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Chronic Far-UVC (222nm) Light Exposure of SKH-1 Hairless Mice Does Not Cause Detectable Eye Pathology or Visual Deficits

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ABSTRACT

Purpose: Far-UVC light (200–235 nm) is a new antimicrobial technology proposed for use in occupied spaces. In contrast to conventional germicidal UV light (254 nm), theoretical considerations and emerging safety data suggest that the decreased penetration depth of shorter wavelength far-UVC light causes less damage to vulnerable eye and skin tissue. This study examined the ocular effects of chronic far-UVC exposure in hairless, immune-competent SKH-1 mice after long-term exposure.

Methods: Over 66 weeks, five days/week, eight hours/day, 48 each male and female mice were exposed to high (400 mJ/cm^2), medium (130 mJ/cm^2), low (55 mJ/cm^2), or no (0 mJ/cm^2) far-UVC (222 nm) light. Visual acuity and contrast sensitivity was determined using optokinetic methods, slit lamp examinations were made of the anterior segment, and intraocular pressure was determined. Analysis of corneal images quantified the extent of corneal neovascularization.

Results: No significant differences in visual acuity, contrast sensitivity, intraocular pressure, or corneal neovascularization were observed between unirradiated animals and exposure groups. All groups, including unexposed controls, exhibited some degree of corneal neovascularization. Male mice had significantly lower visual acuity and contrast sensitivity than females. Stratified by gender, there was no exposure condition-based difference in contrast sensitivity. These findings were consistent whether each animal's eyes were averaged. or if all eyes were assessed individually.

Conclusion: There was no relationship between far-UVC dose and visual acuity, contrast sensitivity, ocular pressure, or corneal neovascularization. Female mice had significantly higher visual acuity and contrast sensitivity. No ocular pathologies were observed, even at 400 mJ/cm^2, substantially above the recently enacted ACGIH safety threshold of 160 mJ/cm^2 for 222 nm ocular exposures. More sensitive or detailed corneal examinations, longer daily exposures, or higher far-UVC doses, may be useful to define thresholds for human eye safety.

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Far-UVC exposure; SKH-1 mice; contrast sensitivity-testing; optomotor response; corneal neovascularization

Introduction

The high incidence of iatrogenic infection in healthcare settings,[1] as well as the morbidity and mortality associated with community-acquired respiratory pathogens,[2] emphasize the need for disinfection technology that can be used while a room is occupied. The COVID-19 pandemic has heightened awareness of the potential use of far-UVC (200–235 nm) light technology to reduce risk for infection by airborne pathogens while, at the same time, limiting damage to human tissue.[3,4] Unlike conventional 254 nm germicidal lamps, which can penetrate more deeply into skin and eye tissue, 222 nm far-UVC has a smaller penetration depth.[5,6]

Far-UVC light has been shown to reduce airborne influenza and norovirus concentrations substantially.[7,8] Of particular relevance to the Covid-19 pandemic, doses below 1.0 mJ/cm^2 were reported to inactivate 90% of two airborne human coronaviruses[9] whilst 12.4 mJ/cm^2 inactivated 99.7%.[10] Other studies with SARS-CoV-2 on surfaces or in solution reported similar efficacies.[11,12] Far-UVC light is also bactericidal, reducing levels of common hospital-borne infections such as Escherichia coli, Staph aureus, and Pseudomonas aeruginosa ten-fold at doses ranging from 2 to 17 mJ/cm^2.[13] All of these exposure levels are well below the ACGIH Threshold Limit Value for eye exposure of 160 mJ/cm^2 over an 8-hour period,[14] but higher doses may be necessary to inactivate hardier microbial pathogens.[15] Notably, effective fungicidal levels for far-UVC exposure have been reported to be around 467 mJ/cm^2, well above the occupational limit.[16] A better understanding of potential adverse ocular

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outcomes at these higher doses is therefore needed to establish evidence-based dose limits for far-UVC light to ensure eye safety.

Acute, high dose skin exposure studies using human volunteers did not observe erythema with doses up to 500 mJ/cm^2, and in one case study, a single subject was exposed to 18,000 mJ/cm^2 without ill effect.[17,18] However, with no natural human exposure to far-UVC, chronic far-UVC exposure studies are limited to experimental animal models. Earlier work from our laboratories demonstrated the skin safety profile of chronic far-UVC exposure in a SKH-1 hairless albino mouse model. We reported no UV-induced skin pathology, weight change, or overall mortality.[19] The current manuscript reports the results of comprehensive, periodic ocular examinations in this same chronically exposed murine cohort.

A large body of epidemiological, experimental animal, and human clinical research indicates serious risk for ocular pathologies following UVC (254 nm), UV-B, or UV-A-exposure, including photokeratitis, pterygium, pinguecula, photophobia, cataract, and macular degeneration.[20,21] In addition to pathological changes, these conditions are also often associated with visual deficits in acuity or contrast sensitivity.[22] In contrast, only one study assessed visual deficits associated with chronic (one year), low-dose far-UVC irradiation.[23]

Studies evaluating ocular effects or potential eye pathologies arising from far-UVC exposure in human volunteers utilized either acute exposures[24,25] or low-dose chronic or prolonged exposures.[23,26] Pitts exposed a small number of participants to various wavelengths of light in the conventional UVC and far-UVC range. A photokeratitis threshold of 8 mJ/cm^2 was reported after exposure to 245–255 waveband conventional germicidal UVC. In comparison, participants exhibited photokeratitis following exposure to 10 mJ/cm^2 215–225 nm waveband light, and after exposure to 13 mJ/cm^2 225–235 waveband light.[24] A recent paper, however, suggested that the far-UVC induced photokeratitis thresholds were overestimated due to uncertainties introduced by stray-light (out-of-pass-band) spectral radiant energy, permitting higher wavelengths to damage the cornea.[27]

