

# Quantitative Evaluation of the Supercontinuum Laser Eye Dazzling Effect: in vivo Experimental Research

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## Research

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# Abstract

**Background:** Laser eye dazzling affects the visual performance through the instant high-intensity light stimulation. The temporary loss or deterioration of the visual function may occur when radiated by lasers. To quantitatively evaluate the dazzling effect of each spectrum band of supercontinuum laser, we conducted an experimental research for exploring the safety and dazzling of animals' eyes.

**Methods:** Under the condition of dark adaption, the laser with different power densities and spectral bands was output, and the rabbit eyes were radiated by normal incident mode for 0.25 s. The fundus of the rabbit eyes was examined through the inspection mirror, and the upper limit of safe power density was explored. Rabbit eyes were radiated at the upper limit of safe power density, and the microscopic damage model was established for pathomorphological analysis. The eyes were radiated with blinding light for 0.1 s. The visual electrophysiological signals were collected dynamically and the recovery time of ERG-b amplitude was recorded and analyzed after laser radiation.

**Results:** Under dark adaptation, the upper limit of safe power density was 247.00 mW/cm<sup>2</sup> in the VS, 194.00 mW/cm<sup>2</sup> in the VIS, 1184.00 mW/cm<sup>2</sup> in the IS, and 1052.00 mW/cm<sup>2</sup> in the FS. The above power densities of laser radiation in rabbit eyes could cause pathological changes of retinal structure, such as local bulge, uneven thickness and disorder of inner and outer nuclear layers, local inflammatory exudation and so on. When the power density was 8.00 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eye was 4.11 ± 0.67 s. When the power density was 12.00 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eye was 4.16 ± 0.55 s. The recovery time of ERG-b wave was 4.50 ± 0.94 s at the power density of 4.60 mW/cm<sup>2</sup> in the full spectrum-1, 3.81 ± 0.11 s at the power density of 5.00 mW/cm<sup>2</sup> in the full spectrum-2, and 628.00 mW/cm<sup>2</sup> in the infrared spectrum. The recovery time of ERG-b wave was only 0.84 ± 0.09 s.

**Conclusion:** The VS, FS, FS-1 and FS-2 of the supercontinuum laser had a good dazzling effect on rabbit eyes, and the dazzling effect was enhanced with the increase of radiation power density, but the infrared spectrum had a little dazzling effect.

## 1 Introduction

Laser dazzling is to interfere with the visual function of normal eyes through the stimulation of instantaneous strong light, which makes people appear vertigo, vision decline and even temporary blindness. The principle is that strong light stimulation of the fundus of the eye will lead to the isomerization of the photosensitive chemical component of the retinal rhodopsin chromophores, which is bleaching and decomposition, thus causing the human eye to lose or reduce the response ability to external light stimulation, temporary loss of the visual function, and accompanied by psychological tension and even panic. In turn, the target's ability to act and react to the outside world is lost or reduced transiently <sup>[1],[2]</sup>. In addition to the physical process of retina bleaching, laser dazzling may also cause visual transmission channel interference, visual synthesis dysfunction of brain and psychological

deterrence. Therefore, laser dazzling technology has a wide application prospect in the military and public security fields. Laser dazzling device can not only cause temporary vision loss of the target but also not cause physical damage, which has become an important direction in the current research of high-tech non-lethal laser incapacity weapons<sup>[3]</sup>, laser radar or illuminations of car driver<sup>[4]-[7]</sup>. At present, there are some reports about the development of laser dazzling weapons, car driver illuminations, but no specific parameters are involved. Therefore, it is of great significance to carry out in-depth research on the biological effects of laser dazzling.

The supercontinuum laser source not only has the high intensity, high brightness and good directivity of the laser source, but also has the characteristics of the wide spectrum of the traditional source<sup>[8],[9]</sup>. It has been used in basic science, industry, communication and medicine<sup>[10]-[12]</sup>. Supercontinuum laser has two advantages: first, the spectrum distribution is very wide, and the traditional laser protection equipment can only filter a single or a few wavelengths of laser and cannot achieve the effect of complete protection<sup>[13]</sup>. Further, we have developed optical imaging-based evaluation method to quantitatively analyze the supercontinuum laser-induced injuries and wound healings<sup>[14]</sup>. Second, the use of low peak-power continuous or quasi continuous laser, which was different from the Q-switched giant pulse laser, can effectively reduce the damage to the human eyes, not only increase the safety, but also appropriately increase the amount of laser radiation, to achieve a stronger dazzling effect. Therefore, the supercontinuum laser can be used in the research and development of laser dazzling devices, and it has important research value.

Current researches mainly focused on the dazzling effect of single laser wavelength. Furthermore, charge coupled device (CCD) detector is widely used to evaluate the laser dazzling of some special lasers<sup>[15]-[18]</sup>. While these methods were undirected for evaluating the performance of laser dazzling. Electroretinogram (ERG)<sup>[19]</sup> was also used to reflect the bio-current change under the high-intensity laser stimulus. It is a functional measurement tool for visual function changes<sup>[20],[21]</sup>. Furthermore, it is also a useful method of laser eye treatment for panretinal photocoagulation<sup>[22]-[24]</sup>. Hence, it would be a useful tool for evaluating the biological effect of laser dazzling of different kinds of lasers.

This research focused on quantitative evaluation of the supercontinuum laser-induced dazzling biological effect. Two important parameters of the laser-induced dazzling were investigated, namely the minimum radiation power density and maximum safe radiation power density. The former determines the lower limit of radiation power density that can cause the dazzling effect, the latter determines the upper limit of radiation power density that will not cause permanent damage to the target retina. Moreover, the recovery time of animal retinal current signals after laser radiation was used to quantitatively evaluate the dazzling efficiency of each segment of the supercontinuum laser, and explore the dose-effect relationship between the power density of each segment of the supercontinuum laser and the dazzling effect of the rabbit eye, so as to provide biological reference for the development of the supercontinuum laser dazzling weapon.

