Optics Communications 370 (2016) 160–167

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

# Rainbow glare by retinal imaging

Han-Ying Sun [a,b], Yao-Ting Chiang [c], Shang-Min Yeh [d], Shuan-Yu Huang [a,b], Chi-Ting Horng [e], Hsiang-Chen Wang [c,*]

[a] Department of Optometry, Chung Shan Medical University, Taichung 40201, Taiwan
[b] Department of Ophthalmology, Chung Shan Medical University Hospital, Taichung 40201, Taiwan
[c] Graduate Institute of Opto-Mechatronics, National Chung Cheng University, 168, University Rd., Min-Hsiung, Chia-Yi 62102, Taiwan
[d] Department of Optometry, Central Taiwan University of Science and Technology, Taichung 40201, Taiwan
[e] Medical Education Center, Kaohsiung Armed Forced General Hospital, Kaohsiung City 80284, Taiwan

ARTICLE INFO

*Article history:*
Received 3 December 2015
Received in revised form
27 February 2016
Accepted 4 March 2016
Available online 12 March 2016

*Keywords:*
Femtosecond phenomena
Color vision
Ophthalmic optics and devices
Visual optics
Refractive surgery

ABSTRACT

This study aims to determine whether IntraLase surgery can cause rainbow glare. Monte-Carlo ray tracing method is used to study visual conditions of an ordered microstructure array on the cornea. A corneal flap in the simulated eye model can generate numerous microbubbles caused by IntraLase surgery. Moreover, this study evaluates the visual performance under different conditions such as the size and interval of the microbubble structure on the cornea with vary incident angles and diameters of light. The results of this study can help elucidate the real cause of rainbow glare as a side effect of IntraLase.


## 1. Introduction

Rainbow glare is an optical boundary effect first discussed in studies by Krueger et al. [1]. An obvious radial distribution of the rainbow light strip referred to as rainbow glare can occur visually after LASIK operation of 15 kHz far infrared ray IntraLase. The occurrence of rainbow glare is attributed to diffraction caused by regularly arranged bubbles on the surface of a corneal flap of a patient after IntraLase surgery. This phenomenon is mainly classified into two types. As described by the majority of patients, 4–12 radial rainbow stripes with strong symmetry appear as the far white light is visible in a dark background, with rainbow stripes showing blue to red colors from inside to outside; in the other type, 4 to 12 micro spots of the same color around the traffic lights appear, as though the patient sees traffic lights from afar [2]. Krueger et al. used 15 kHz far infrared ray IntraLase and focusing optics with a relatively small numerical aperture to experiment. Blur is formed by poor focusing of larger focused point and energy that can increase the incidence of rainbow glare. Improved IntraLase using focusing optics with a large numerical aperture can reduce rainbow glare [1]. Bamba et al. increased the increment of the pulse frequency of IntraLase by 60 kHz, which can reduce rainbow glare. The incidence of rainbow glare is related to laser energy. When laser energy ranges from 1.0 to 1.1 μJ, the incidence of rainbow glare is 11.6%, which is 4.1% higher than the incidence of rainbow glare when laser energy is set to 0.8 μJ. Studies have suggested that rainbow glare is not associated with age, gender, and refractive index of the patient [3]. Ackermann et al. have identified that the main mechanism of rainbow glare is diffraction effect caused by grating effect. If a random spot laser is used during the opening treatment of the corneal flap, the incidence of rainbow glare can be effectively reduced. Studies have also determined that shortening the microstructure space and size of the corneal flap to 3 μm can effectively reduce the incidence of rainbow glare. The reason is that the first-order diffraction fringe caused by rainbow glare is larger than the visible range of the retina. The smaller grating constant microstructure enhances the effect of diffraction grating, reversely causing poor visual quality after surgery [2].

At present, information regarding rainbow glare features come from medical journals [1–3]. The majority of the diagnostic methods are limited to the description and understanding of the incidence and phenomenon of rainbow glare, which are obtained using diagnostic questionnaires. However, this method can only provide the initial description of rainbow glare and cannot thoroughly explain the generation mechanism of rainbow glare. Moreover, IntraLase is very expensive, impeding the study of

* Corresponding author.
*E-mail address:* hcwang@ccu.edu.tw (H.-C. Wang).

http://dx.doi.org/10.1016/j.optcom.2016.03.019
0030-4018/

rainbow glare under different conditions (different microstructure size, incident light diameters, and wavelengths). Therefore, this study aims to establish a human eye model generating rainbow glare and to evaluate the imaging result of light diffracted on the human retina, passing through the human eye model with a microstructure of corneal flap by ray tracing. The variables (e.g., microstructure size, incident light diameter, and wavelength) are adjusted to evaluate the generation mechanism of rainbow glare under different conditions. The rainbow glare graphics shown in the literature mostly consist of fiber halogen light sources shining on the sample processed by IntraLase (slide or test silica gel). The images generate first-order to excessively dense diffraction phenomenon. However, rainbow glare bands that patients observe range from 4 to 12 bands only. The experiment cannot realistically simulate the phenomenon as observed by the eyes. Therefore, this study performs calculations by using an eye optical model with the corneal flap subject to conditions provided in the literature. The study also accurately determines the phenomenon of rainbow glare as described in the literature under different conditions and distances of the light source.