In a prolonged exposure study over three consecutive five-hour days, Kousha et al.[26] found no change in self-reported ocular discomfort or eye dryness in students exposed to far-UVC light from ceiling-mounted lamps in the room they were working. Exposure intensity varied by participant position, with most receiving less than 20 mJ/cm^2 and no participant receiving more than 50 mJ/cm^2, measured at the top of the head. No measurements were made to ascertain actual eye doses. In another study, six physicians, five of whom wore glasses, spent a mean of 6.7 h/week in an office illuminated with ceiling-mounted far-UVC lights.[23] The authors calculated a maximum theoretical far-UVC exposure of 6.4 mJ/cm^2 as the daily dose theoretically received by a 170 cm subject staring at the lamp for eight hours. As the subjects only spent an average of one hour per day in the room, the authors suggested the daily eye dose maximum was well under 2.8 mJ/cm^2. Not unexpectedly, periodic slit lamp examination revealed no signs of acute keratitis, corneal erosion, conjunctival hyperemia, lid skin erythema, pterygium, cataract, or lid tumors in any subjects. Most recently, an acute exposure study reported no evidence of photokeratitis, hyperemia, change in visual acuity, or any other evidence of ocular damage after five subjects were exposed to between 22.5 and 75 mJ/cm^2 over a two to six-hour period.[25]

Several studies have examined the effects of far-UVC exposure on the eyes of rats and mice following very high intensity exposure for short periods of time,[28,29] or only a single exposure.[30] One study evaluated three day per week exposure over 10 weeks.[31] Most ocular safety studies in animal models focused on pyrimidine dimer formation as the main outcome without examining visual function or other physiological endpoints reflecting underlying ocular cell damage. The approaches in the animal studies assumed that far-UVC induced damage would be similar to that seen after 254 nm light exposure, where cyclo-pyrimidine dimer formation is the main form of DNA damage and of the most health concern. Notably, the authors of these studies did not report any far-UVC dose-related morphological or histological changes in the animal's corneas.

The current manuscript details, for the first time, quantitative determinations of vision, including acuity and contrast sensitivity, in a murine model of chronic far-UVC exposure. We also detail abnormal corneal morphology in the SKH1 mouse model, including significant corneal neovascularization. This observation may provide new insights into the molecular mechanisms underlying the *Hr* gene defect that characterizes the SKH1 strain. We conclude that under the experimental conditions utilized, far-UVC did not result in significant visual deficits or anterior segment structural changes.

Methods

Animals and far-UVC exposure

48 male and 48 female mice (SKH1-Elite Mouse 477; Charles River Labs, Wilmington, MA) were exposed to one of four far-UVC light exposure conditions for eight hours per day 5 days per week over 66 weeks (12 male and 12 female mice per condition) between noon and 8 pm. The four groups included high (400 mJ/cm^2), medium (130 mJ/cm^2), low (55 mJ/cm^2), and unexposed (0 mJ/cm^2) per 8 h. Our earlier publication provides a detailed description of the experimental conditions, dosimetry, and lamp setup.[19] Briefly, 8-week-old SKH-1 mice were placed in 35x35 cm acrylic cages covered with wire mesh that allowed 79% direct light transmission. KrCl excimer microplasma lamps (Eden Park Illumination, Eden Park, IL) with optic filters to limit off-peak emissions provided light exposure over 8 h, 5 days a week for 66 weeks. The average intensity in each condition was confirmed with calibrated radiation-sensitive film (OrthoChromic Film OC-1 (Orthochrome Inc., Hillsborough, NJ)).[32]

All protocols were approved by the Columbia University Institutional Animal Care and Use Committee (IACUC) and were consistent with those approved by the American Association for Accreditation of Laboratory Animal Care (AAALAC), and the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research.

Optokinetic testing

Optokinetic acuity and contrast sensitivity tests were performed using a Cerebral Mechanics (Alberta, Canada) OptoMotry©

system as previously described.[33,34] Briefly, at periodic intervals, mice were placed into a square enclosure surrounded by 4-monitors displaying a rotating pattern of white and gray lines at a given spatial frequency. Head rotation, indicative of tracking, was observed by an overhead video camera. Tracking in the direction of pattern rotation within the first second of presentation was counted as a positive detection of the grid pattern. The highest spatial frequency that a mouse could successfully track determined acuity. To assess contrast sensitivity, the grid density was set at 0.064 cycles/degree and the contrast between the white and gray lines was incrementally decreased to quantify the contrast sensitivity threshold for each eye.

Experimenters were blind to the exposure conditions of mice during optokinetic testing, slit lamp exams and intraocular pressure measurements.

Ocular pressure

After 66 weeks of chronic exposure, animals were euthanized by CO_2 asphyxiation with death confirmed by cervical dislocation. Prior to euthanasia, animals were anesthetized by ketamine/xylazine (100 mg/kg, 20 mg/kg respectively) and intraocular pressure quantified by a Tonolab© tonometer using a disposable iCare probe. Pressure measurements for each eye were made in quadruplicate and averaged.

Neovascularization

Periodically, non-dilated images of each eye were documented using a Nikon FS-3 Zoom Photo Slit Lamp and PixelLink (Nikon, Tokyo, Japan) PL-B872CU camera. Image area of the cornea within the contour of the iris was isolated and manually marked by an evaluator denoting vasculature, opaque deposits, and out of focus areas of the image that could not be assessed. (Figure 1) Marking was done using the Sketchbook (Sketchbook, Inc. San Francisco, CA) application on a Samsung Galaxy Tab S6 Lite. Evaluators were blind to condition and sex of the animals being assessed. Total image size minus areas that could not be assessed due to glare or poor image focus was calculated to determine total analyzable area. The number of pixels marked as vasculature or opaque deposits as a percentage of total analyzable area was calculated for each cornea. Images were analyzed using the opensource software ImageJ2 with additional Fiji plugins.

Statistical analysis

Comparisons across exposure groups were made using linear regression between average 8 h exposure dose in mJ/cm^2 and the continuous outcome of interest. Between-sex differences were assessed using a two-tailed student's t-test. Each analysis was conducted on each animal's eyes averaged together. Additional sensitivity analysis was conducted with each eye analyzed separately to increase the detection of unilateral changes. All statistical analyses were conducted in R Studio v12.2022.12.0.