## 2 Materials And Methods

### 2.1 Animals

120 rabbits were used in this research. Their body weight was approximately 5.0 kg. There was no abnormality in the fundus observed by ophthalmoscopic observation. These experimental animals are kept in single cages by the Experimental Animal Center of Beijing Institute of Radiation Medicine. These animals were fed routinely for 3 to 7 days before the experiment. Experiment was carried out after no abnormality. Animal experiments with pigs were performed in accordance with the Beijing Institute of Radiation Medicine Experiment Animal Center-approved animal protocols. All experiments were performed in accordance with the guidelines of the IACUC-DWZX-2019-502.

### 2.2 Laser radiation method

Supercontinuum laser (SuperK EXTREME EXW-12, NKT Photonics, Denmark) was used to radiate the rabbit eyes. The spectral bands were divided into six bands: 1) visible spectrum (VS): 550 nm-760 nm, which can simulate the laser that passes through the laser protective goggle which prevents the green and infrared laser. 2) visible to infrared spectrum (VIS): 400 nm-900 nm, which was the spectrum from visible to infrared light; 3) infrared spectrum (IS): 900 nm-2400 nm, which was the middle infrared light spectrum; 4) full spectrum (FS): 400 nm-2400 nm, which was the full spectrum of the supercontinuum laser; 5) full spectrum 1 (FS-1): 400 nm-2400 nm, whose frequency were same as the FS, but the weight of each spectrum is not same; 6) full spectrum 2 (FS-2): 400 nm-2400 nm, whose frequencies were same as the FS and FS-1, but the weights of each spectrum were not same.

Laser was transmitted by optical fiber, and then expanded laser beam and collimated through a lens, it was limited by a diaphragm. The shutter was used to control radiation time, LABMAX TOP (Coherent Inc., Santa Clara, CA USA) was applied to monitor the power density of the supercontinuum laser. TES-1339 illuminometer was used to detect the ambient light illumination (Fig. 1(a)). The experiment was carried out under the condition of dark adaptation, and the ambient background illumination was set to be no higher than 0.01 Lux. The beam-limiting diaphragm was used to control the size of the laser spots that reached the pupil of the experimental animal, that is, the diameter of the aperture that was illuminated is set to be approximately 7.3 mm. During the experiment, the laser energy in the pupil of the animal was measured and calculated with a laser power meter before each radiation.

### 2.3 Study on the safety of supercontinuum laser-induced dazzling

After the rabbit eyes were dilated by compound topical eye drops, and the rabbits were fixed in the rabbit box, and the rabbit eyes were placed in front of the laser source. The dazzling laser was radiated directly into the rabbit eyes, and the power density increased gradually from small to large. Each power density was used to irradiate 2–6 rabbit eyes for 10 consecutive times with a radiation duration of 0.25 seconds. The fundus of rabbit eyes was examined with ophthalmoscopes immediately after the radiation

until the minor fundus injury was found. The power density of the first undetected eye injury was think as the upper limit of safe power density.

## **2.4 Pathomorphological analysis of eye injury induced by supercontinuum laser in rabbits**

The rabbit eyes were radiated at the upper limit of safe power density, and each rabbit eye was radiated by 50 times. Each radiation duration was 0.25 s. The microscopic injury model of rabbit eyes was established, and the laser radiation spots were scattered in the area near the center of the retina, to facilitate the sampling of the laser radiation area during pathological section. Hematoxylin-eosin staining (H&E) was performed to observe the pathomorphological changes of the animal eye tissues under light microscope. The rabbit eyes were removed from the animals after 24 h laser staining, and preserved in eyeball fixations. H&E was performed to observe the pathomorphological changes of the rabbit eye specimens.

## **2.5 Evaluation of visual ERG-b wave for dazzling efficiency**

Rabbit eyes were dilated by compound topicamide eye drops. The rabbits were anesthetized with Sumianxin injection and were fixed in electrostatic shielding box of rabbit. The rabbit eyes were placed in front of the laser. The related electrode and electrode were respectively fixed on the center of the auricle and the forehead, the corneal electrode was placed in the eye in the conjunctival sac, and the electrode was confirmed with good surface contact. Before, during and after laser radiation, the rabbit eyes were radiated with a white reference flash of 2 Hz at a frequency of 1 time per second. The flash and the laser were as close to the same axis as possible. The dynamic electroretinogram (ERG) (Fig. 1 (b)) waves were collected according to the international standard method of ERG, and the amplitude changes of ERG-b wave before and after laser radiation were measured. The transient disappearance occurred or decreased in amplitude of ERG-b wave that indicates the occurrence of glare phenomenon, and the recovery time of ERG-b wave is the time taken from the moment when the dazzling laser illuminates until the amplitude of ERG-b wave returned to the pre-illumination level. The degree of laser dazzling was usually measured by the recovery time and amplitude of ERG-b wave. The longer the recovery time of ERG-b wave was, the lower the amplitude was and the more serious the dazzling effect was.

## **2.6 Statistical analysis**

SPSS 13.0 software was used to analyze the data results, which are expressed as  $\bar{x} \pm s$ . One-way analysis of variance was used for comparisons between groups, and the LSD-t test was used for further comparisons. The difference was statistically significant at  $P < 0.05$ .

# **3 Results**

## **3.1 Safety evaluation of eye injury caused by supercontinuum laser under dark adaptation**

Under dark adaptation, namely, the ambient background illumination was less than 0.01 Lux, each spectrum band of the supercontinuum laser was radiated to the rabbit eye for 10 consecutive times with

each radiation duration of 0.25 s. In the range of different radiation doses, the ocular fundus injury was observed by ophthalmoscopic immediately after the laser dose was radiated from low to high.

