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Review

405 nm light technology for the inactivation of pathogens and its potential role for environmental disinfection and infection control

M. Maclean [a,*], K. McKenzie [a], J.G. Anderson [a], G. Gettinby [b], S.J. MacGregor [a]

[a] The Robertson Trust Laboratory for Electronic Sterilisation Technologies, University of Strathclyde, Glasgow, UK
[b] Department of Mathematics and Statistics, University of Strathclyde, Glasgow, UK

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S U M M A R Y

Background: Although the germicidal properties of ultraviolet (UV) light have long been known, it is only comparatively recently that the antimicrobial properties of visible violet–blue 405 nm light have been discovered and used for environmental disinfection and infection control applications.
Aim: To review the antimicrobial properties of 405 nm light and to describe its application as an environmental decontamination technology with particular reference to disinfection of the hospital environment.
Methods: Extensive literature searches for relevant scientific papers and reports.
Findings: A large body of scientific evidence is now available that provides underpinning knowledge of the 405 nm light-induced photodynamic inactivation process involved in the destruction of a wide range of prokaryotic and eukaryotic microbial species, including resistant forms such as bacterial and fungal spores. For practical application, a high-intensity narrow-spectrum light environmental disinfection system (HINS-light EDS) has been developed and tested in hospital isolation rooms. The trial results have demonstrated that this 405 nm light system can provide continuous disinfection of air and exposed surfaces in occupied areas of the hospital, thereby substantially enhancing standard cleaning and infection control procedures.
Conclusion: Violet–blue light, particularly 405 nm light, has significant antimicrobial properties against a wide range of bacterial and fungal pathogens and, although germicidal efficacy is lower than UV light, this limitation is offset by its facility for safe, continuous use in occupied environments. Promising results on disinfection efficacy have been obtained in hospital trials but the full impact of this technology on reduction of healthcare-associated infection has yet to be determined.

Introduction

Although intensive efforts over recent years are making an impact, healthcare-associated infections (HCAIs) still regularly occur and continue to pose a major challenge. In addition to the significant morbidity and financial costs, concern over

* Corresponding author. Address: ROLEST, Department of Electronic and Electrical Engineering, University of Strathclyde, Royal College Building, 204 George Street, Glasgow G1 1XW, UK. Tel.: +44 (0)141 548 2891; fax: +44 (0)141 552 5398.
E-mail address: michelle.maclean@strath.ac.uk (M. Maclean).

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contraction of HCAIs is one of the greatest fears of patients being admitted to hospital.[1] Infection control procedures such as handwashing are of critical importance in addressing the HCAI problem; however, greater awareness of the hospital environment as a source of nosocomial pathogens has led to renewed focus on hospital cleaning and disinfection. Whereas effective physical cleaning remains essential for infection control and aesthetic reasons, there has been an upsurge of interest in the development of new cleaning and decontamination technologies.[2,3] Several of these employ novel methods of delivering antimicrobial chemicals, whereas others use the antimicrobial properties of light to enhance disinfection, and it is this latter approach that forms the topic of this review.[4–6]

The most germicidal wavelengths of light fall within the ultraviolet (UV) range and UVC (240–260 nm) irradiation has traditionally been used for disinfection, particularly for air and medical device decontamination applications.[7–9] More recently the antimicrobial properties of violet–blue visible light have emerged as an area of increasing research interest. Although less germicidal than UVC light, violet–blue light with wavelengths in the region of 405 nm has proved effective for inactivation of a range of microbial species, and exploitation of these wavelengths may provide alternative methods of antimicrobial treatment for infection control applications. This paper supplies a brief background on the use of light for environmental decontamination applications within hospitals before presenting a detailed description of the broad spectrum antimicrobial effects of violet–blue light and how this knowledge has led to the development and clinical evaluation of a 405 nm light environmental disinfection system. In addition to environmental decontamination applications, other potential uses of violet–blue light for infection control purposes such as skin and wound treatment have been highlighted in recent literature but these topics are out with the scope of the current review.[10–17]

