A novel light source with tuneable uniformity of light distribution for artificial daylight photodynamic therapy

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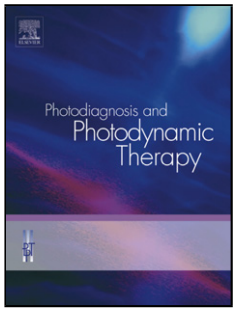

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Title

A tuneable approach to uniform light distribution for artificial daylight photodynamic therapy

Authors

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Highlights:

- Irradiation spectrum from novel light source is matched with PpIX-effective daylight spectrum using independent multiwavelength LED control
- Novel light source can produce high enough effective dose to meet minimum dPDT recommendations
- Improvements in uniformity of light distribution across curved surfaces through manually directing light emission

Abstract

Objectives: Implementation of daylight photodynamic therapy (dPDT) is somewhat limited by variable weather conditions. Light sources have been employed to provide artificial dPDT indoors, with low irradiances and longer treatment times. Uniform light distribution across the target area is key to ensuring effective treatment, particularly for large areas. A novel light source is developed with tuneable direction of light emission in order to meet this challenge.

Methods: Wavelength composition of the novel light source is controlled such that the protoporphyrin-IX (PpIX) weighed spectra of both the light source and daylight match. The uniformity of the light source is characterised on a flat surface, a model head and a model leg. For context, a typical conventional PDT light source is also characterised. Additionally, the wavelength uniformity across the treatment site is characterised.

Results: The PpIX-weighted spectrum of the novel light source matches with PpIX-weighted daylight spectrum, with irradiance values within the bounds for effective dPDT. By tuning the direction of light emission, improvements are seen in the uniformity across large anatomical surfaces. Wavelength uniformity is discussed.

Conclusions: We have developed a light source that addresses the challenges in uniform, multiwavelength light distribution for large area artificial dPDT across curved anatomical surfaces.

Keywords

photodynamic therapy, PDT, uniformity, light source, actinic keratosis

Introduction

Photodynamic therapy (PDT) is an effective treatment for actinic keratosis (AK), basal cell carcinoma (BCC) and Bowen's disease[1,2]. A pro-drug (generally 5-aminolaevulinic acid or methylaminolevulinate) of the photosensitiser protoporphyrin IX (PpIX) is applied to the skin in a cream base and with

conventional hospital-based PDT, after an incubation period usually of 3 hours, irradiation is undertaken using either red or blue light. The preferential uptake PpIX in abnormal cells enables specific treatment of diseased tissue, whilst sparing normal skin. Conventional PDT of large treatment areas is typically painful[3,4], and has specific requirements regarding accurate light delivery. Daylight PDT (dPDT) is an alternative for the treatment of superficial AK, whereby daylight is used as the light source for treatment. With dPDT, the incubation time for the pro-drug application is reduced to 30 minutes and patients then expose themselves to daylight for at least 2 hours, whilst wearing SPF50 sun-screen to protect exposed skin from the ultraviolet radiation (UVR). One of the main advantages of dPDT over conventional PDT is the reduction in pain[5], thought to be due to a combination of lower irradiance and less PpIX accumulation in the skin[6]. Additionally, larger areas of skin are more easily treated with dPDT, making it particularly applicable to the treatment of extensive areas of field-change AK. Furthermore, dPDT has been shown to be as effective as conventional PDT for AK[4,5,7,8].

One of the main limitations in prescribing dPDT is the unpredictability of the weather. It has been proposed that there is a minimum daylight dose that a patient should receive for effective treatment[4,5,9–12]. Additionally, the ambient temperature should be comfortable enough for the patient to remain outdoors for the duration of treatment. A European consensus published in 2015 recommended a minimum PpIX-weighted daylight dose of 8 J cm^{-2} and ambient temperature of at least 10°C [13].

In order to address the unpredictability of delivery of dPDT due to weather conditions, researchers have utilised a greenhouse in order to provide a comfortable atmosphere regardless of outdoor temperatures[14]. Patients may receive effective treatment sitting in a conservatory as the glass permits transmission of visible light, albeit at a reduced rate. There is evidence to show that even at high latitudes (~60°N) there may still be enough light for effective dPDT in a conservatory for much of the year[15]. However, this method is still ultimately dependent on there being enough light available.

