ISBN 978-3-902842-60-2

International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

TECHNICAL REPORT

Infrared Cataract

CIE 221:2016

UDC: 617.741-004.1 Descriptor: Cataract. Grey cataract

THE INTERNATIONAL COMMISSION ON ILLUMINATION

The International Commission on Illumination (CIE) is an organization devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in about 40 countries.

The objectives of the CIE are:

1. To provide an international forum for the discussion of all matters relating to the science, technology and art in the fields of light and lighting and for the interchange of information in these fields between countries.
2. To develop basic standards and procedures of metrology in the fields of light and lighting.
3. To provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting.
4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
5. To maintain liaison and technical interaction with other international organizations concerned with matters related to the science, technology, standardization and art in the fields of light and lighting.

The work of the CIE is carried out by Technical Committees, organized in seven Divisions. This work covers subjects ranging from fundamental matters to all types of lighting applications. The standards and technical reports developed by these international Divisions of the CIE are accepted throughout the world.
A plenary session is held every four years at which the work of the Divisions and Technical Committees is reported and reviewed, and plans are made for the future. The CIE is recognized as the authority on all aspects of light and lighting. As such it occupies an important position among international organizations.

LA COMMISSION INTERNATIONALE DE L'ECLAIRAGE

La Commission Internationale de l'Eclairage (CIE) est une organisation qui se donne pour but la coopération internationale et l'échange d'informations entre les Pays membres sur toutes les questions relatives à l'art et à la science de l'éclairage. Elle est composée de Comités Nationaux représentant environ 40 pays.

Les objectifs de la CIE sont :

1. De constituer un centre d'étude international pour toute matière relevant de la science, de la technologie et de l'art de la lumière et de l'éclairage et pour l'échange entre pays d'informations dans ces domaines.
2. D'élaborer des normes et des méthodes de base pour la métrologie dans les domaines de la lumière et de l'éclairage.
3. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
4. De préparer et publier des normes, rapports et autres textes, concernant toutes matières relatives à la science, la technologie et l'art dans les domaines de la lumière et de l'éclairage.
5. De maintenir une liaison et une collaboration technique avec les autres organisations internationales concernées par des sujets relatifs à la science, la technologie, la normalisation et l'art dans les domaines de la lumière et de l'éclairage.

Les travaux de la CIE sont effectués par Comités Techniques, organisés en sept Divisions. Les sujets d'études s'étendent des questions fondamentales, à tous les types d'applications de l'éclairage. Les normes et les rapports techniques élaborés par ces Divisions Internationales de la CIE sont reconnus dans le monde entier.
Tous les quatre ans, une Session plénière passe en revue le travail des Divisions et des Comités Techniques, en fait rapport et établit les projets de travaux pour l'avenir. La CIE est reconnue comme la plus haute autorité en ce qui concerne tous les aspects de la lumière et de l'éclairage. Elle occupe comme telle une position importante parmi les organisations internationales.

DIE INTERNATIONALE BELEUCHTUNGSKOMMISSION

Die Internationale Beleuchtungskommission (CIE) ist eine Organisation, die sich der internationalen Zusammenarbeit und dem Austausch von Informationen zwischen ihren Mitgliedsländern bezüglich der Kunst und Wissenschaft der Lichttechnik widmet. Die Mitgliedschaft besteht aus den Nationalen Komitees in rund 40 Ländern.

Die Ziele der CIE sind:

1. Ein internationales Forum für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen Ländern zu sein.
2. Grundnormen und Verfahren der Messtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
4. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

Die Arbeit der CIE wird durch Technische Komitees geleistet, die in sieben Divisionen organisiert sind. Diese Arbeit betrifft Gebiete mit grundlegendem Inhalt bis zu allen Arten der Lichtanwendung. Die Normen und Technischen Berichte, die von diesen international zusammengesetzten Divisionen ausgearbeitet werden, sind auf der ganzen Welt anerkannt.
Alle vier Jahre findet eine Session statt, in der die Arbeiten der Divisionen berichtet und überprüft werden, sowie neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

Published by the

COMMISSION INTERNATIONALE DE L'ECLAIRAGE
CIE Central Bureau
Babenbergerstrasse 9, A-1010 Vienna, AUSTRIA
Tel: +43(1)714 31 87
e-mail: ciecb@cie.co.at
www.cie.co.at

ISBN 978-3-902842-60-2

International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

TECHNICAL REPORT

Infrared Cataract

CIE 221:2016

UDC: 617.741-004.1 Descriptor: Cataract. Grey cataract

The following members of TC 6-49 “Infrared Cataract“ took part in the preparation of this Technical Report. The committee comes under Division 6 “Photobiology and Photochemistry”.

