Endoillumination during vitrectomy and phototoxicity thresholds

Pieter R van den Biesen, T Berenschot, Rudolf M Verdaasdonk, Huib van Weelden, D van Norren

Abstract

Aim—To assess the retinal phototoxicity hazards of and to provide safety margins for endoillumination during vitrectomy.

Methods—The absolute power and spectral distribution from various light sources and filter combinations that are commercially available for vitreous surgery were measured. The maximal exposure times based on the ICNIRP safety guidelines for photochemical and thermal injury of the aphakic eye were calculated. Additionally, the effect of various measures that reduce the risk of phototoxicity was evaluated.

Results—Measurements of the spectrum and energy indicated that the ICNIRP safety guidelines for photochemical retinal damage are exceeded within 1 minute for nine out of 10 combinations tested. With an additional 475 nm long pass filter, light levels below 10 mW, and a distance from light probe to retina of at least 10 mm, the allowable exposure time can be increased up to 13 minutes. Thermal damage can be anticipated when the light probe touches the retina.

Conclusion—Commercially available light sources for endoillumination during vitrectomy are not safe with respect to photochemical retinal damage. Even with maximal precautions macular phototoxic damage remains a factual danger during vitrectomy.

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FC Donders Institute of Ophthalmology, Department of Biomedical Engineering, and Institute of Dermatology, University Hospital Utrecht, Utrecht, Netherlands
P R van den Biesen
T Berenschot
R M Verdaasdonk
H van Weelden
D van Norren

Correspondence to:
Dr P R van den Biesen, FC Donders Institute of Ophthalmology, University Hospital Utrecht, PO Box 85500, 3508 GA Utrecht, Netherlands
p.vdbiesen@oogh.azu.nl

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In ophthalmology, many diagnostic and therapeutic devices are equipped with a bright light source to illuminate the fundus of the eye. The emitted light is potentially harmful to the retina. In particular, short wavelengths in the visible spectrum are noxious but, in certain conditions, infrared radiation can be hazardous too. In most instances the light is applied through the intact eye. Since the lens is a good absorber of blue and ultraviolet, the irradiance threshold for retinal damage is relatively high. During trans pars plana vitrectomy, however, the fibreoptic endoillumination bypasses the eye media and the threshold for damage by visible radiation to the retina is substantially decreased. When the light probe touches the retina even thermal damage might occur. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) gives safety guidelines for illumination of the fundus in both phakic and aphakic subjects.[1] We measured the spectrum and energy output from various light sources that are commercially available for vitreous surgery and checked them against the ICNIRP safety guidelines for the aphakic eye.

Methods

SPECTRAL ANALYSIS

The spectral distribution of the various light sources was determined in combination with a standard fibreoptic endoillumination probe for vitreous surgery (Fiberoptic Endoilluminator, Storz Ophthalmics, St Louis, MO, USA). The probe consisted of a 300 μm silica fibre embedded in a 20 gauge needle hand piece with a typical acceptance angle of 20 degrees in water. The fibre was positioned 25 cm from the entrance of a calibrated spectroradiometer (model 742, Optronic Laboratories, Orlando, FL, USA) and the light spot from the fibre was aligned with the centre of the radiometer. The spectrum was measured with a resolution of 1 nm in the range 250–800 nm, either at the maximum of the illumination output or at the level recommended by the manufacturer. The measurements were processed with calibration curves of the spectroradiometer. This resulted in the relative spectral output.

POWER OUTPUT

The absolute output was determined with a radiometer with integrated lock-in amplifier (Power Radiometer Rk-5710, Laser Precision Corp, Utica, NY, USA). Using auxiliary optics, the light spot from the illumination probe was focused down to the 10 mm diameter opening of the radiometer so that all light was accepted. The radiometer provided a measurement with an accuracy of 0.05 mW. The measurement was repeated three times by repositioning the hand piece and rotating the coupler to the light source. This procedure produced a variation in the order of 10%. The measurements were either performed at maximum power or, when available, at the level recommended by the manufacturer. After corrections for reflection losses from the auxiliary optics, and in combination with the relative figures from the spectral analysis, figures in mW/cm^2/nm were obtained. Some illumination systems had multiple filter options. The power spectrum was obtained for all filter settings from each light source.