Alternatively, others have attempted to replicate dPDT indoors by using artificial light sources. Contrasting with conventional PDT, artificial dPDT requires the use of much lower irradiance light delivery incident on the treatment area coupled with a longer treatment time, thus retaining the relative pain-free nature of dPDT. An important consideration in utilising light sources for artificial dPDT is the emission spectrum of

the light source. The PpIX-weighted dose is a measure of the light effective on the photosensitiser itself over a given time, i.e. how much of the incident light is used by the photosensitiser. This is dependent on the absorption spectrum of PpIX [16]. Therefore, different wavelengths of light have a greater or lesser effect on the activation rate of the photosensitiser. O'Gorman *et al.* used a white LED source to deliver artificial dPDT and reported comparable efficacy and pain scores to dPDT with improved remission at 9 months[12]. A follow up study by Manley *et al.* suggested that the spectral distribution of the white LED, which targeted the longer wavelength absorption peaks of PpIX, may have been the reason for the sustained remission[17]. A summary of some of the artificial light sources that have been developed for dPDT has also been published by Lerche *et al.*[14]. However, these light sources were not specifically developed for dPDT and therefore are not optimised for this purpose as they do not produce equivalent PpIX-weighted spectral outputs.

Furthermore, these sources do not produce a uniform irradiance on the target surface and thus an even distribution of light delivery across the entire treatment field is not feasible, particularly on curved surfaces such as the scalp or lower leg. These non-uniformities in light distribution from the Aktilite CL16 and CL128 PDT lamps has been shown to be critical in planning treatment doses[17,18]. The work on light-emitting textiles for PDT by Mordon *et al.* have also incorporated uniformity as important design criteria[19].

We report on the development of a proof-of-principle light source that addresses these issues by providing uniform illumination over a large surface area and matching the spectral distribution of PpIX-weighted solar irradiance.

Materials and Methods

The developed light source (Figure 1) contains LED chips (LZ7, LED Engin, US) which are capable of independently emitting 7 distinct wavebands of light. The LEDs are controlled via a constant current LED driver (iDrive Force 12, Integrated System Technologies, UK), and a laptop computer operating digital

multiplex (DMX) control software (Daslight DVC1, Daslight, US). The light was directed in to an acrylic rod, which acts as a macro-waveguide, with one LED chip at either end. Light was initially contained within the rod due to total internal reflection. However, the acrylic rod has a diffuse coating across one half of its curved surface, which scattered the incident light allowing it to exceed the critical angle and be emitted from the rod. In our light source, there were sixteen of these acrylic rods within an opaque Perspex box forming a 350 x 400 mm illumination aperture. Each acrylic rod could be individually rotated, allowing for control over the direction of the emitted light.

Using the independent wavelength control, the PpIX weighted spectral irradiance of the light emitted was matched to a typical daylight spectrum equivalent to 20 J cm^{-2} PpIX effective dose (measured at 10:00 GMT on the 25th of March 2015 at 51.58°N, 1.32°W). The spectral irradiance of the light source is confirmed by measurement at a distance of 240 mm on a double grating scanning spectroradiometer (DM150, Bentham Instruments, Reading, UK) and compared to the PpIX-weighted daylight spectrum. The measurement distance of 240 mm was chosen primarily as a practical distance to carry out subsequent measurements on the device, however in this context absolute distance is of less interest than the changes in uniformity possible with the new light source.