## 2. Establishment of the rainbow glare eye model

### 2.1. Human eyeball optical model

This study intends to establish an eye model that generates rainbow glare. To accurately simulate the performance of the human eye, the internal structure of the human eyeball, corneal microstructure, medium parameters, incident light source, and the environmental parameters generating rainbow glare are examined. The established eyeball model is expected to attain perfect focusing, thus obtaining accurate calculation of rainbow glare. The eyeball model as Arizona eye model in this study is a perfect eye model without spherical aberration, coma aberration, astigmatism, myopia, and hyperopia [4–6]. Parameters of the eye model are shown in Table 1. Fig. 1 shows an airy disk generated from far light source that are focused on the human retina by eye model simulation using the parameters listed in Table 1. The human eye model established in this study can accurately show the optical image on the retina.

### 2.2. Establishment of the microstructure of the corneal flap

We hypothesize that the generation of rainbow glare is attributed to diffraction caused by bubbles on the surface of the corneal flap after corneal flap surgery by IntraLase. Therefore, we establish a surface of the corneal flap with microstructure. According to the calculation using different microstructure sizes listed in Ref. [7], the microstructure bubbles caused generally by IntraLase has a diameter ranging from 8 to 9 μm and spot spacing ranging from 8 to 9 μm. The arrangement exhibits square and hexagonal patterns. In IntraLase, the corneal flap is excised in a regular arrangement to avoid laser spots and thus centralize to the same focus repeatedly, particularly for laser with high repetition frequency. Centralizing the energy is easier as more energy is absorbed within a period of time, causing corneal burn due to high energy absorption in the corneal stroma. Therefore, this study aims to place microparticles within 140 μm from the top of the cornea, as shown in Fig. 2(a). The microstructure and spot spacing each measure between 5 and 9 μm. The granular medium in a refractive index is set to general air refractive index n is set to 1, and the corneal medium refractive index is set to 1.376. The profile is shown in Fig. 2(b). When light enters the eye, light not interfacing with the microstructure, focuses through the eye's optics with minimal deviation onto the retina.

**Table 1**
Human eye model related parameters.

| Name | Radius (mm) | Conic constant | Index of refraction | Thickness (mm) | Diameter (mm) |
|---|---|---|---|---|---|
| Anterior corneal | 7.8 | −0.25 | 1.376 | 0.55 | 12 |
| Posterior corneal | 6.5 | −0.25 | | | |
| Anterior lens | 12.0 | −7.52 | 1.42 | 3.767 | 10 |
| *Posterior lens | −5.22 | −1.35 | | | |
| Iris | – | – | – | – | 4.7 |
| Aqueous | – | – | 1.337 | 61.3 | 2.97 |

The light interfacing with the microstructure scatters and diffracts, deviating from focus onto the retina. This unfocused veiling luminance produces rainbow glare and reduced image contrast.

### 2.3. Rainbow glare environmental parameters

The light source's size and distance used in the simulation of rainbow glare are similar to the description of rainbow light in Ref. [1]. In this study, rainbow glare testers hold a middle hole of opaque white paper and placed a white light source in front of this white paper in a room without other lighting devices exist. The participant is required to draw the distribution of the rainbow glare bands on the paper. The rainbow glare graphic drawn by the participant shows a white light source in the middle, 12 rainbow glare bands with colors ranging from blue to red in the surrounding space from the inside to the outside. Fig. 3 shows the calculation of the background parameters. We simulate a white paper held by patient about 55 cm distant to the corneal apex. The diameter of the hole in the center ranges from 1 to 5 mm. The simulated beam wavelengths include positively incident 460 nm blue light, 510 nm cyan light, 555 nm green light, and 660 nm red light, forward incidence. To perform the simulation, the light passes through the corneal flap with a 5–9 μm microstructure, pupil, and crystalline lens to focus on the retina. The experiment simulates the visual perception of the white light incident to the retina through overlapping point distribution function graphs of all wavelengths on the retina.

## 3. Human visual evaluation system

### 3.1. Disability glare

Disability glare is generally caused by scattering of light within the eyes [8]. Scattered light in the human eye can see as superimposing a layer of white light on the original image, thereby reducing the human visual effects. The generated scattering light overlaps a layer of white light screen on the original image observed by the person to reduce the visible effect of the human eyes. The condition deteriorates with the aging eye. For the elderly, disability glare can lead to a more significant visual decline. Cataract has been identified as a common cause of scattering. The scattering method is based on variation of the internal lens medium, which affects transparency of the eye. When the internal lens absorbs too much UV energy, lens become emulsification as egg white is cooked, causing scattering of light, which prompts the occurrence of disability glare. Disability glare caused by light scattering may be attributed to the irregular shape of the corneal surface and the corneal flap resulting from the early stage of IntraLase surgery [9].