Results

Visual acuity

There is no published data on the average lifespan of SHK-1 mice, but the survival curves previously published by our group suggest far shorter life expectancy than that reported for wild type mice such as pigmented C57BL/6 or albino BALB/c.[19] Thus, due to mortality, only 73 of 96 animals were assessed for visual acuity at the end of the 66-week study (37 males, 36 females).

There was no significant difference in visual acuity between treatment conditions, as demonstrated by linear regression between acuity and exposure dose ($F = 0.0942$ on 1 and 71 DF, $p = 0.7598$) (Figure 2). Visual acuity was significantly higher amongst females than males ($p < 0.0001$, 95%CI= 0.0469c/d to 0.0941c/d). Eleven mice did not demonstrate tracking behavior in one direction, indicating unilateral vision loss. Across exposure conditions, the number of animals with a unilateral lack of tracking was one in the low exposure condition, six in medium exposure condition, and two in the high exposure condition. All animals who displayed a unilateral lack of tracking were males.

Contrast sensitivity

Contrast sensitivity was significantly higher in females compared to male animals (95%CI: 0.223 – 5.051, $p = 0.0331$)

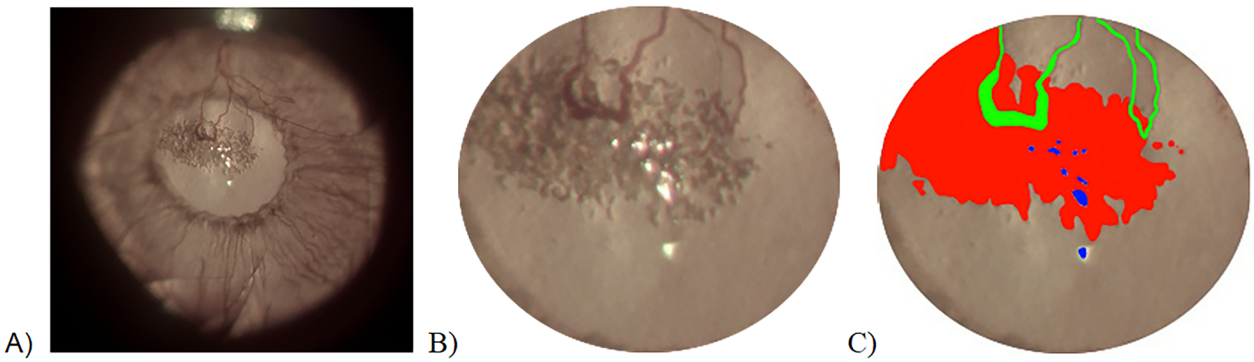

Figure 1. Process of vasculature analysis. A) Original image of animal's eye with extensive neovascularization and deposition. B) The photograph was cropped to eliminate normal iris stromal vasculature from image analysis. C) An evaluator blind to condition and sex of each animal annotated the cornea. The number of pixels occupied by vasculature (green) and opaque deposition (red) were measured. Analyzable area was measured by the total number of pixels in the cornea image minus areas where glare or lack of focus prevent assessment (blue).

(Figure 3). Due to time constraints, to maintain treatment schedules, female mice in the medium exposure group were not evaluated for contrast sensitivity. Collapsing sexes within each group, contrast sensitivity did show a significant effect of exposure group ($F=2.827$, df = 1 ($N=57$), $p=0.0473$). Pairwise t-tests demonstrated that the only significant between group differences were seen between the medium exposure group and each other group (Supplemental Table 1). When stratified by sex, there was no effect of group on contrast sensitivity in male ($F=2.297$, df = 1 ($N=37$), $p=0.1386$) or female animals ($F=1.252$, df = 1, ($N=20$), $p=0.278$).

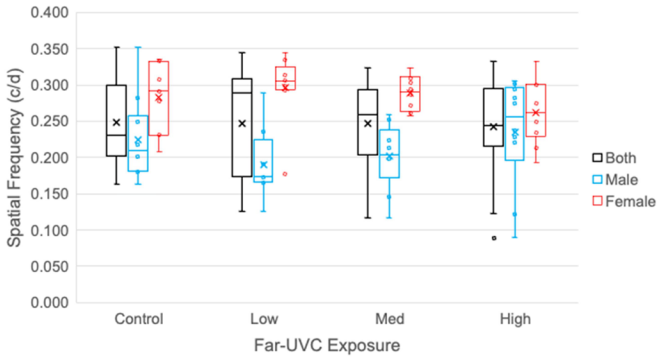

Figure 2. Average visual acuity as assessed by optokinetic testing by sex (male-blue, female-red, combined-black) and by far-UVC exposure condition (unexposed control, low, medium and high dose).

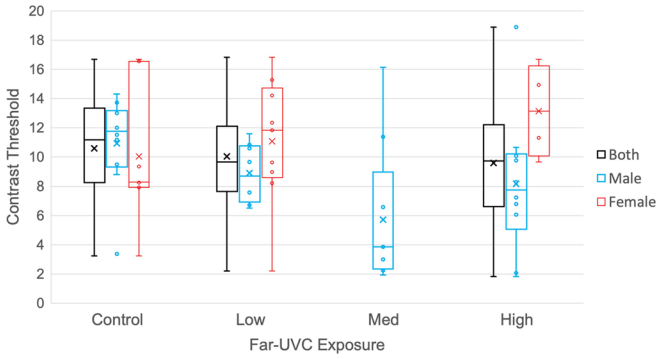

Figure 3. Average contrast sensitivity as assessed by optokinetic testing by sex (male-blue, female-red, combined-black) and by far-UVC exposure condition (unexposed control, low, medium and high dose). Contrast sensitivity for female mice in the medium exposure condition was not assessed.