Authors:

Okuno, T. (Chair)	**Japan**
Kojima, M.	Japan
Schulmeister, K.	Austria
Shang, Y.-M.	Chinese Taipei
Sliney, D.	USA
Söderberg, P.	Sweden
Stuck, B.	USA
Suzuki, Y.	Japan
Tengroth, B.	Sweden

CONTENTS

INFRARED CATARACT

Summary

There has long been a debate about the dose response curve, action spectrum and mechanism for the production of infrared cataracts. Some scientists believe that the damage mechanism is purely thermal, others suggest that there is some evidence that it could be photochemical. If the mechanism is photochemical, a strong wavelength dependence in the near infrared spectral region will be present, and this will have great significance for lamp safety, IR-A medical devices, occupational exposure limits and the design of industrial eye protection. With the advent of high-power infrared LEDs and diode lasers as well as wavelength-tuneable infrared lasers (e.g. Titanium Sapphire laser), it is now possible for the first time to conduct a definitive and conclusive laboratory study of the action spectrum for infrared cataract. Manufacturers of LEDs, lamps and lasers should be intensely interested in the results of such studies. If the aetiology (cause) is purely thermal, the ambient temperature as well as the spectral content of the infrared irradiation becomes important and this is reviewed in this report. Currently the weight of evidence suggests that the aetiological mechanism is thermal.

CATARACTE À INFRAROUGE

Resume

Depuis longtemps, la courbe représentative de la relation dose/réponse, le spectre d'efficacité ainsi que les mécanismes responsables des cataractes à infrarouge font débat. Certains scientifiques estiment que la causalité des dommages est purement thermique. D'autres suggèrent qu'il y ait quelques arguments en faveur d'un mécanisme photochimique. Si le mécanisme est photochimique, une forte dépendance vis à vis des longueurs d'onde dans la région spectrale du proche infrarouge devrait être observée, et ceci aura une grande importance pour la sécurité des sources, des appareillages médicaux émettant des IR-A, les limites d'exposition au travail et la conception des protections oculaires dans l'industrie. Avec la survenue des LEDs infrarouge de forte puissance et des lasers diodes ainsi que des lasers infrarouges à longueurs d'ondes variables (par exemple, laser Saphir-Titane), il est aujourd'hui possible, pour la première fois, d'effectuer une étude princeps très concluante du spectre d'efficacité de la cataracte infrarouge. Les fabricants de LEDs, lampes et lasers se doivent d'être attentifs aux résultats de ces études. Si l'étiologie (cause) est purement thermique, la température ambiante comme le spectre d'émission du rayonnement infrarouge deviennent des facteurs importants qui font l'objet d'une analyse critique dans le présent rapport. Actuellement, les éléments de preuve suggèrent que le mécanisme causal est thermique.

INFRAROT-KATARAKT

Zusammenfassung

Die Dosis-Wirkungskurve, das Wirkungsspektrum und die Art der Wirkungsweise für die Induzierung von Infrarot-Katarakt waren lange Thema von wissenschaftlichen Diskussionen. Einige Wissenschaftler sind der Ansicht, dass der Schädigungsmechanismus rein thermisch sei, während andere Hinweise dafür sehen, dass der Mechanismus photochemisch sein könnte. Wenn der Mechanismus photochemisch wäre, würde es eine starke Wellenlängenabhängigkeit im nahen infraroten Wellenlängenbereich geben, was eine hohe Relevanz für die Sicherheit von Lampen, IR-A Medizingeräten, Arbeitsplatz-Expositionsgrenzwerte und für die Auslegung von Augenschutz hätte. Mit der Verfügbarkeit von Hochleistungs-Infrarot-LEDs und Diodenlasern, wie auch von abstimmbaren Infrarotlasern (z.B. Titan Saphir Laser) wurde es möglich, aussagekräftige experimentelle Studien zum Wirkungsspektrum für infrarotinduzierte Katarakt durchzuführen. Hersteller von LEDs, Lampen und Lasern sollten an den Resultaten dieser Studien hohes Interesse haben. Sollte die Ätiologie (Ursache) rein thermisch sein, dann sind die Umgebungstemperatur sowie die Aufteilung auf spektrale Bereiche der

Infrarotstrahlung relevant, was in diesem Report diskutiert wird. Die aktuell verfügbaren Daten sind mit einem thermischen Wirkungsmechanismus konsistent.