Rabbit eyes were radiated with the VS of the supercontinuum laser under dark adaptation, and the radiation dose range was 247.00-313.00 mW/cm<sup>2</sup>. The observation results showed that the power density was 247.00-263.00 mW/cm<sup>2</sup>. Twenty-six rabbit eyes were radiated with the visible spectrum of supercontinuum laser, and no damage was found in fundus examination. When the power density was 289.00 mW/cm<sup>2</sup>, the two rabbit eyes were radiated, and the fundus examination showed a slight white lesion in one eye. When the power density was 313.00 mW/cm<sup>2</sup>, two rabbit eyes were radiated, and 1 rabbit eye was found to have blood spots by fundus examination.

Under the condition of dark adaptation, the 8 rabbit eyes of were radiated with the VIS of the supercontinuum laser. The observation results showed that when the laser power density was 194.00 mW/cm<sup>2</sup>, the eyes of 8 rabbits were radiated. No damage was found in the fundus examination. The eyes of rabbits were radiated with the IS of the supercontinuum laser, and the radiation dose range was 1120.00-1200.00 mW/cm<sup>2</sup>. The observation results showed that the power density was within the above range. A total of 14 rabbit eyes were radiated, and no damage was found in fundus examination.

Rabbit eyes were radiated with the FS of supercontinuum laser under dark acclimation, and the radiation dose range was 1039.00-1530.00 mW/cm<sup>2</sup>. The observation results showed that when the power density was 1039.00-1050.00 mW/cm<sup>2</sup>, a total of 14 rabbit eyes were radiated, and no damage was found in the fundus examination. When the power density was 1530.00 mW/cm<sup>2</sup>, 3 rabbit eyes were radiated, and 1 rabbit eye was found to have haemorrhagic spots by fundus examination.

### **3.2 Pathomorphological analysis of rabbit eye injuries induced by supercontinuum laser under dark adaptation**

Under dark adaptation, each spectrum band of the supercontinuum laser was used to radiate continuously at the upper limit of safe power density for 50 times at the fine-tuning angle, each radiation duration was 0.25 s. The eyes of the rabbits were taken for pathomorphological analysis 24 h after laser radiation.

The experimental results showed that, when the power density of the VS was 252.00 mW/cm<sup>2</sup>, it caused slight changes in the structure of the retina after radiation, with disordered arrangement of internal and external nuclear layers, irregular morphology and local bulges, as shown in Fig. 5A1, 5A2 and 5A3. When the power density of the VIS was 194.00 mW/cm<sup>2</sup>, it caused slight changes in the retinal structure and local bulge after radiation of the rabbit eyes, with uneven and disordered thickness of internal and external nuclear layers, and local inflammatory exudation, as shown in Fig. 5B1, 5B2, and 5B3. When the power density of the full spectrum was 1050.00 mW/cm<sup>2</sup>, it caused slight changes in the retinal structure, local bulge, uneven thickness of internal and external nuclear layers, and local inflammatory exudation after radiation, as shown in Fig. 5C1, 5C2, and 5C3.

The above pathological experimental results showed that the laser radiation amount determined by fundus examination would not cause macro retinal damage, but showed a certain degree of damage in microscopic pathomorphology. Although these injuries may be automatically repaired, they should be avoided as far as possible from the perspective of safety. Therefore, the upper limit of safe power density of each spectral segment should be lower than the upper limit of safe power density determined by fundus examination.

### **3.3 Visual ERG-b wave evaluation of the dazzling effect of supercontinuum laser in rabbit eyes under dark adaptation**

#### ***1) Effect of the recovery time of ERG-B wave with the VS in rabbit eyes***

Under dark adaptation, the IS of supercontinuum laser radiated the rabbit eye for 0.1s, and the change of ERG-b wave recovery time with power density in the rabbit eye is shown in Fig. 3. When the power density was between 0.20–1.60 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eyes was less than 3 s. When the power density was 2.00 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eyes was 3.28 ± 0.73 s. When the power density was 15.00 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eyes was 5.19 ± 0.40 s. When the power density was 60.00 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eyes was 6.65 ± 0.38 s. When the power density reached 180.00 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eyes was 10.80 ± 0.29 s, which was significantly higher than that in groups with power density lower than 160.00 mW/cm<sup>2</sup>, and the difference was statistically significant ( $p < 0.01$ ). The above results indicated that the recovery time of ERG-b wave was positively correlated with the increase of power density when the VS of supercontinuum laser was radiated to rabbit eyes under dark adaptation. The power density of dazzling laser was higher than 8.00 mW/cm<sup>2</sup>, and the recovery time of ERG-b wave was higher than 4 s, hence it had good dazzling effect.

#### ***2) Effect of the recovery time of rabbit eye ERG-b wave with the IS under dark adaptation***

Under dark adaptation, the supercontinuum laser infrared spectrum was radiated for 0.1 s. The recovery time of ERG-b wave in rabbit eyes was less than 0.25 s when the power density was between 71.70 mW/cm<sup>2</sup> and 521.00 mW/cm<sup>2</sup>, which indicated that no obvious dazzling occurred. When the power density was 628.00 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eyes was 0.84 ± 0.09 s. These results showed that, when the IS of supercontinuum laser effected on rabbit eyes, the ERG-b wave backed quickly after interference, there were no obvious dazzle. We would conclude that, when the power density of the IS of the laser reached a very high level, through visible laser filter residue after visible laser power density also reached a certain level, thus can cause very weak dazzling effect.

#### ***3) Effect of the recovery time of ERG-b wave in rabbit eyes with the FS under dark adaptation***

Under dark adaptation, the FS of supercontinuum laser radiated the rabbit eye for 0.1 s, and the change of ERG-b wave recovery time with power density in the rabbit eye is shown in Fig. 4. When the power

density was between 0.02 and 0.98 mW/cm<sup>2</sup>, the recovery time of ERG-b wave was less than 2 s. When the power density was 2.50 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eyes was 2.84 ± 0.56 s. When the power density was 12.00 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eyes was 4.16 ± 0.55 s. When the power density was 117.00 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eyes was 7.54 ± 0.46 s. When the power density was 210.00 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eyes was 8.72 ± 0.46 s. When the power density reached 1000.00 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eyes was 19.76 ± 0.90 s, which was significantly higher than that in other groups, and the difference was statistically significant ( $p < 0.01$ ). The above results indicated that the recovery time of ERG-b wave is positively correlated with the increase of power density when the FS of supercontinuum laser was radiated to rabbit eyes under dark adaptation. However, when the power density increased from 2.50 mW/cm<sup>2</sup> to 1000.00 mW/cm<sup>2</sup>, the power density increased by 400 times, while the rabbit eye ERG-b wave recovery time only increased from 2.84 s to 19.76 s, which increased by approximately 7 times. This indicated that, with the significant increase of the power density of dazzling laser, the recovery time of ERG-b wave in rabbit eyes showed a trend of slow increase. When the power density of dazzling laser was higher than 12.00 mW/cm<sup>2</sup>, and the recovery time of ERG-b wave was higher than 4 s, therefore it also had a good dazzling effect.