Corneal neo-vascularization

A total of 83 eyes across 54 different animals were of sufficient image quality to be analyzed. Of the corneas assessed, 72 showed some degree of vascularization, and 46 showed variable amounts of subepithelial deposition/haze. Only 7 corneas showed no sign of either pathology. Typical images of corneal neovascularization and accompanying subepithelial deposits are shown in Figure 4. Corneas exhibited variable numbers of vessels that originated at the limbus and extended into the stroma from any quadrant. While some were relatively straight and few in number (Figure 4(A)), others showed bifurcations, tortuous paths, or looped back towards their origin (Figure 4(B)). In some, but not all cases, dark, irregular stromal deposits of unknown nature appeared in the general vicinity of the vasculature but was not always coincident with the vessels themselves (Figure 4(C)). The variety in their presentation, number, depth, and location made them more difficult to assess individually, separate and apart from any overall measures of opacity. There was no significant difference between dose groups in total vascularized area as a percentage of total analyzable area of each cornea ($F=0.5608$, df = 3, ($N=84$), $p=0.2046$) (Figure 5). The total opaque area, including the stromal deposits, as a percentage of total analyzable area of each cornea was found to have no significant difference between dose groups ($F=1.976$, df = 3, ($N=84$), $p=0.1244$). There was a very weak association between greater total opaque area and lower visual acuity ($R^2=0.0984$).

Male mice were found to have a statistical trend towards higher percent vascularized area than female mice (95%CI= -1.351% to 2.048%, $p=0.0851$). Male mice were found to have a significantly higher percent area covered in opaque deposits than female mice (95%CI = 5.669% to 18.2728%, $p=0.0003$).

Intraocular pressure

Intraocular pressure did not differ between exposure groups ($F=0.7517$, df = 1, ($N=65$), $p=0.3892$), or between sexes (95%CI= -0.967 to 2.098, $p=0.464$) (Figure 6). Following optokinetic testing but prior to euthanasia, 8 animals died before they could have their ocular pressures assessed (5 males, 3 females).

Discussion

The normal visual activity of SKH-1 mice is poorly characterized as this murine model is primarily used in dermatological research. The findings of significant, progressive corneal neovascularization and opaque stromal deposits in unexposed control animals is a novel finding that may offer clues to other unreported functions of the *Hr* gene. The nature and origin of the opaque deposits are unclear and future histopathological studies may be informative. One possibility is that they represent coagulated blood from leaky vessels in the stroma. No corneas exhibited deposits in the absence of any corneal neovascularization. Curiously, SKH-1 corneal neovascularization was briefly noted 30 years ago in a paper describing subepithelial corneal neovascularization in immunodeficient nude (nu/nu) mice, but no images were provided.[35] No follow-up studies or mechanistic investigations of this phenomena in SKH-1 mice have been published. A mechanistic explanation for corneal neovascularization in nu/nu mice was later explored in an orthotopic transplantation study between normal BALB/c and nude mice, reporting putative increases in angiogenic activity in corneal epithelium and accompanying decreases in anti-angiogenic factors in the corneal stroma, but this observation was not extended to the SKH-1 strain.[36] Because the same phenomena was noted in immune-incompetent nude mice and immune-competent SKH-1 mice, the authors speculated that corneal

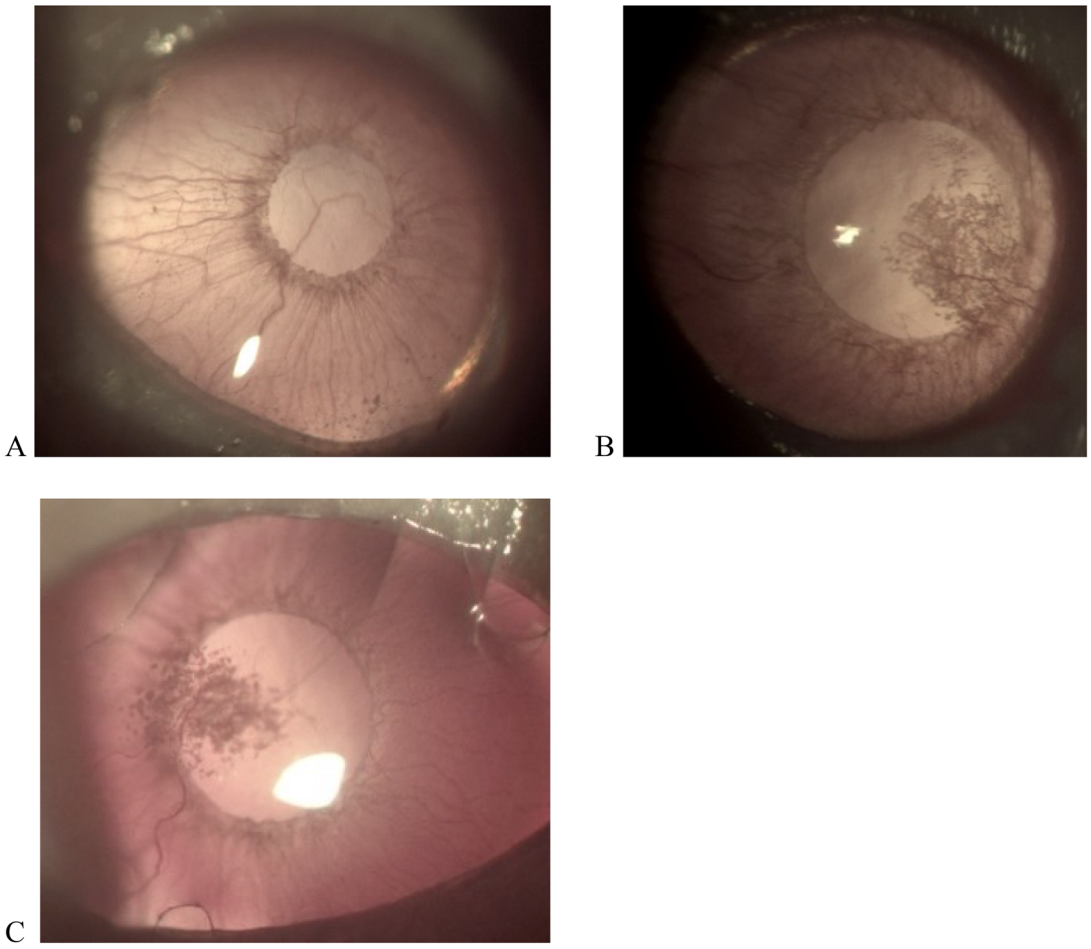

Figure 4. Typical images of undilated SKH-1 mouse eyes with extensive corneal neovasculature seen across all exposure groups. A) Eye with relatively few numbers of vessels and no accompanying stromal deposits; B) Eye with both loopback and tortuous vessels and deposits; C) Eye with a small number of vessels but a large opaque area of stromal deposition.