With all rods directing the light vertically, the uniformity of light distribution was measured across a flat surface, a model lower leg and a model head (Figure 2). Measurements were taken with a broadband irradiance detector (RW-3703-2 with P9710, Gigahertz-Optik, Germany) at defined measurement intervals on each target surface at a distance of 240 mm from the light source, with measurements performed in triplicate. For each measurement surface, the acrylic rods were subsequently manually rotated to obtain an optimised uniformity of light distribution. The experiments were repeated with a typical Aktilite PDT lamp (Aktilite CL-128, Galderma, UK) at a clinically relevant distance of 80 mm and the resultant uniformity compared with our artificial dPDT light source. Firstly, in the context of a 50x100 mm treatment area, which is clinically relevant as the maximum area treated at the Photobiology Unit, Dundee with a single lamp and is within the maximum area recommended for treatment with the Aktilite lamp (90 x 190 mm). We then explored larger uniform treatment areas, which were feasible with the artificial dPDT source.

To determine wavelength uniformity of the light source, an array spectrometer (QE65000, Ocean Optics, US) is used to capture spectra at 10 mm intervals along the length of the 150 mm rod at a distance of 240 mm from the light source. The light source was set to emit from red, green and violet LEDs of approximately equal irradiances from either end of the rod. Light output at the peak wavelength in each of the green and violet readings were normalised to the red. This provided the relative change of green and violet light with respect to red light, and hence an indication of the wavelength uniformity, along the length of the rod.

Results

Optimised spectrum:

The irradiances for the unweighted daylight and artificial daylight spectra were 3.12×10^5 mW m^{-2} and 6.57×10^4 mW m^{-2} respectively (Figure 3a), and the PpIX-weighted irradiances were 2.54×10^4 mW m^{-2} and 7.80×10^3 mW m^{-2} (wavelength range 380-800 nm, Figure 3b). At a distance of 240 mm, the artificial dPDT lamp was capable of delivering 5.6 J cm^{-2} of PpIX-weighted daylight dose for a treatment time of 2 hours.

Uniformity:

Figures 4, 5 and 6 show the results of the uniformity measurements on each surface for the unoptimised and optimised artificial dPDT source and the Aktilite CL-128. Each cell in the grid-like representation is a percentage of the maximum irradiance measured. Uniformity itself was measured as the coefficient of variation (CoV) which is equal to the standard deviation divided by the average irradiance over the selected illumination area, multiplied by 100 (expressed as a percentage). A low CoV represents high uniformity. The uniformity parameters are summarised in Table 1, firstly for the 50 x 100 mm treatment area, and then for a much larger area. Large areas were individually chosen with relevance to the anatomical site.

Wavelength Uniformity:

The relative change in green (527 nm) and violet (403 nm) wavelengths across the length of one of the rods with respect to red (628 nm) was examined. Figure 7 shows relative drops of 18% and 24% towards the centre of the rod for green and violet light respectively with respect to red light at a distance of 240 mm.

Discussion

We have developed a unique light source that is capable of replicating the PpIX-weighted daylight spectrum, providing representative artificial dPDT (Figure 3b). There is some debate about what exactly the recommended parameters are with respect to minimum daylight dose for effective treatment, with most studies putting this figure in the range of 3.5-8 J cm^{-2} PpIX-weighted daylight dose. The treatment dose available from the artificial light source (5.6 J cm^{-2} at a distance of 240 mm) is within these parameters recommended for effective dPDT. The light system we have developed is based on a novel form of illumination and delivers an equivalent PpIX-weighted daylight dose within these margins. Based on our data the light source should be capable of providing effective treatment whilst also preserving the relative painlessness of dPDT when compared to conventional PDT. However further work is required to confirm this in a randomised controlled study.

The developed light source is also entirely modular with respect to constituent wavelengths, and may be tailored as desired as each of the 7 waveband emitters is addressed and controlled individually. This may include targeting different photosensitisers, dynamically changing the wavelengths during treatment or providing patient specific therapy through wavelength selection dependent on diagnosis and thickness of diseased tissue.

As there is already a strong evidence base behind dPDT for AK, this informed our approach of mimicking the PpIX-weighted daylight spectrum in this work. However, others have approached the concept of low irradiance PDT with light sources of differing spectra to that presented in this work. Notably, low irradiance red light has been shown to be as effective as conventional PDT in the treatment of superficial basal cell carcinoma, Bowen's disease and AK[20], while an operating room light used for low irradiance PDT has

shown effective in treating AK[12]. Additionally, the rate of PpIX photobleaching was investigated for a number of low irradiance light sources[14]. These findings show that there is currently no consensus as to the 'optimum' spectrum for artificial dPDT, and that replicating the PpIX-weighted daylight spectrum remains a viable option.