EXPOSURE LIMITS

Retinal exposure limits for thermal and blue light photochemical retinal hazard were calculated using the guidelines given by the International Commission on Non-Ionizing
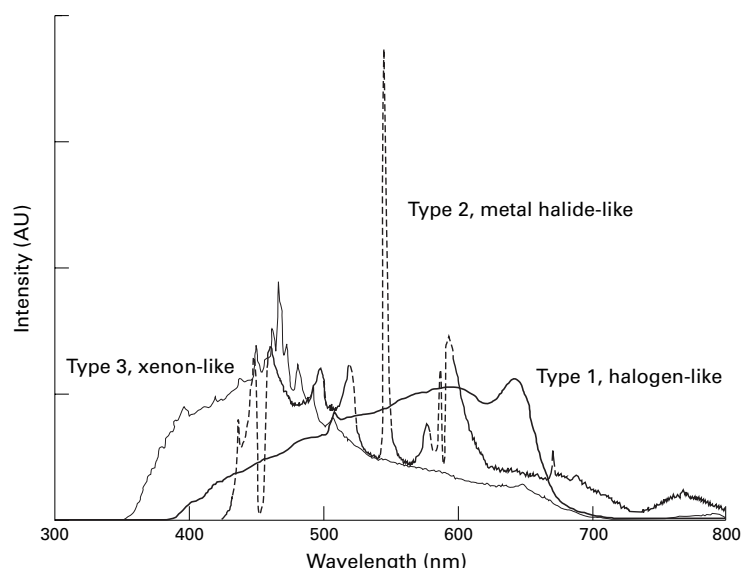
Figure 1 Spectral radiance of the three types of light sources investigated in this study. The spectral distributions are normalised to their integrated radiances.

Radiation Protection.[1] They supply threshold radiances, which we transformed to threshold irradiances at the retina, with a 3 mm pupil diameter. For a spectral irradiance $L(\lambda)$, the blue light photochemical hazard rule for is given by:

$$\sum_{300}^{700} L(\lambda) \cdot A(\lambda) \cdot t \cdot \Delta\lambda \leq 15 \, \text{kJm}^{-2}$$

For the blue light hazard function, $A(\lambda)$, we used the aphakic hazard function from Table 1 of the ICNIRP guidelines.[1]

For 10 µs < t < 10 seconds and a 3 mm pupil diameter, the retinal thermal hazard rule is defined as:

$$\sum_{380}^{1400} L(\lambda) \cdot R(\lambda) \cdot \Delta\lambda \leq \frac{0.75}{\alpha \cdot t^{0.25}} \, \text{kWm}^{-2}$$

Here $R(\gamma)$ is the retinal thermal hazard function and α is the angular subtense of the source in radians—that is, for sources outside the eye the mean light source dimension divided by the viewing distance. The rule is valid for 1.7 mrad < α < 0.1 rad. For the retinal thermal hazard rule no values are given for the aphakic eye.

Therefore, we calculated a correction factor from the blue light hazard function and the aphakic hazard function for photochemical light damage and used this to modify the retinal thermal hazard function $R(\lambda)$, given in Table 1 of the ICNIRP guidelines, into an aphakic function $R'(\lambda)$. For application of the retinal thermal hazard rule with intraocular light sources, we transformed it to:

$$\sum_{380}^{1400} L(\lambda) \cdot R'(\lambda) \cdot \Delta\lambda \leq \frac{12.8}{d \cdot t^{0.25}} \, \text{MWm}^{-2}$$

The angular subtense α induces a particular spot on the retina, which can be described by its diameter. This spot diameter d (µm) is used in the retinal thermal hazard rule for intraocular light sources above and is given by:

$$d = d_f + 2 \cdot l \cdot \tan(\beta)$$

Here β is the acceptance angle of the fibre, d_f the fibre diameter, and l the distance of the top of the probe to the retina in micrometres. The parameter d was also used to calculate the irradiance at the retina from the power output at the top of the probe. We used a fibre with d_f =300 µm.

Results

SPECTRAL DISTRIBUTION
The light sources investigated could be divided into three types. Figure 1 shows typical spectral radiances. Type 1 is a halogen-like source, type 2 a metal halide-like source, and type 3 a xenon-like source. Integrated power, including the fibre optics, is shown in Table 1.

BLUE LIGHT PHOTOCHEMICAL RETINAL HAZARD
The blue light photochemical hazard depends on the effective energy delivered onto the retina. Thus, knowing the maximum permissible dose and the power of a source, a maximum exposure time follows. Vice versa, given a particular illumination time, a maximum power output can be calculated. Table 1 shows the time to reach the guideline thresholds for blue light photochemical retinal hazard for the various light sources. All but one of the sources show threshold times of less than 1 minute.