1 Introduction

For over three decades, health and safety officials have provided guidance on worker exposure to infrared radiation (Sliney and Wolbarsht, 1980; ICNIRP, 2013; ACGIH, 2014). With the increasing interest in the use of infrared light-emitting diodes (LEDs), infrared semiconductor diode lasers, heat lamps and infrared warming devices, questions of human safety, health and hygiene have arisen. The traditional occupational medical literature described industrial heat cataract as resulting from intense infrared radiation exposure over a lifetime in hot industrial environments. Traditional infrared lamps are tungsten lamps with a visible-blocking filter glass envelope. Today, infrared light-emitting diodes (LEDs) are becoming widely used as well. The potential cataractogenic risks of infrared radiation exposure from LEDs, conventional lamps and blackbody emitters are therefore considered in this document.

NOTE Radiometric units: The convention recommended for SI units by the BIPM is to employ $W \cdot m^{-2}$ and $J \cdot m^{-2}$ for the units of irradiance and radiant exposure; however, because nearly all photobiological and medical studies cited employed $W \cdot cm^{-2}$ ($mW \cdot cm^{-2}$) and $J \cdot cm^{-2}$ ($mJ \cdot cm^{-2}$) in their publications, we have provided both for easy comparison by the reader.

2 Historical evidence

2.1 Case reports

Many of the individual case reports in the ophthalmic medical literature appeared during the early 20th century in ophthalmology journals. Cramer (1907) reported on glass-blowers' cataract in the glass production industry. Robinson (1903), Snell (1907), and Robinson (1907) reported classical cases of what was later identified as "heat cataract." In the metals industries, Cridland (1915; 1916; 1921), Johnstone (1944) and Roberts (1921) reported cases with similar ophthalmic findings as "glassblowers" cataract, with instances of pseudoexfoliation of the anterior capsule of the lens that had been reported earlier in glass blowers.

In the United Kingdom (UK), the Workmen's Compensation Acts of 1896 and 1906 led the British government to request the Royal Society (UK) to investigate how and why "glare and heat" appeared to produce early cataracts among workers in the glass-making and iron-smelting industries, i.e. during their working lifetimes. Brock (2007) provides a very interesting review of the work of the Glass Workers' Cataract Committee between 1908 and 1928. This Royal Society Committee included chemists, physiologists and ophthalmologists. This review also describes the history of the first type of Crookes glass to filter out visible and infrared radiation by Sir William Crookes (1914). While providing relief for industrial workers, the research also laid the foundation for the glass types used in sunglasses.

By the 1950s, some clinicians were questioning the validity of the thesis of a "heat cataract" and Dunn (1950), an occupational physician at a steel plant in the USA, argued that there was no such aetiology, although most ophthalmic texts continued to cite the connection (Duke-Elder and MacFaul, 1972). Certainly by 1950, industrial glass manufacturing and steel manufacturing processes had changed from those employed a half-century earlier, and working conditions and durations of worker exposures had changed, as well as nutritional status of the general public.

2.2 Epidemiology

More than a century ago physicians were recognizing an apparent connection of early-onset cataract with workers in the glass industry. Dr. T. M. Legge, an inspector in the Departmental Committee on Compensation for Industrial Diseases (UK), was one of the first to attempt to report on "glassblowers" cataract (Legge, 1907). In the USA, Parsons (1910) reported on these findings in the UK. Robinson (1907) followed up with a number of cases of 'bottle-makers' cataract and still much later, Lydahl and Philipson (1984b) and Lydahl and Glansholm (1985) found evidence of an increased incidence of cataract in workers in the Swedish art glass industry.