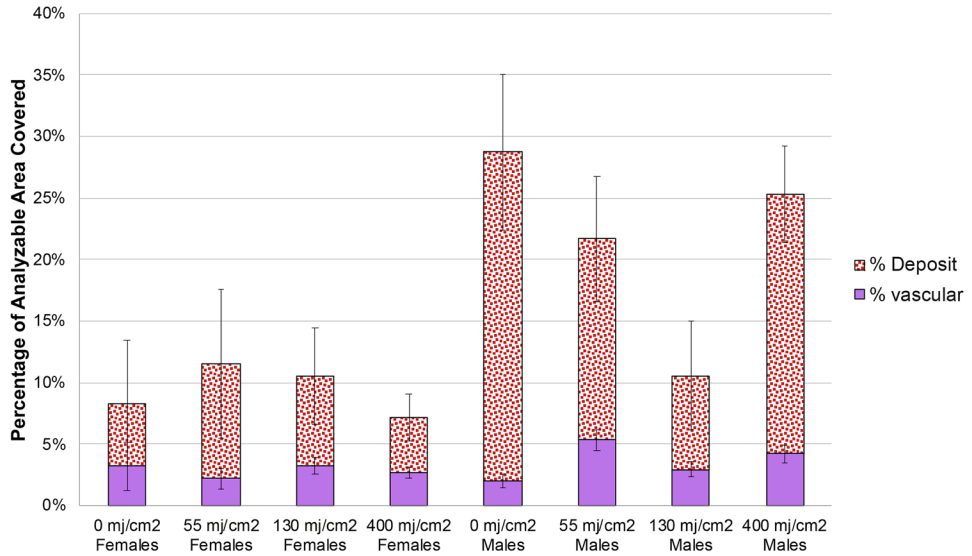

Figure 5. Average percentage of total corneal area covered by vasculature or opaque haze. Separated by sex and exposure dose.

neovascularization in hairless mice was not immune mediated, but rather reflected other unknown genetic factors in both strains. That hypothesis is supported by the lack of an observed inflammatory dose-response between corneal neovascularization and far-UVC exposure observed in the current study. Nevertheless, more detailed immunohistological study of far-UVC exposed corneas could reveal cellular features of inflammatory responses in the cornea or conjunctiva that were not observed by slit lamp exam. To our knowledge, no other studies that have explored the relationship between the SKH-1

genotype and corneal neovascularization and this manuscript is the first to publish corneal images of SKH-1 mice.

Across all outcome measures evaluated, there was no significant effect of far-UVC exposure on visual acuity, contrast sensitivity, ocular vascularization, or intra-ocular pressure (Table 1). The only outcome that showed a significant effect of exposure was the significantly reduced contrast sensitivity seen in the medium exposure group, however, this difference vanished when stratified by sex indicating that sex was the confounder driving the difference. The medium exposure condition was also unique in that only male animals were evaluated for contrast sensitivity. Since females had significantly higher contrast sensitivity than males, we tested if the apparent exposure group difference was instead driven by between-sex differences. When the contrast sensitivity of only the male animals was compared across exposure conditions, there was no longer a significant difference between groups ($F=2.755$, df = 3 ($N=37$), $p=0.0579$). This comparison indicates that there was no effect of dose on contrast sensitivity.

The proportion of corneal area covered by neovascularization and/or opaque deposits demonstrated a similar pattern as that noted for acuity and contrast sensitivity; with differences seen between sexes but not exposure groups. Male mice had on average 3.62% of their corneal surface vascularized compared to 2.82% in female mice, a trend, but not a statistically significant difference. The association between visual acuity and proportion of corneal area opacified by vasculature or haze was very weak, but this is consistent with findings in humans, which have not shown a consistent relationship between vascularization and visual acuity.[37]

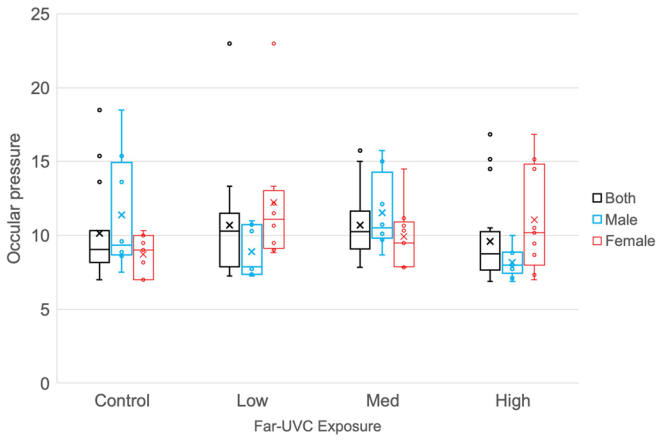

Figure 6. Average ocular pressure as assessed in quadruplet by tonometry. Grouped by sex (male-blue, female-red, combined-black) and by far-UVC exposure condition (unexposed control, low, medium and high dose).

Since the effect size of unilateral ocular changes may have been diminished in a single animal by averaging values for both eyes, a sensitivity analysis was also done in which each eye was evaluated independently. The findings were consistent with the findings seen when both eyes from each animal were averaged together. As with the analysis of both eyes averaged together, the only significant difference detected was in the contrast sensitivity measure. In both cases, the difference was no longer seen when the analysis was stratified by sex, indicating that contrast sensitivity differences were confounded by sex. It is not clear why male SKH-1 mice have a deterioration in both contrast vision and visual acuity relative to females, but this might reflect heretofore unreported sex-related ocular differences in this strain. One possibility that may be explored in future studies using ERG measures and retinal histopathology is that there could be sex-based differences in retinal function. Sex-based differences in retinal function have been reported in both mice and rats.[38,39] Other sex-based differences (e.g. in dermal thickness) have been reported in this strain.[40] While SKH1 mice are deficient in *Hr* expression due to aberrant splicing, reports suggest that these mice express 8.5% of the normal full-length *Hr* transcript,.[41] However, it is not clear if there are differences in expression related to sex.