It is a trivial matter to irradiate a large treatment area with, for example, a light source with a larger illumination aperture or by moving the light source further away. However, it is non-trivial to produce a uniform light distribution across the larger treatment area. Taking the Aktilite as an example, this LED array light source gives a reasonable uniformity across its intended working area on a flat surface. However, when uniformity is considered on curved surfaces, i.e. the head and lower leg, the performance of the device over its intended working area is diminished, leading to under-treated sites depending on the positioning of the lamp. As shown in our experiments, utilising a larger light source from a greater distance can increase the uniformity of the irradiance profile on curved surfaces (Figure 6a and 6c), but there remain characteristic non-uniformities in the light distribution. To address the underlying issue, we have been able to tune the uniformity of light distribution on the flat and curved treatment sites with the artificial dPDT light source (Figures 4b, 5b and 6b). This is an achievement that is not possible with any other PDT light source that we are aware of.

Table 1 details the CoV found for different measurement areas on the flat surface, head and leg. For the flat surface with a measurement area of 50 x 100 mm, only two measurement points were used and therefore it was reasonably straightforward to select the target area and achieve a good uniformity with either device. However, for the leg and head the differences in uniformity were much more apparent due to the curvature of the surfaces, particularly on the leg. For the larger surface areas measured, the benefit of tuneable light distribution was even more apparent, with considerable improvements in uniformity with the optimised light source compared to the unoptimised source. Due to the smaller illumination aperture, it is not surprising that the Aktilite had a high CoV for large measurement areas. However, the contrast of the optimised and unoptimised CoV values illustrate that, although improvements are made regardless, the solution is not simply a matter of having a larger light source. Control over the direction of light gives a more uniform distribution of light on flat and curved surfaces. This highlights the need for the development

of novel light sources for artificial dPDT, and the drawbacks in simply repurposing existing light sources, or indeed employing larger aperture light sources, for large area uniform treatment.

For the leg, our results did not show any meaningful increase in uniformity along the longitudinal direction (Figure 6), largely due to the fact that the rods were oriented along this direction. With the angular control we currently exercise, it is only possible to affect the light distribution in one axis. However, the light distribution up to 300 mm along the longitudinal direction of the leg was reasonably uniform regardless. The advantage of this new light source was seen largely in the axial direction, where uniformity could be extended around the contours of much of the leg. As is the case with measuring the leg, the uniformity along the axis of the rods did not change significantly between the unoptimised and optimised measurements on the head. However, we were able to increase the uniformity across the head as a whole (Figure 5). This offers the ability to uniformly treat larger areas on the scalp with a single light source, which is currently not possible with conventional PDT lamps.

An important factor to consider is wavelength uniformity across the target site, specifically in multiwavelength illumination applications, as consistent wavelength distribution across the target site will ensure consistent and predictable treatment. It was found that the proportions of red, green and violet light were not consistent across the selected measurement profile (Figure 7), however understanding the merit of these results in the context of artificial dPDT is limited as such data for more conventional methods of multiwavelength LED arrangements are typically not available. Although these wavelength shifts were not entirely eliminated in this design, consideration and characterisation of this parameter is an important first step towards wavelength uniformity at the treatment site.

Conclusion

We have developed a unique artificial dPDT light source which replicates the PpIX-weighted daylight spectrum, and delivers uniform light distribution to flat and curved treatment sites. The dose delivered by the light source is within the parameters for adequate light dose for effective treatment, and a tuneable

approach to wavelength allows for good matching to the daylight spectrum, thus providing a representative and comparable treatment modality. The lamp design currently exhibits inconsistencies in wavelength distribution at a distance from the source, however future developments will be focused on making progress towards ensuring that each point at the treatment site is subject to a consistent irradiation spectrum. Adjustable uniformity of light distribution is achieved to great effect with this design, and is shown for the contours on the head and lower leg. It is anticipated that a next-generation light source will be developed from these principles, using what we have learned with the prototype device in this body of work. Such a light source would aim to be suitable for use in a clinical study to determine the effectiveness of this design as a light source for artificial dPDT.