#### ***4) Effect of the recovery time of ERG-b wave in rabbit eyes with the FS-1 on under dark adaptation***

Under dark adaptation, when the IS of supercontinuum laser radiated the rabbit eye for 0.1s, and the change of ERG-b wave recovery time with power density in the rabbit eye is shown in Fig. 2. When the power density was between 0.06–0.24 mW/cm<sup>2</sup>, the recovery time of ERG-b wave was less than 1 s. When the power density was 0.45 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eyes was 1.71 ± 0.63 s. When the power density was 4.60 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eyes was 4.50 ± 0.94 s. When the power density reached 93.30 mW/cm<sup>2</sup>, the recovery time of ERG-b wave in rabbit eyes was 9.82 ± 1.53 s, which was significantly higher than that in other groups, and the difference was statistically significant ( $p < 0.01$ ).

The above results indicated that the recovery time of ERG-b wave was positively correlated with the increase of power density when the IS of supercontinuum laser irradiates the rabbit eye under dark adaptation. The power density of dazzling laser was higher than 4.6 mW/cm<sup>2</sup>, and the recovery time of ERG-b wave was higher than 4 s, therefore it also has good dazzling effect.

#### ***5) Effect of the recovery time of ERG-b wave in rabbit eyes with the FS-2 under dark adaptation***

Under dark adaptation, when the FS of supercontinuum laser radiated the rabbit eye for 0.1s, the change of ERG B-wave recovery time with power density in the rabbit eye is shown in Fig. 6. When the power density was between 0.03 and 0.70 mW/cm<sup>2</sup>, the recovery time of ERG-b wave was less than 2 s. In the range of 1.10-3.00 mW/cm<sup>2</sup>, the average recovery time of ERG B-wave in rabbit eyes was 2.26 s, and there was no statistical difference among all groups. When the power density was 5.00 mW/cm<sup>2</sup>, the

recovery time of ERG-b wave in rabbit eyes was  $3.81 \pm 0.11$  s. When the power density was  $23.40$   $\text{mW}/\text{cm}^2$ , the recovery time of ERG-b wave in rabbit eyes was  $5.27 \pm 0.10$  s. When the power density reached  $40.00$   $\text{mW}/\text{cm}^2$ , the recovery time of ERG-b wave in rabbit eyes was  $6.06 \pm 0.19$  s, which was significantly higher than that in other groups, and the difference was statistically significant ( $p < 0.01$ ). The above results indicated that the recovery time of ERG-b wave can also be prolonged with the increase of power density when the FS-2 of supercontinuum laser was radiated to rabbit eyes under dark adaptation, and there was a positive correlation. The power density of dazzling laser was higher than  $5.50$   $\text{mW}/\text{cm}^2$ , and the recovery time of ERG-b wave was higher than 4 s, therefore, it also had a good dazzling effect.

## 4 Discussions

Currently, ERG is the most commonly used method to study the biological effects of laser dazzling. The experimental animals, which are like human eyes, are rabbits and rhesus monkeys. It is objective, quantitative and simple to evaluate the effect of laser dazzling by recording the time required for the recovery of the ERG-b wave of the retinal response to the flash stimulus after laser radiation [25]. Here, we found that, the recovery time was positively correlated with the radiation dose in a certain range, and the amplitude gradually returned to the pre-radiation level with the radiation time. The dazzling effect caused by laser flash did not cause organic damage to the eye tissue. Research on the biological effects of laser dazzling provides the biological experimental basis on equipment finalization and efficiency evaluation of laser dazzling device or some other application of lasers, and then the direct evaluation method based on the retinal ERG can provide direct information of eyes' dazzling effect.

In this experiment, the VS, IS and FS of supercontinuum laser were used to irradiate the eyes of rabbits, and the damage of fundus was examined through ophthalmoscope, so as to analyze the upper limit of safe power density of each spectrum band of the laser without causing the damage of rabbit eyes. The experimental results showed that under the condition of dark adaptation, each spectral band of the supercontinuum laser was radiated for 0.25 s. The upper limit of safe power density without damage in fundus examination was  $247.00$   $\text{mW}/\text{cm}^2$  for the VS,  $194.00$   $\text{mW}/\text{cm}^2$  for the VIS,  $1184.00$   $\text{mW}/\text{cm}^2$  for the IS, and  $1052.00$   $\text{mW}/\text{cm}^2$  for the FS, respectively. When the power density of the VS was higher than  $289.00$   $\text{mW}/\text{cm}^2$ , light white lesions or bleeding lesions were found in the fundus examination of rabbits, and when the power density of the FS was up to  $1530$   $\text{mW}/\text{cm}^2$ , there was bleeding lesions in the fundus examination of rabbits.