Inactivation of micro-organisms by light in the hospital environment

Records of observations on the antibacterial effects of light go back to the latter part of the 19th century and these early historical observations have been documented by Kowalski.[18] The germicidal effects of light received further attention during the early part of the 20th century and the appreciation of the decontamination effect of light was translated into early hospital design features where natural ventilation and exposure to sunlight were regarded as beneficial.[19] The roles of sunlight and natural ventilation for controlling the transmission of infections within healthcare settings has recently been reviewed by Hobday and Dancer, who provide a detailed record of the early–mid-20th century observations on the effects of natural sunlight on a wide range of nosocomial pathogens.[20] Although natural light and ventilation were originally considered beneficial, modern hospital design has tended to reduce these features. Recent interest in the application of 'artificial' lighting within hospitals has been with regard to energy reduction issues but also how lighting can affect the mood and circadian rhythm of patients.[21,22] Light from artificial sources with wavelength emission in the UV range can have significant antimicrobial effects and new technologies for hospital decontamination have been developed around this concept.[6,23–25]

The most widespread applications of ultraviolet germicidal irradiation (UVGI) has been for air and water disinfection, as well as for decontamination of devices.[26–28] More recently, with the increased emphasis that has been directed towards enhanced decontamination of the hospital environment, novel technologies have been developed for the rapid delivery of UVC radiation to exposed surfaces in clinical areas. Several of these are automated or manually positioned robotic systems using either continuous or pulsed UV emission sources.[6,25] Detailed information on UVGI and other 'no-touch' automated room disinfection systems is provided in a recent review by Otter *et al.*[6]

Antimicrobial effects of violet–blue light

Until relatively recently light within the visible spectrum (400–700 nm) was considered to have little biocidal effect compared to UVC light due to the lower photon energy of these wavelengths. Wavelengths of violet–blue light, particularly around 405 nm, have, however, been shown to possess antimicrobial capabilities, and there is scope for exploiting these wavelengths for the control of problematic micro-organisms in many areas of application including the disinfection of air and exposed surfaces in the clinical environment. The following section provides an overview of the antimicrobial inactivation mechanism, and the antimicrobial efficacy of high-intensity 405 nm violet–blue light.

Violet–blue light inactivation mechanism

Investigations into the mechanism of action of 405 nm violet–blue light indicate that photodynamic inactivation occurs as a result of the photo-excitation of intracellular porphyrin molecules within the exposed bacterial cells. Laboratory studies have shown that a range of violet–blue light wavelengths in the region 400–425 nm can be used for bacterial inactivation; however, optimal antimicrobial activity has been found at 405 nm.[29–35] This peak in activity correlates with the absorption maximum of porphyrin molecules, termed the Soret band, being in this wavelength region.[36] Exposure to light of this wavelength induces an oxygen-dependent photo-excitation reaction within exposed micro-organisms, where excited porphyrins react with oxygen or cell components to produce reactive oxygen species (ROS), causing oxidative damage and microbial cell death.[29,37–41] Cell death has been accredited to oxidative damage to the cell membrane, with a recent study demonstrating disruption of the cytoplasmic content and cell walls of exposed *Staphylococcus aureus*, and it is likely that, due to the non-selective nature of ROS, multi-target damage will be induced in the microbial cells.[10]

Antimicrobial effects of violet–blue light

Extensive laboratory studies have shown that 405 nm light, and the wider violet–blue light wavelengths, have a broad spectrum of activity, with successful inactivation demonstrated for a wide range of organisms, including antibiotic-resistant bacterial strains such as meticillin-resistant *Staphylococcus aureus* (MRSA).[30–32] Bacterial species which have demonstrated susceptibility include HCAI-associated organisms, including *S. aureus*, *Clostridium difficile*, *Acinetobacter*