Conflicts of interest

S.I. has received honoraria and travel expenses from Galderma and Spirit Healthcare. P O'M and EE have received travel expenses from Galderma. Blueside Photonics Ltd (NH) is an independent photonics company based in the UK developing LED lighting products and services for the use in the biophotonics and general lighting application areas; Blueside Photonics assisted in the development of the tuneable LED light source but were not involved in the testing and evaluation work described.

Acknowledgments

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References

[1] C.A. Morton, R.M. Szeimies, A. Sidoroff, L.R. Braathen, European guidelines for topical photodynamic therapy part 1: treatment delivery and current indications - actinic keratoses, Bowen's disease, basal cell carcinoma, J. Eur. Acad. Dermatology Venereol. 27 (2013) 536–544. doi:10.1111/jdv.12031.

[2] D.M. Ozog, A.M. Rkein, S.G. Fabi, M.H. Gold, M.P. Goldman, N.J. Lowe, G.M. Martin, G.S. Munavalli, Photodynamic Therapy: A Clinical Consensus Guide, Dermatologic Surg. 42 (2016) 804–827. doi:10.1097/DSS.0000000000000800.

[3] S.K. Attili, R. Dawe, S. Ibbotson, A review of pain experienced during topical photodynamic therapy-Our experience in Dundee, Photodiagnosis Photodyn. Ther. 8 (2011) 53–57. doi:10.1016/j.pdpdt.2010.12.008.

[4] D.M. Rubel, L. Spelman, D.F. Murrell, J. See, D. Hewitt, P. Foley, C. Bosc, D. Kerob, N. Kerrouche, H.C. Wulf, S. Shumack, Daylight photodynamic therapy with methyl aminolevulinate cream as a convenient, similarly effective, nearly painless alternative to conventional photodynamic therapy in actinic keratosis treatment: a randomized controlled trial., Br. J. Dermatol. 171 (2014) 1–8. doi:10.1111/bjd.13138.

[5] S.R. Wiegell, M. Haedersdal, P.A. Philipsen, P. Eriksen, C.D. Enk, H.C. Wulf, Continuous activation of PpIX by daylight is as effective as and less painful than conventional photodynamic therapy for actinic keratoses; a randomized, controlled, single-blinded study., Br. J. Dermatol. 158 (2008) 740–6. doi:10.1111/j.1365-2133.2008.08450.x.

[6] W.J. Cottrell, A.D. Paquette, K.R. Keymel, T.H. Foster, A.R. Oseroff, Irradiance-dependent photobleaching and pain in δ- aminolevulinic acid-photodynamic therapy of superficial basal cell carcinomas, Clin. Cancer Res. 14 (2008) 4475–4483. doi:10.1016/j.pestbp.2011.02.012.Investigations.

[7] J.-P. Lacour, C. Ulrich, Y. Gilaberte, V. Von Felbert, N. Basset-Seguin, B. Dreno, C. Girard, P.

Redondo, C. Serra-Guillen, I. Synnerstad, M. Tarstedt, A. Tsianakas, A.W. Venema, N. Kelleners-Smeets, H. Adamski, B. Perez-Garcia, M.J. Gerritsen, S. Leclerc, N. Kerrouche, R.M. Szeimies, Daylight photodynamic therapy with methyl aminolevulinate cream is effective and nearly painless in treating actinic keratoses: a randomised, investigator-blinded, controlled, phase III study throughout Europe., J. Eur. Acad. Dermatology Venereol. 29 (2015) 2342–2348. doi:10.1111/jdv.13228.

[8] M.C. Fargnoli, A. Piccioni, L. Neri, S. Tambone, C. Pellegrini, K. Peris, Conventional vs. daylight methyl aminolevulinate photodynamic therapy for actinic keratosis of the face and scalp: An intra-patient, prospective, comparison study in Italy, J. Eur. Acad. Dermatology Venereol. 29 (2015) 1926–1932. doi:10.1111/jdv.13076.