Table 1 Integrated power of light sources and time (in minutes) to reach the ICNIRP threshold guidelines for blue light photochemical retinal hazard. Sources of various brands (brand 1–4) were measured with filters that were provided by the manufacturer (filter A–E) or without filter (no filter). Maximal exposure time was calculated for a 10 mm distance between retina and light source, a 300 µm fibre diameter and a 20° acceptance angle. In addition, we evaluated the effect of adding three different long pass filters

Light source	Integrated power (mW)	Calculated threshold exposure time (minutes)			
		without filters	with GG475	with OG450	with OG435
Metal halide, brand 1, no filter	40.8	0.2	1.7	0.5	0.3
Metal halide, brand 1, filter A	29.4	0.5	2.0	0.8	0.6
Metal halide, brand 1, filter B	43.4	0.2	1.4	0.5	0.3
Metal halide, brand 2, no filter	38.5	0.4	1.9	0.8	0.5
Metal halide, brand 2, filter C	24.4	0.8	2.7	1.1	0.9
Halogen, brand 3, no filter	8.4	2.1	13.2	5.6	4.0
Halogen, brand 4, no filter	22.4	0.8	4.0	1.7	1.2
Xenon, brand 2, filter C	46.2	0.4	1.2	0.5	0.4
Xenon, brand 2, filter D	35.9	0.1	1.6	0.5	0.3
Xenon, brand 2, filter E	64.1	0.1	1.1	0.4	0.3

Table 2 Threshold time (in minutes) according to the ICNIRP guidelines for blue light photochemical retinal hazard with an OG 475 filter, for various working distances and power outputs, for a 300 µm fibre diameter and 20° acceptance angle. Sources of various brands (brand 1–4) were measured with filters that were provided by the manufacturer (filter A–E) or without filter (no filter)

Power (mW)	10.0	5.0	10.0
Distance (mm)	5	5	10
Light source			
Metal halide, brand 1, no filter	2.0	4.0	6.9
Metal halide, brand 1, filter A	1.7	3.5	6.0
Metal halide, brand 1, filter B	1.8	3.6	6.2
Metal halide, brand 2, no filter	2.2	4.3	7.4
Metal halide, brand 2, filter C	1.9	3.9	6.6
Halogen, brand 3, no filter	3.2	6.4	11.1
Halogen, brand 4, no filter	2.6	5.2	8.9
Xenon, brand 2, filter C	1.6	3.3	5.7
Xenon, brand 2, filter D	1.7	3.3	5.7
Xenon, brand 2, filter E	2.1	4.2	7.2

Moreover, these values are calculated for a 10 mm working distance. In practice, shorter distances will occur.

Possible measures to increase the maximal exposure time are (1) using a long pass filter to avoid blue light reaching the retina, (2) lowering the output, or (3) increasing the distance between fibre and retina. We calculated the effect of additional long pass filters by multiplication of the spectral content of each light source with the spectral transmittance of the particular filter. Results are shown in Table 1. The influence of a particular filter differs for the various light sources, depending on their spectral content. Table 2 shows time limits for various working distances and power outputs with a GG475 filter. Note that doubling the distance has more effect on the time limits than halving the power.

RETINAL THERMAL HAZARD

For retinal thermal hazard, guideline threshold power depends on exposure time and spot size. Therefore, for a given time and working distance this limit is either exceeded, or not. Table 3 shows the results for power settings as advocated by the manufacturer, with and without additional filters. Without additional filters, all but one of the light sources exceeded the guideline threshold for 1 second illumina-

Table 3 Indication of thermal retinal damage with a 300 µm fibre diameter and a 20° acceptance angle, according to the ICNIRP guidelines. Sources of various brands (brand 1–4) were measured with filters that were provided by the manufacturer (filter A–E) or without filter (no filter)

Distance (mm)	0	0	0	0
Time (s)	1.0	1.0	1.0	1.0
Light source	*without filters*	*with GG475*	*with OG450*	*With OG435*
Metal halide, brand 1, no filter	Yes	Yes	Yes	Yes
Metal halide, brand 1, filter A	Yes	Yes	Yes	Yes
Metal halide, brand 1, filter B	Yes	Yes	Yes	Yes
Metal halide, brand 2, no filter	Yes	Yes	Yes	Yes
Metal halide, brand 2, filter C	Yes	No	No	Yes
Halogen, brand 3, no filter	No	No	No	No
Halogen, brand 4, no filter	Yes	No	No	Yes
Xenon, brand 2, filter C	Yes	Yes	Yes	Yes
Xenon, brand 2, filter D	Yes	No	Yes	Yes
Xenon, brand 2, filter E	Yes	Yes	Yes	Yes

tion and a 0 mm working distance—that is, with the probe in direct contact with the retina.