The results of pathological experiments showed that under dark adaptation, the radiation of the VS, IS and FS of supercontinuum laser at the upper limit of safe power density with the radiation duration of 0.25 s would not cause the visible damage under the ophthalmoscopic examination, while it would cause pathological changes of the microscopic structure of the retina of the rabbit eye. It may lead to local uplift, uneven thickness of internal and external nuclear layers, disordered arrangement of internal and external nuclear layers, local inflammation and other problems. Accurate security dazzling power density

limit also need further study, which did not lead to retinal pathological microstructure change. While, when maximum power density decreased from 0.1 to 0.5 times, according to the conventional evaluation methods, it would not cause pathological changes in the microstructure. Therefore, as a preliminary study result, before further experimental studies, the reference value of the upper limit of safe power density under dark adaptation on the premise of giving priority to the principle of safety can be set as: 24.70 mW/cm<sup>2</sup> in the VS, 19.40 mW/cm<sup>2</sup> in the VIS, 105.20 mW/cm<sup>2</sup> in the FS, and 118.40 mW/cm<sup>2</sup> in the IS.

The results of visual electrophysiological evaluation showed that under the condition of dark adaptation, the recovery time of ERG-b wave was less than 0.5 s when the dazzling radiation duration was 0.1 s, and the recovery time of ERG-b wave was only approximately 0.8 s when the power density of supercontinuum laser infrared spectrum was less than 521.00 mW/cm<sup>2</sup>, and the power density was as high as 628.00 mW/cm<sup>2</sup>. The dazzling effect was very weak, so the spectrum band cannot be used as a dazzling spectrum segment; when the power density of the visible spectrum was 17.00 mW/cm<sup>2</sup>, it was close to the upper limit of the safe power density of 24.70 mW/cm<sup>2</sup>, and the recovery time of ERG-b wave was approximately 5.6 s. Therefore, this spectrum band had a good dazzling effect. When the power density of the FS was 117.00 mW/cm<sup>2</sup>, it was slightly higher than the upper limit reference value of the safe radiation power density of 105.20 mW/cm<sup>2</sup>, and the recovery time of ERG-b wave was approximately 7.5 s, which is longer than that of the visible spectrum segment. Therefore, the spectrum band had a better dazzling effect. When the power density of FS-1 was 4.60 mW/cm<sup>2</sup>, the recovery time of ERG-b wave was approximately 4.2 s, and when the power density of FS-2 was 5.50 mW/cm<sup>2</sup>, the recovery time of ERG-b wave was approximately 4.5 s. Therefore, both two spectral bands had good dazzling effect. If the recovery time of ERG-b wave was up to 4 s, the power density of the dazzling laser in the VS of supercontinuum laser was approximately 8.00 mW/cm<sup>2</sup>, it is approximately 12.00 mW/cm<sup>2</sup> in the FS, it was approximately 4.60 mW/cm<sup>2</sup> in the FS-1, and it was between 5.00-5.50 mW/cm<sup>2</sup> in the FS-2. According to the dazzling effect, under dark adaptation, the dazzling effect of the FS-1 and the FS-2 was stronger, and the dazzling effect of the FS-1 was slightly stronger than that of the FS-2, which was obviously stronger than that of the FS. The dazzling effect of the VS is between the three, while the dazzling effect of the IS basically has no dazzling effect.

## 5 Conclusion

In summary, we investigated and evaluated the laser dazzling effect with ERG-b wave. Results suggested that, under dark adaptation, when the VS, FS, FS-1 and FS-2 of supercontinuum laser radiated rabbit eyes, it could make the recovery time of rabbit eyes ERG-b wave more than 4 s, all of them had a good dazzling effect, and the dazzling effect strengthened and increased with the radiation power density, while when the IS of supercontinuum laser radiated rabbit eyes ERG-b back quickly after the wave was interference, hence there is no dazzling effect. Under dark adaptation, the upper limit of safe power density radiated by each spectral band of supercontinuum laser will cause changes in the structure of retina. Security should be a priority in practical application. The reference value of the upper limit of safe power density under dark adaptation on the premise of giving priority to the principle of safety can be set as: 24.70 mW/cm<sup>2</sup>

in the VS, 19.40 mW/cm<sup>2</sup> in the VIS, 105.20 mW/cm<sup>2</sup> in the FS, and 118.40 mW /cm<sup>2</sup> in the IS. Both the full spectrum and the visible spectrum showed a good dazzling effect at the above radiation doses. These results provide a good biological basis for the application of supercontinuum laser dazzling.

## Declarations

### Availability of data and materials

The datasets used during the current study are available from the corresponding author upon reasonable request.

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### Competing interests

The authors declare that they have no competing interests.

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### Authors' contributions

Dr. Yingwei Fan participated in animal experiments, collected and analyzed the data and was a major contributor in the writing of the manuscript. Ms. Qiong Ma participated in animal anatomy work, collected and analyzed the data. Ms. Jie Liang and Prof. Zhenkun Luo participated in animal experiments. All authors read and approved the final manuscript. Dr. Yingwei Fan and Prof. Hongxiang Kang contributed to the study design and data analyses and revised the manuscript.

### Ethical Approval and Consent to participate

Not applicable.

### Consent for publication

Not applicable.