The overall findings of this study support the ocular safety of far-UVC light under the exposure conditions and doses reported. Nevertheless, the observation that some mice were unable to track in one direction but not the other raises a potential note of caution. Nine male mice did not demonstrate tracking behavior in one direction, indicating a unilateral lack of vision (low = 1; medium = 6; high = 2). This effect was not seen in the females tested and in none of the unexposed mice of either sex. In human populations, unilateral vision loss is more common than bilateral visual loss.[42] Eye pathologies frequently occur unilaterally, with the contralateral eye developing ocular issues many years later, and in some cases not demonstrating pathology at all.[43] Future studies may clarify this observation.

There are a few limitations of this study. Several mice in each cohort died over the course of the 66-week exposure prior to testing visual acuity, contrast sensitivity, or intraocular pressure, reducing study power somewhat. Furthermore, our original report on skin damage detailed variability between cages based on position in relation to the overhead

Table 1. Average values and standard error of the mean for each outcome measure. The dose is averaged over an 8-hour exposure.

Group	Dose (mJ/cm^2)	Sex	Acuity (c/d)	Contrast Sensitivity	Ocular Pressure (psi)	Cornea % Area Vascularized	Cornea % Area Deposits
Control	0	Both	0.249 ± 0.015	10.56 ± 0.93	10.14 ± 0.84	2.33%±0.66%	20.59%±5.37%
		Male	0.225 ± 0.018	10.93 ± 1.00	11.40 ± 1.40	1.99%±0.56%	26.77%±6.32%
		Female	0.284 ± 0.018	10.03 ± 1.85	8.71 ± 0.52	3.19%±1.98%	5.13%±5.13%
Low	55	Both	0.247 ± 0.018	10.03 ± 0.86	10.69 ± 1.00	4.17%±0.69%	13.76%±3.88%
		Male	0.190 ± 0.018	8.89 ± 0.71	8.90 ± 0.64	5.32%±0.83%	16.35%±5.08%
		Female	0.297 ± 0.016	11.05 ± 1.47	12.25 ± 1.63	2.20%±0.82%	9.31%±6.03%
Med	130	Both	0.248 ± 0.013	5.73 ± 1.63	10.69 ± 0.59	3.09%±0.44%	7.45%±2.88%
		Male	0.202 ± 0.015	5.73 ± 1.63	11.55 ± 0.91	2.96%±0.60%	7.60%±4.45%
		Female	0.289 ± 0.008	N/AN/A	9.92 ± 0.71	3.22%±0.68%	7.31%±3.88%
High	400	Both	0.243 ± 0.014	9.58 ± 1.31	9.62 ± 0.69	3.38%±0.38%	12.38%±2.38%
		Male	0.224 ± 0.023	8.15 ± 1.53	8.16 ± 0.32	4.20%±0.76%	21.11%±3.90%
		Female	0.261 ± 0.014	13.14 ± 1.61	11.07 ± 1.19	2.65%±0.46%	4.51%±1.86%

light source. Additionally, some mice were observed to huddle together during the daylight exposure times, which may have attenuated each individual mouse's ocular far-UVC exposure somewhat. Nevertheless, video recordings during exposures and our reported far-UVC film measurements provide some confidence in our estimates of far-UVC exposure. We have begun designing a follow-up experiment with improved lamp designs, far-UVC exposures during nocturnal hours, periodic fluorescein slit-lamp examinations, and post-mortem corneal histology measures to expand upon these initial findings.

Therapeutic drugs and medical devices are always associated with some degree of risk, and regulatory and public approval hinges upon benefits greatly outweighing downside health concerns. The COVID-19 pandemic has greatly amplified the value of being able to disinfect the air in occupied spaces. At the same time, there is a tremendous need to reduce the high morbidity and mortality associated with community and hospital-acquired infections. This study's conclusion that chronic exposure to far-UVC light did not induce functional changes in vision or intra-ocular pressure and did not elevate the background incidence of corneal neovascularization bodes well for the safety of the technology. Nevertheless, further study is needed to better define potential biological markers of far-UVC damage to determine evidence-based exposure limits.[44] Our laboratories are engaged in assessing a variety of biochemical, molecular, and cellular damage endpoints that can be used to reliably determine functional upper limits for far-UVC damage in human eye tissue so that engineering controls can be employed to maximize anti-microbial efficacy while limiting human adverse health concerns.

This study was designed to quantify functional changes in vision in a murine model of chronic far-UVC exposure. Although far-UVC exposure may penetrate the tear film and cause damage to the outer layers of the corneal and conjunctival epithelium,[45] the findings herein suggest minimal clinically significant impact on vision, at least for the physiologic and functional endpoints evaluated in this study under these defined exposure conditions.

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Disclosure statement

Arden, Folkerts, Ramey, Welch, Mahmoud, Brenner, and Kleiman have no conflicts of interest to declare.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, NK, upon reasonable request.