[9] S.R. Wiegell, M. Haedersdal, P. Eriksen, H.C. Wulf, Photodynamic therapy of actinic keratoses with 8% and 16% methyl aminolaevulinate and home-based daylight exposure: a double-blinded randomized clinical trial, Br. J. Dermatol. 160 (2009) 1308–1314. doi:10.1111/j.1365-2133.2009.09119.x.

[10] S.R. Wiegell, J. Heydenreich, S. Fabricius, H.C. Wulf, Continuous ultra-low-intensity artificial daylight is not as effective as red LED light in photodynamic therapy of multiple actinic keratoses., Photodermatol. Photoimmunol. Photomed. 27 (2011) 280–5. doi:10.1111/j.1600-0781.2011.00611.x.

[11] S.R. Wiegell, S. Fabricius, M. Gniadecka, I.M. Stender, B. Berne, S. Kroon, B.L. Andersen, C. M??rk, C. Sandberg, K.S. Ibler, G.B.E. Jemec, K.M. Brocks, P.A. Philipsen, J. Heydenreich, M. Haedersdal, H.C. Wulf, Daylight-mediated photodynamic therapy of moderate to thick actinic keratoses of the face and scalp: A randomized multicentre study, Br. J. Dermatol. 166 (2012) 1327–1332. doi:10.1111/j.1365-2133.2012.10833.x.

[12] S.M. O'Gorman, J. Clowry, M. Manley, J. McCavana, L. Gray, A. Kavanagh, A. Lally, P. Collins, Artificial White Light vs Daylight Photodynamic Therapy for Actinic Keratoses, JAMA Dermatology. 152 (2016) 1–7. doi:10.1001/jamadermatol.2015.5436.

[13] C.A. Morton, H.C. Wulf, R.M. Szeimies, Y. Gilaberte, N. Basset-Seguin, E. Sotiriou, S. Piaserico, R.E. Hunger, S. Baharlou, A. Sidoroff, L.R. Braathen, Practical approach to the use of daylight photodynamic therapy with topical methyl aminolevulinate for actinic keratosis: a European consensus., J. Eur. Acad. Dermatology Venereol. 29 (2015) 1718–1723. doi:10.1111/jdv.12974.

[14] C. Lerche, I. Heerfordt, J. Heydenreich, H.C. Wulf, Alternatives to Outdoor Daylight Illumination for Photodynamic Therapy—Use of Greenhouses and Artificial Light Sources, Int. J. Mol. Sci. 17 (2016) 309. doi:10.3390/ijms17030309.

[15] P. O'Mahoney, M. Khazova, M. Higlett, T. Lister, S. Ibbotson, E. Eadie, Use of illuminance as a guide to effective light delivery during daylight photodynamic therapy in the U.K., Br. J. Dermatol. 176 (2017) 1607–1616. doi:10.1111/bjd.15146.

[16] S. Prahl, Protoporphyrin IX dimethyl ester, (n.d.). http://omlc.org/spectra/PhotochemCAD/html/149.html (accessed July 25, 2016).

[17] M. Manley, P. Collins, L. Gray, S. O'Gorman, J. McCavana, Quantifying the radiant exposure and effective dose in patients treated for actinic keratoses with topical photodynamic therapy using daylight and LED white light, Phys. Med. Biol. 63 (2018). doi:10.1088/1361-6560/aa9ea7.

[18] H. Moseley, Light distribution and calibration of commercial PDT LED arrays., Photochem. Photobiol. Sci. 4 (2005) 911–4. doi:10.1039/b507325a.

[19] J.-B. Tylcz, C. Vicentini, S. Mordon, Light emitting textiles for a photodynamic therapy, Elsevier Ltd, 2016. doi:10.1016/B978-0-08-100574-3.00004-7.

[20] S. Ibbotson, J. Ferguson, Ambulatory photodynamic therapy using low irradiance inorganic light-emitting diodes for the treatment of non-melanoma skin cancer: An open study, Photodermatol. Photoimmunol. Photomed. 28 (2012) 235–239. doi:10.1111/j.1600-0781.2012.00681.x.

