated the function of a cornea and macula using a Babinet-Soleil compensator and an acetate radial analyzer passing linear polarized monochromatic laser light through the components and photographing the projected images. These images are simulated Haidinger's brushes, and by choosing the orientation of the incoming laser light a pattern with the contrast of the red line in figure 1 can be produced.

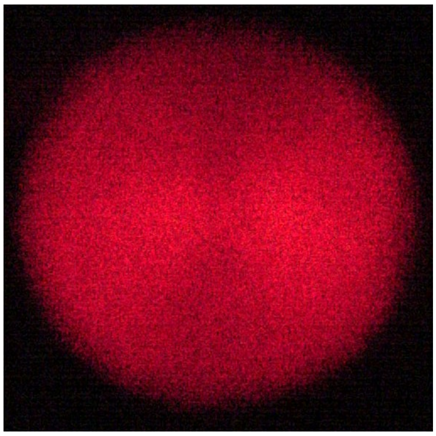

Abb. 2 *Brush pattern simulated with monochrome light. The contrast between the dark and the bright red areas is 0.54.*

3 Conclusion

For white light incident on the macula the contrast or color difference between the blue and yellow areas may decrease significantly when the pigment density decreases in macular degeneration. This would make it harder to perceive the brush pattern and may indicate macular degeneration at an early stage.

4 Support

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5 References

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