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## Figures

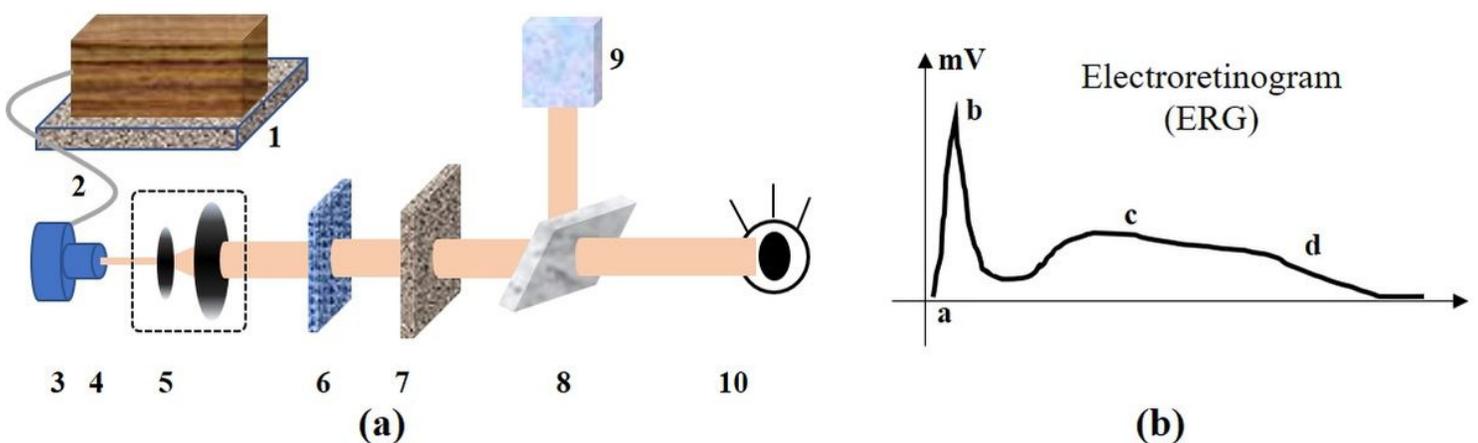
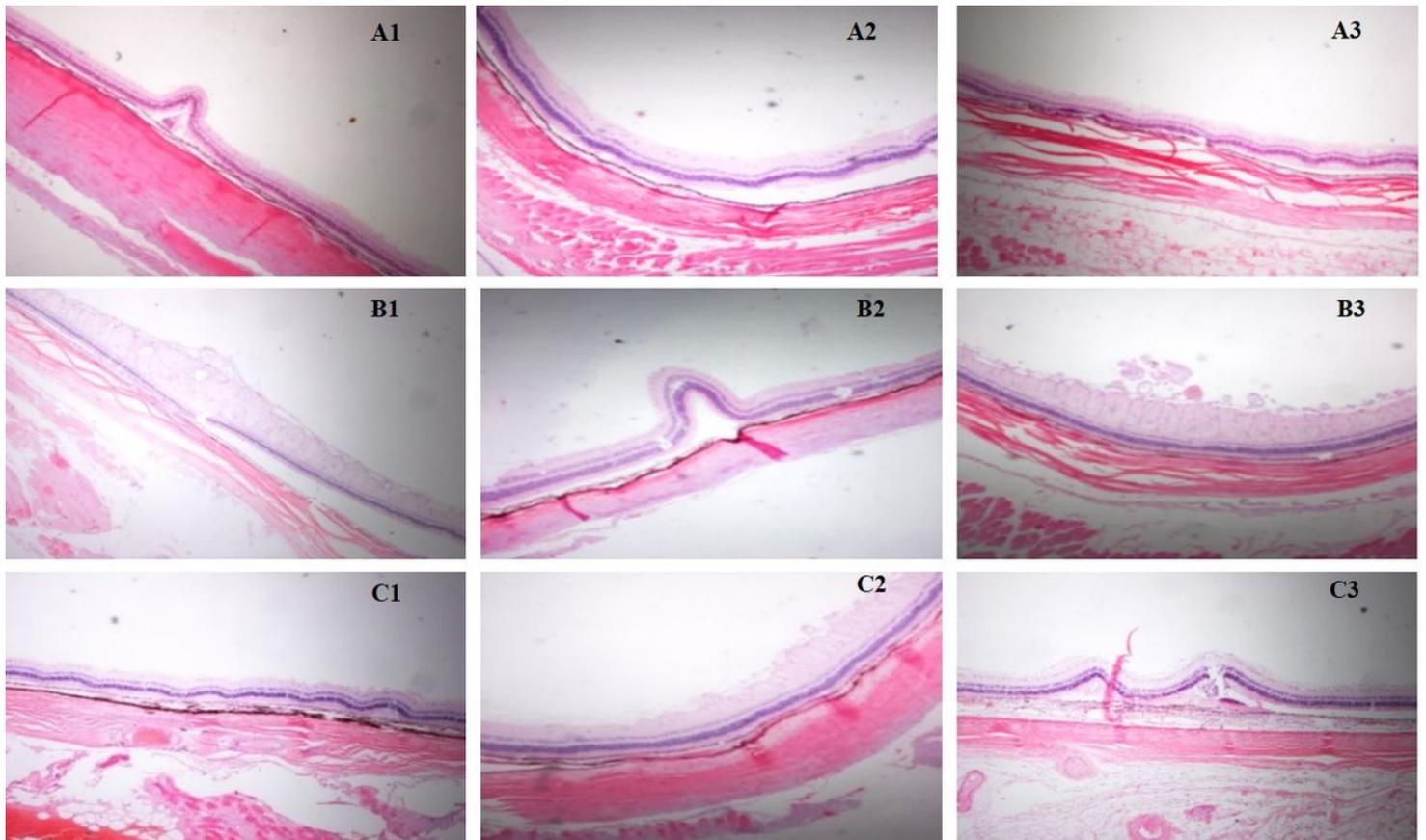