References

1. Ramos-Rincon JM, Lopez-Sampalo A, Cobos-Palacios L, Ricci M, Rubio-Rivas M, Díaz-Simón R, Martín-Escalante MD, Castañeda-Pérez S, Fernández-Madera-Martínez R, Beato-Perez JL, SEMI-COVID-19 Network, et al. Nosocomial COVID-19: a nationwide Spanish study. Gerontol. 2023;69(6):671–683. doi:10.1159/000527711.
2. Aliberti S, Cruz CS, Amati F, Sotgiu G, Restrepo MI. Community-acquired pneumonia. Lancet. 2021;398(10303):906–919. doi:10.1016/S0140-6736(21)00630-9.
3. Brenner DJ. Far-UVC Light at 222 nm is showing significant potential to safely and efficiently inactivate airborne pathogens in occupied indoor locations. Photochem Photobiol. 2023;99(3):1047–1050. doi:10.1111/php.13739.
4. Hessling M, Haag R, Sieber N, Vatter P. The impact of far-UVC radiation (200-230 nm) on pathogens, cells, skin, and eyes - a collection and analysis of a hundred years of data. GMS Hyg Infect Control. 2021;16: doc07. doi:10.3205/dgkh000378.
5. Buonanno M, Randers-Pehrson G, Bigelow AW, Trivedi S, Lowy FD, Spotnitz HM, Hammer SM, Brenner DJ. 207-nm UV light - a promising tool for safe low-cost reduction of surgical site infections. I: in vitro studies. PLoS One. 2013;8(10):e76968. doi:10.1371/journal.pone.0076968.
6. Finlayson L, Barnard IR, McMillan L, Ibbotson SH, Brown CT, Eadie E, Wood K. Depth penetration of light into skin as a function of wavelength from 200 to 1000 nm. Photochem Photobiol. 2022;98(4):974–981. doi:10.1111/php.13550.
7. Welch D, Buonanno M, Grilj V, Shuryak I, Crickmore C, Bigelow AW, Randers-Pehrson G, Johnson GW, Brenner DJ. Far-UVC light: a new tool to control the spread of airborne-mediated microbial diseases. Sci Rep. 2018;8(1):2752. Erratum in: sci Rep. 2021 Sep 7;11(1):18122. doi:10.1038/s41598-018-21058-w.
8. Buonanno M, Kleiman NJ, Welch D, Hashmi R, Shuryak I, Brenner DJ. 222 nm far-UVC light markedly reduces the level of infectious airborne virus in an occupied room. Sci Rep. 2024;14(1):6722. 20 doi:10.1038/s41598-024-57441-z.
9. Buonanno M, Welch D, Shuryak I, Brenner DJ. Far-UVC light (222 nm) efficiently and safely inactivates airborne human coronaviruses. Sci Rep. 2020;10(1):10285. doi:10.1038/s41598-020-67211-2.
10. Welch D, Buonanno M, Buchan AG, Yang L, Atkinson KD, Shuryak I, Brenner DJ. Inactivation rates for airborne human coronavirus by low doses of 222 nm far-UVC radiation. Viruses. 2022;14(4):684. doi:10.3390/v14040684.
11. Kitagawa H, Nomura T, Nazmul T, Kawano R, Omori K, Shigemoto N, Sakaguchi T, Ohge H. Effect of intermittent irradiation and fluence-response of 222 nm ultraviolet light on SARS-CoV-2 contamination. Photodiagnosis Photodyn Ther. 2021;33:102184. doi:10.1016/j.pdpdt.2021.102184.
12. Ma B, Gundy PM, Gerba CP, Sobsey MD, Linden KG. UV Inactivation of SARS-CoV-2 across the UVC Spectrum: krCl* excimer, mercury-vapor, and light-emitting-diode (LED) sources. Appl Environ Microbiol. 2021;87(22):e0153221. doi:10.1128/AEM.01532-21.
13. Griffin DT, Gourlay T, Maclean M. The antibacterial efficacy of far-UVC light: a combined-method study exploring the effects of experimental and bacterial variables on dose–response. Pathogens. 2024;13(8):698. doi:10.3390/pathogens13080698.
14. American Conference of Governmental Industrial Hygienists, 2022 Threshold Limit Values and Biological Exposure Indices. Cincinnati, Ohio: American Conference of Governmental Industrial Hygienists. 2022.