Discussion

Measurements of the spectrum and energy output of commercially available light sources for endoillumination indicate that the ICNIRP safety guidelines for retinal damage by visible light are exceeded within 3 minutes. For nine out of 10 sources the safe exposure time is even less than 1 minute. Within this very short exposure time guideline thresholds are surpassed irrespective of the filters that are advocated by the manufacturer and even when the probe is kept at a distance of 10 mm from the retina. The safety limits for thermal damage were exceeded for all but one of the sources when the light probe is in contact with the retina for 1 second.

Since there are no retinal phototoxicity thresholds available in literature that are both weighted for wavelength as well as specific for endoillumination during vitreous surgery, we based our calculations for visible light on the guidelines for the intact aphakic eye as provided by the ICNIRP. Thus, the actual thresholds may even be lower since the ICNIRP guidelines account for absorption by cornea and vitreous. The difference in threshold is probably small because most of the light that is absorbed by cornea and vitreous does not pass the fibre optics either. Although not stated, the ICNIRP guidelines are probably based on experiments of Ham *et al*[2] This implies that a safety factor of 33 is incorporated.[3] To calculate threshold exposure times for actual photochemical damage, the figures in Tables 1 and 2 should be multiplied by this factor 33.

Given these results, it is not surprising that several authors have reported retinal pigment epithelial damage that can be attributed to light toxicity from an endoillumination probe.[4-7] In a controlled clinical trial for macular hole repair surgery 7% of patients had presumptive photochemical retinal toxicity with a significantly worse visual outcome.[8] This number is an underestimation of the actual percentage of light toxicity since blue light damage at threshold values is located in the photoreceptors and not in the retinal pigment epithelium.[9] The actual occurrence of light damage can not be assessed because there is no current technique that can differentiate phototoxic damage exclusive to photoreceptors from photoreceptor disturbances that are due to the disease that is being treated.

To reduce the risk of retinal phototoxicity we advocate the following measures. Firstly, a 475 nm long pass filter should be incorporated into the optic pathway. Exposure times can thus be prolonged significantly (Table 1). In addition, any photochemical damage can be assessed with funduscopy or fluorescein angiography since toxicity from light with a wavelength longer 475 nm will always affect the retinal pigment epithelium.[9] Without filtering of the light below 475 nm, isolated photoreceptor damage may occur which might go unnoticed. Although the 475 nm filter brings about a yel-

lowish colour of the illumination light, it is our experience that most surgery can be completed without compromise to visibility. Only when delicate membranes have to be removed from the retinal surface, may short exposure with white light be needed.

Secondly, the output power from the fibreoptic should be measured before starting surgery and should be adjusted to 10 mW or less. We have found a significant variation in the transmittance of illumination fibres, especially when they are being reused (unpublished results).

Thirdly, the tip of a standard fibreoptic should kept at a distance of at least 10 mm from the retina. This means that the illuminated field should include a larger area than the retina inside the temporal vascular arcades. Illuminating just the area between the vascular arcades, which has a diameter of about 10 mm, would correspond with a fibreoptic distance of only 5 mm. To avoid thermal damage, the fibreoptic should not touch the retina. Although the results reported here only hold true for the attached retina, it seems prudent not to use the light probe as an instrument to manipulate the detached retina, since photochemical damage may occur. Thermal damage in the detached retina is unlikely since damage in the attached retina mainly results from light absorption in the retinal pigment epithelium.

Depending on the type of light source used, the above mentioned measures increase the safe exposure time of the posterior pole from less than 1 minute to up to 11 minutes. This time limit is still unrealistic in vitreoretinal surgery. In practice, at least a part of the safety factor that is incorporated in the ICNIRP guidelines will be consumed. Thus, macular phototoxic damage remains a factual danger during vitrectomy, even with maximum precautions.

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