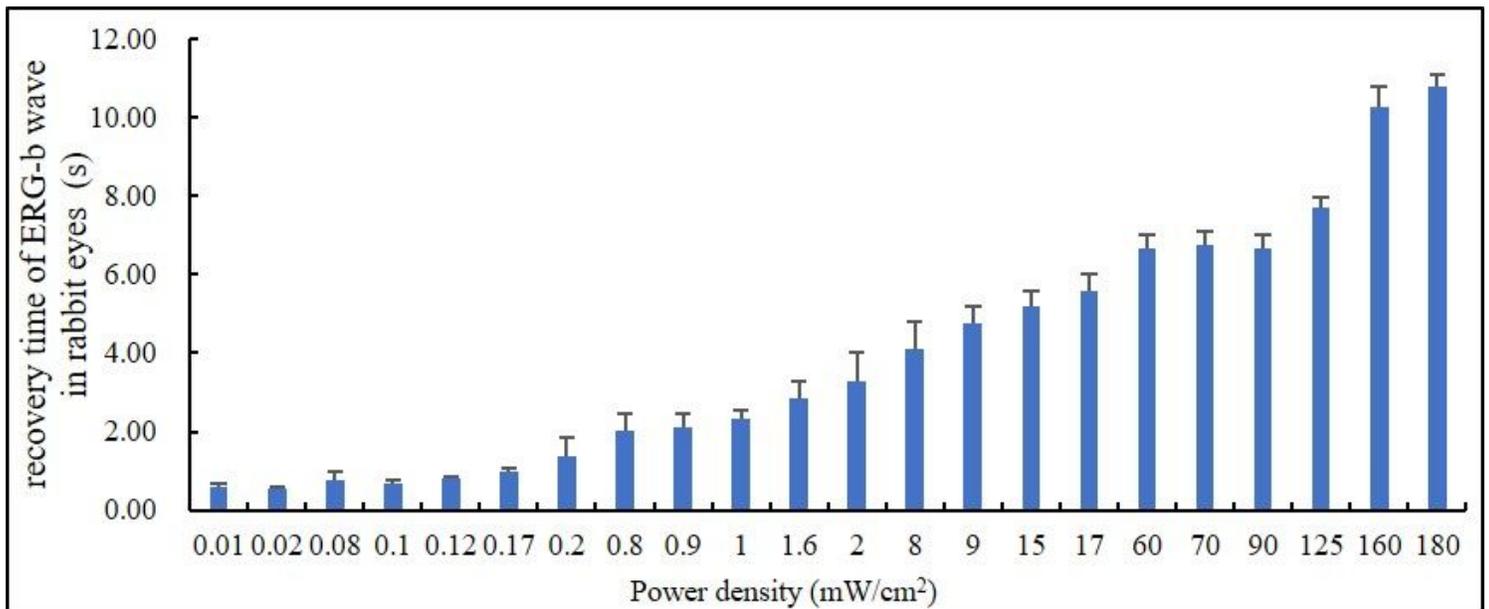
Figure 1

(a) The optical path of a supercontinuum laser visible spectrum illuminating an experimental animal's eyes; (b) Electroretinogram (ERG) of the eyes. 1. Laser; 2. Fiber; 3. Coupler; 4. Laser output; 5. Beam expander; 6. Electrical shutter; 7. Diaphragm; 8. Beam splitter; 9. Power meter; 10. The rabbit eyes.



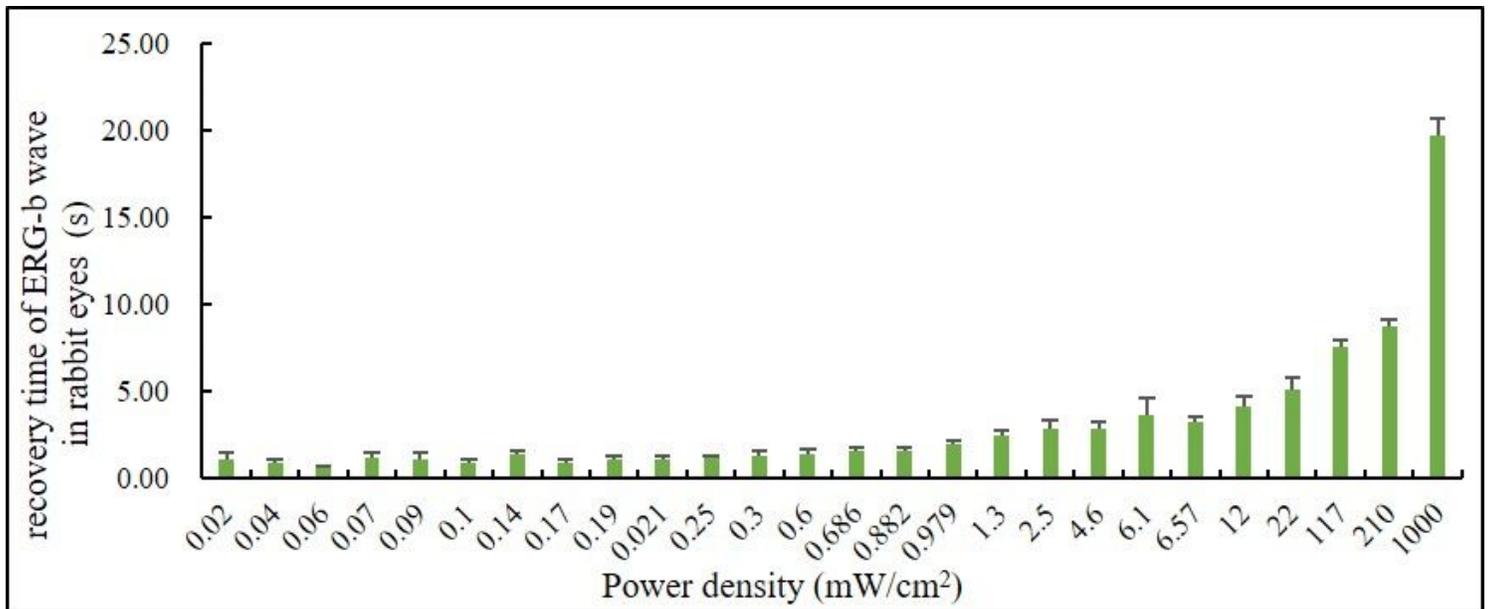
**Figure 2**

Pathomorphological changes of rabbit eye injuries induced by each spectrum band of supercontinuum laser under dark adaptation (VS: A1: The retina was structurally altered with local eminence; A2: The internal and external nuclear layers were disordered; A3: The internal and external nuclear layers were disordered and irregular in shape; VIS: B1: There was local exudation, and the thickness of inner and outer nuclear layer was uneven; B2: The retina was structurally altered with local eminence; B3: There was a local inflammatory exudation; FS: C1: The retinal structure changes, the inner and outer nuclear layer thickness was not uniform; C2: There were structural changes in the retina with local inflammatory exudation; C3: The retina was structurally altered with local eminence)