15. Petersen C, Buonanno M, Guan L, Hinzer A, Urbano J, Hashmi R, Shuryak I, Parker S, Welch D. Susceptibility of extremophiles to far-UVC light for bioburden reduction in spacecraft assembly facilities. Life Sci Space Res (Amst). 2024;41:56–63. doi:10.1016/j.lssr.2024.01.006.
16. Smith BJ, Sampson BJ, Copes WE, Takeda F, Janisiewicz WJ, Stafne ET, Sakhanokho HF, Carroll JB. UVC (254 nm) and far UVC (222 nm) irradiation affects in vitro growth of Colletotrichum sp. isolates and their infection of detached strawberry leaves. PhytoFrontiers. 2024;4(4):634–642. doi:10.1094/PHYTOFR-03-24-0016-R.
17. Fukui T, Niikura T, Oda T, Kumabe Y, Ohashi H, Sasaki M, Igarashi T, Kunisada M, Yamano N, Oe K, et al. Exploratory clinical trial on the safety and bactericidal effect of 222-nm ultraviolet C irradiation in healthy humans. PLoS One. 2020;15(8):e0235948. doi:10.1371/journal.pone.0235948.
18. Eadie E, Barnard IMR, Ibbotson SH, Wood K. Extreme exposure to filtered far-UVC: a case study. Photochem Photobiol. 2021;97(3):527–531. doi:10.1111/php.13385.
19. Welch D, Kleiman NJ, Arden PC, Kuryla CL, Buonanno M, Ponnaiya B, Wu X, Brenner DJ. No evidence of induced skin cancer or other skin abnormalities after long-term (66 week) chronic exposure to 222-nm far-UVC radiation. Photochem Photobiol. 2023;99(1):168–175. doi:10.1111/php.13656.
20. Chawda D, Shinde P. Effects of solar radiation on the eyes. Cureus. 2022;14(10):e30857. doi:10.7759/cureus.30857.
21. Löfgren S, Michael R, Söderberg PG. Impact of age and sex in ultraviolet radiation cataract in the rat. Invest Ophthalmol Vis Sci. 2003;44(4):1629–1633. doi:10.1167/iovs.01-0922.
22. Xiong YZ, Kwon M, Bittner AK, Virgili G, Giacomelli G, Legge GE. Relationship between acuity and contrast sensitivity: differences due to eye disease. Invest Ophthalmol Vis Sci. 2020;61(6):40. doi:10.1167/iovs.61.6.40.
23. Sugihara K, Kaidzu S, Sasaki M, Ichioka S, Takayanagi Y, Shimizu H, Sano I, Hara K, Tanito M. One-year ocular safety observation of workers and estimations of microorganism inactivation efficacy in the room irradiated with 222-nm far ultraviolet-C lamps. Photochem Photobiol. 2023;99(3):967–974. doi:10.1111/php.13710.
24. Pitts DG. The ocular ultraviolet action spectrum and protection criteria. Health Phys. 1973;25(6):559–566. doi:10.1097/00004032-197312000-00002.
25. Sugihara K, Kaidzu S, Sasaki M, Tanito M. Interventional human ocular safety experiments for 222-nm far-ultraviolet-C lamp irradiation. Photochem Photobiol. 2025;101(2):517–526. doi:10.1111/php.14016.
26. Kousha O, O'Mahoney P, Hammond R, Wood K, Eadie E. 222 nm Far-UVC from filtered Krypton-Chloride excimer lamps does not cause eye irritation when deployed in a simulated office environment. Photochem Photobiol. 2024;100(1):137–145. doi:10.1111/php.13805.
27. Sliney DH, Stuck BE. A need to revise human exposure limits for ultraviolet UV-C radiation. Photochem Photobiol. 2021;97(3):485–492. doi:10.1111/php.13402.
28. Kaidzu S, Sugihara K, Sasaki M, Nishiaki A, Igarashi T, Tanito M. Evaluation of acute corneal damage induced by 222-nm and 254-nm ultraviolet light in Sprague–Dawley rats. Free Radic Res. 2019;53(6):611–617. doi:10.1080/10715762.2019.1603378.
29. Kaidzu S, Sugihara K, Sasaki M, Nishiaki A, Ohashi H, Igarashi T, Tanito M. Re-evaluation of rat corneal damage by short-wavelength UV revealed extremely less hazardous property of far-UV-C. Photochem Photobiol. 2021;97(3):505–516. doi:10.1111/php.13419.
30. Chen T-W. Safety and efficacy of 222-nm far-UVC disinfection for ophthalmic surgery. Invest Ophthalmol Vis Sci. 2023;64(8):3125. Abstract.
31. Yamano N, Kunisada M, Kaidzu S, Sugihara K, Nishiaki-Sawada A, Ohashi H, Yoshioka A, Igarashi T, Ohira A, Tanito M, et al. Long-term effects of 222 nm ultraviolet radiation C sterilizing lamps on mice susceptible to ultraviolet radiation. Photochem Photobiol. 2020;96(4):853–862. doi:10.1111/php.13269.
32. Welch D, Brenner DJ. Improved ultraviolet radiation film dosimetry using OrthoChromic OC-1 film. Photochem Photobiol. 2021;97(3):498–504. doi:10.1111/php.13364.
33. Prusky GT, Alam NM, Beekman S, Douglas RM. Rapid quantification of adult and developing mouse spatial vision using a virtual optomotor system. Invest Ophthalmol Vis Sci. 2004;45(12):4611–4616. doi:10.1167/iovs.04-0541.
34. Kleiman NJ, Edmondson EF, Weil MM, Fallgren CM, King A, Schmidt C, Hall EJ. Radiation cataract in Heterogeneous Stock mice after γ-ray or HZE ion exposure. Life Sci Space Res (Amst). 2024;40:97–105. doi:10.1016/j.lssr.2023.09.004.
35. Niederkorn JY, Ubelaker JE, Martin JM. Vascularization of corneas of hairless mutant mice. Invest Ophthalmol Vis Sci. 1990;31(5):948–953. PMID: 1692313
36. Kaminska GM, Niederkorn JY. Spontaneous corneal neovascularization in nude mice. Local imbalance between angiogenic and anti-angiogenic factors. Invest Ophthalmol Vis Sci. 1993;34(1):222–230. PMID: 8425828.
37. Bachman B, Taylor RS, Cursiefen C. The association between corneal neovascularization and visual acuity: a systematic review. Acta Ophthalmol. 2013;91(1):12–19. doi:10.1111/j.1755-3768.2011.02312.x.
38. Ribeiro FM, Gonçalves J, Coelho L, Castelo-Branco M, Martins J. Sex-dependent variations of retinal function and architecture in a neurofibromatosis type I mouse model with normal vision. Exp Eye Res. 2025;253:110279. doi:10.1016/j.exer.2025.110279.
39. Tyszkiewicz C, Hwang SK, Manickam B, Jakubczak B, Walters KM, Bolt MW, Santos R, Liu CN. Sex-related differences in retinal function in Wistar rats: implications for toxicity and safety studies. Front Toxicol. 2023;5:1176665. doi:10.3389/ftox.2023.1176665.
40. Benavides F, Oberyszyn TM, VanBuskirk AM, Reeve VE, Kusewitt DF. The hairless mouse in skin research. J Dermatol Sci. 2009;53(1):10–18. doi:10.1016/j.jdermsci.2008.08.012.
41. Schaffer BS, Grayson MH, Wortham JM, Kubicek CB, McCleish AT, Prajapati SI, Nelon LD, Brady MM, Jung I, Hosoyama T, et al. Immune competency of a hairless mouse strain for improved preclinical studies in genetically engineered mice. Mol Cancer Ther. 2010;9(8):2354–2364. doi:10.1158/1535-7163.MCT-10-020.
42. Foreman J, Xie J, Keel S, Ang GS, Lee PY, Bourne R, Crowston JG, Taylor HR, Dirani M. Prevalence and causes of unilateral vision impairment and unilateral blindness in Australia: the National Eye Health Survey. JAMA Ophthalmol. 2018;136(3):240–248. doi:10.1001/jamaophthalmol.2017.6457.
43. Schuster AK, Nickels S, Pfeiffer N, Schmidtmann I, Wild PS, Münzel T, Beutel ME, Lackner KJ, Vossmerbaeumer U. Frequency of cataract surgery and its impact on visual function-results from the German Gutenberg Health Study. Graefes Arch Clin Exp Ophthalmol. 2020;258(10):2223–2231. doi:10.1007/s00417-020-04770-0.
44. Görlitz M, Justen L, Rochette PJ, Buonanno M, Welch D, Kleiman NJ, Eadie E, Kaidzu S, Bradshaw WJ, Javorsky E, et al. Assessing the safety of new germicidal far-UVC technologies. Photochem Photobiol. 2024;100(3):501–520. doi:10.1111/php.13866.
45. Folkerts IT, Welch D, Buonnano M, Kuryla CL, Brenner DJ, Kleiman NJ. Human Tears provide little protection against far-UVC irradiation in human corneal epithelial cells. Second International Congress on Far-UVC Science and Technology (ICFUST). 2024. Abstract. https://www.eventsforce.net/standrews/frontend/reg/absViewDocumentFE.csp?documentID=3954&eventID=198