In the metals industries, Healy (1921), Coates and Keatinge (1955), Wallace et al. (1971), Lydahl and Philipson (1984a), and Lydahl et al. (1984) all evaluated the incidence of cataract in steel mills and other metal industries where workers were in the near vicinity of molten metals. A more recent study (Dorozhkin, 2003) of infrared exposures in the Russian Federation metals industry found higher irradiance levels in conventional foundry operations than in the more technologically advanced, basic-oxygen steelmaking (oxygen-converter) processes, because of better eye protection afforded by the newer technology. They found that workers with the new technology had less cataract development and less severe lens changes compared to the changes registered in the conventional-foundry workers. The stage of cataract correlated directly with the number of working years, and they also noted a browning of the nucleus (as did earlier studies, e.g. Lydahl, 1984) in workers with more than 15 years of work in hot areas.

The reports published in the early 20th century were mostly case reports and summaries of observations, but would not be considered truly as epidemiological studies in the modern context. The studies by Keatinge et al. (1955) and Coates and Keatinge (1955) and Wallace et al. (1971) were epidemiological studies with controls and incidence values. The findings of these two studies were not very compelling. Wallace et al. (1971) reported a higher prevalence of beginning cataracts, but did not report any, more severe, “compensable” among the workers studied. However, by far the most comprehensive epidemiological study was that of Lydahl et al. (1984). In these Swedish studies (Lydahl et al., 1984), they reported that: “The maximal irradiance registered for longer periods of time was about 150 mW·cm^{-2} (1 500 W·m^{-2}) within 300 nm to 2 600 nm (18 mW·cm^{-2} (180 W·m^{-2}) within 760 nm to 1400 nm), a level that was recorded in several different positions for 30 s to a few minutes.”

3 Mechanisms of pathogenesis

Vogt (1912; 1919) and others suggested that industrial cataract was related to heating of the lens—principally by the large amount of infrared energy emitted by hot glass or metals or furnaces. This was based in no small part to the results of some animal studies by Vogt and later by Verhoeff et al. (1916). Verhoeff et al. argued that heating of the ciliary body might play a key role. However, later, Goldmann (1932; 1933; 1935) performed further animal studies but emphasized the role of iris heating (Goldmann et al., 1950). These animal studies of mechanism will be discussed in greater detail later.

More recently, Wolbarsht (1991) suggested that a photochemical mechanism was plausible. If the classical infrared industrial "heat" cataract is shown to be caused either completely or in part by a photochemical damage mechanism in the lens, then the current eye protection safety standards might not be sufficiently conservative. A photochemical damage mechanism is always highly wavelength specific and limited to a wavelength band of about 100 nm or less. The current occupational and public health exposure limits of the International Commission on Non-Ionizing Radiation Protection (ICNIRP), the American Conference of Governmental Industrial Hygienists (ACGIH) and similar health organizations have an underlying assumption that the damage mechanism is strictly thermal. Okuno (1991, 1994) and others have predicted some spectral dependence of the IR cataract risk based upon absorption of the iris as well as the cornea, aqueous and lens in the IR spectral region between 700 nm and 1900 nm. Exposure guidance (ACGIH, 2014; ICNIRP, 1997) has assumed that all of the IR energy from IR-A and IR-B (780 nm to 3 000 nm) poses a risk to the same extent wherever it is absorbed in the anterior structures of the eye, and – also to minimize needless complexity – there is no strong wavelength dependence assumed. ACGIH (2001) based the original long-term occupational exposure limit on the assumption that the worker was in a very hot work environment; however, since the advent of high-power IR-A LEDs, these limits were shown to be overly conservative and in the 2013 revision of their guidelines, ICNIRP introduced a spectral weighting factor to decrease the impact of wavelengths between 780 nm and 1 000 nm, effectively increasing the limit by a factor of 3,33 (ICNIRP, 2013).

3.1 Characteristics of thermal interaction mechanisms

Thermal injury is a rate process that is highly dependent upon the duration of exposure and heated volume. Thresholds for thermal injury are greatly affected by the level of heat conduction from the irradiated tissue during the exposure and, in some cases, just following exposure if the heated volume is large. It requires an intense exposure within seconds to cause tissue photocoagulation; whereas less intense irradiances may be insufficient to increase tissue temperatures to a level sufficient to coagulate proteins, because surrounding tissue rapidly conducts heat away from the exposed site thus minimizing the temperature increase. Animal experiments (Emery et al., 1975; Kramár et al., 1987) in which lenses were heated using microwave radiation or hot water showed that the critical temperature at which opacities appear