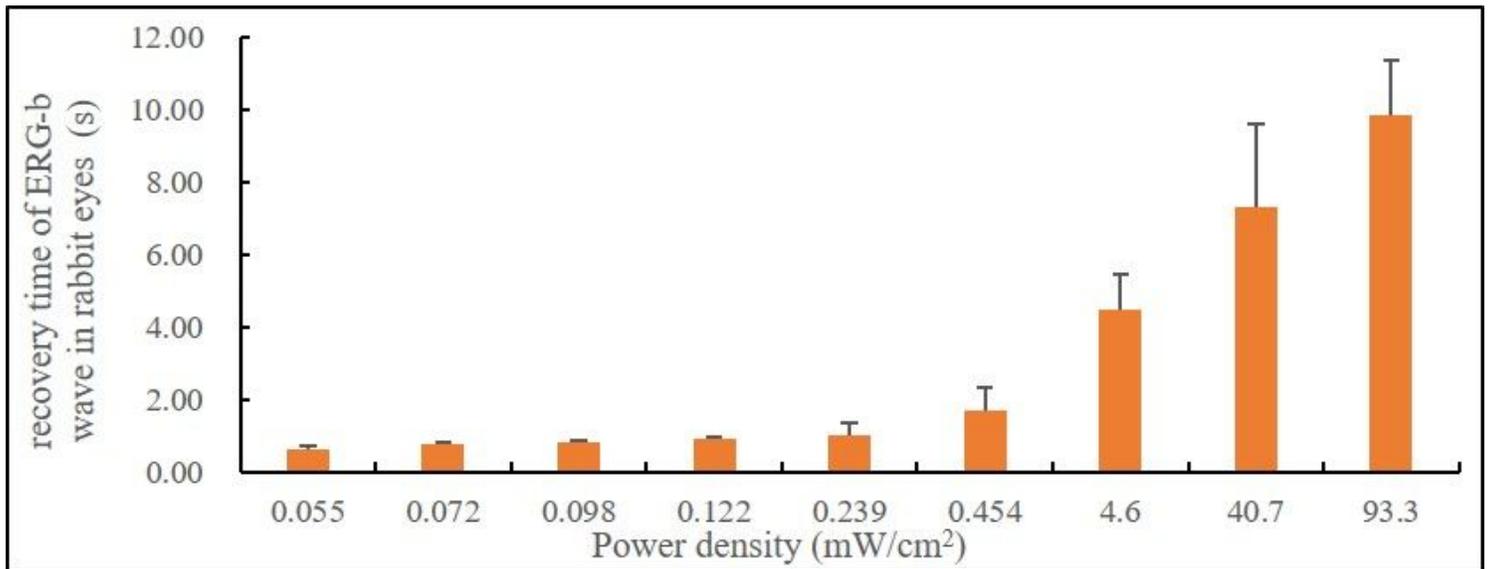
**Figure 3**

Effect of the recovery time of rabbit eye ERG-b wave with the VS under dark adaptation



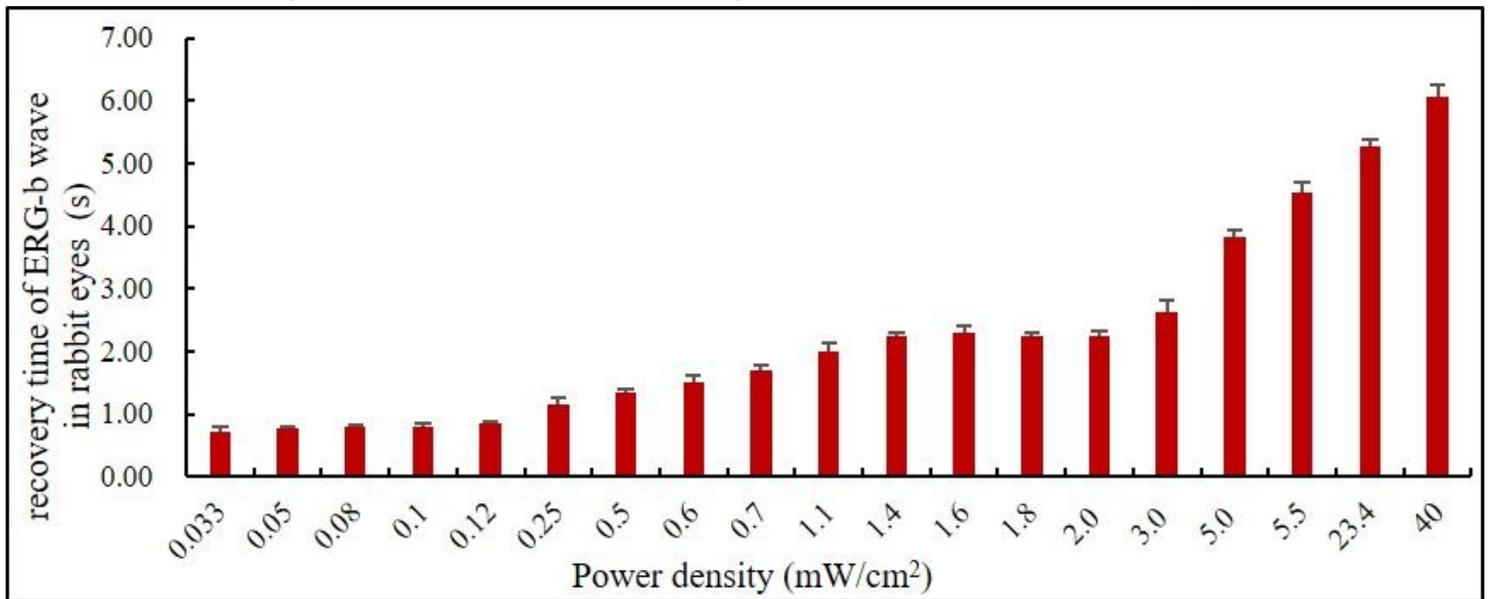
**Figure 4**

Effect of the recovery time of ERG-b wave in rabbit eyes with the FS under dark adaptation



**Figure 5**

Effect of the recovery time of ERG-b wave in rabbit eyes with the FS-1 under dark adaptation



**Figure 6**

Effect of the recovery time of ERG-b wave in rabbit eyes with the FS-s under dark adaptation