Figure captions

Figure 1. The artificial dPDT light source. The 16 rods are shown within the 350 x 400 mm illumination aperture. There is a gap of 40mm between the rods.

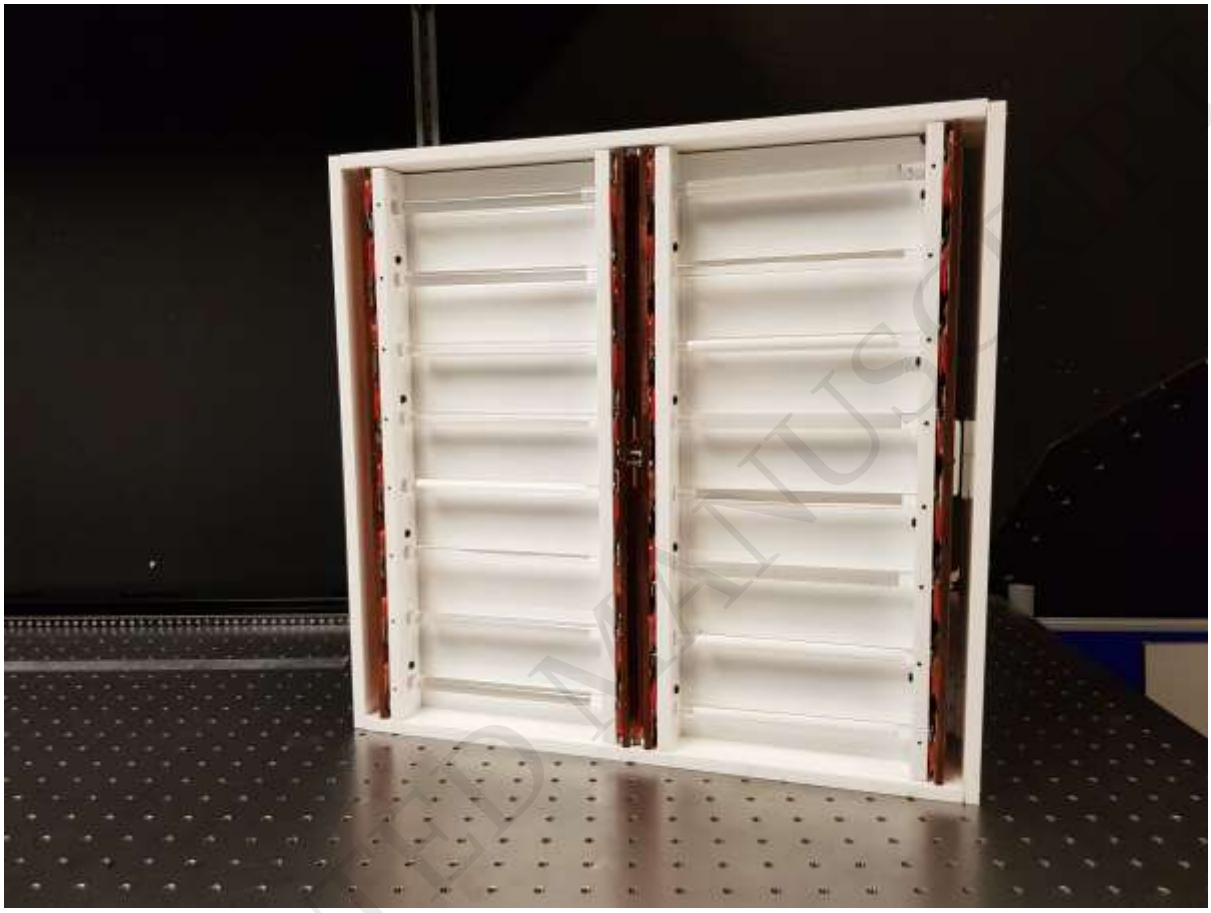


Figure 2. The a) model head and b) model leg measured. Each surface is marked with dots indicating measurement points along their surfaces. The measurement points extend around the curved surfaces of each model.

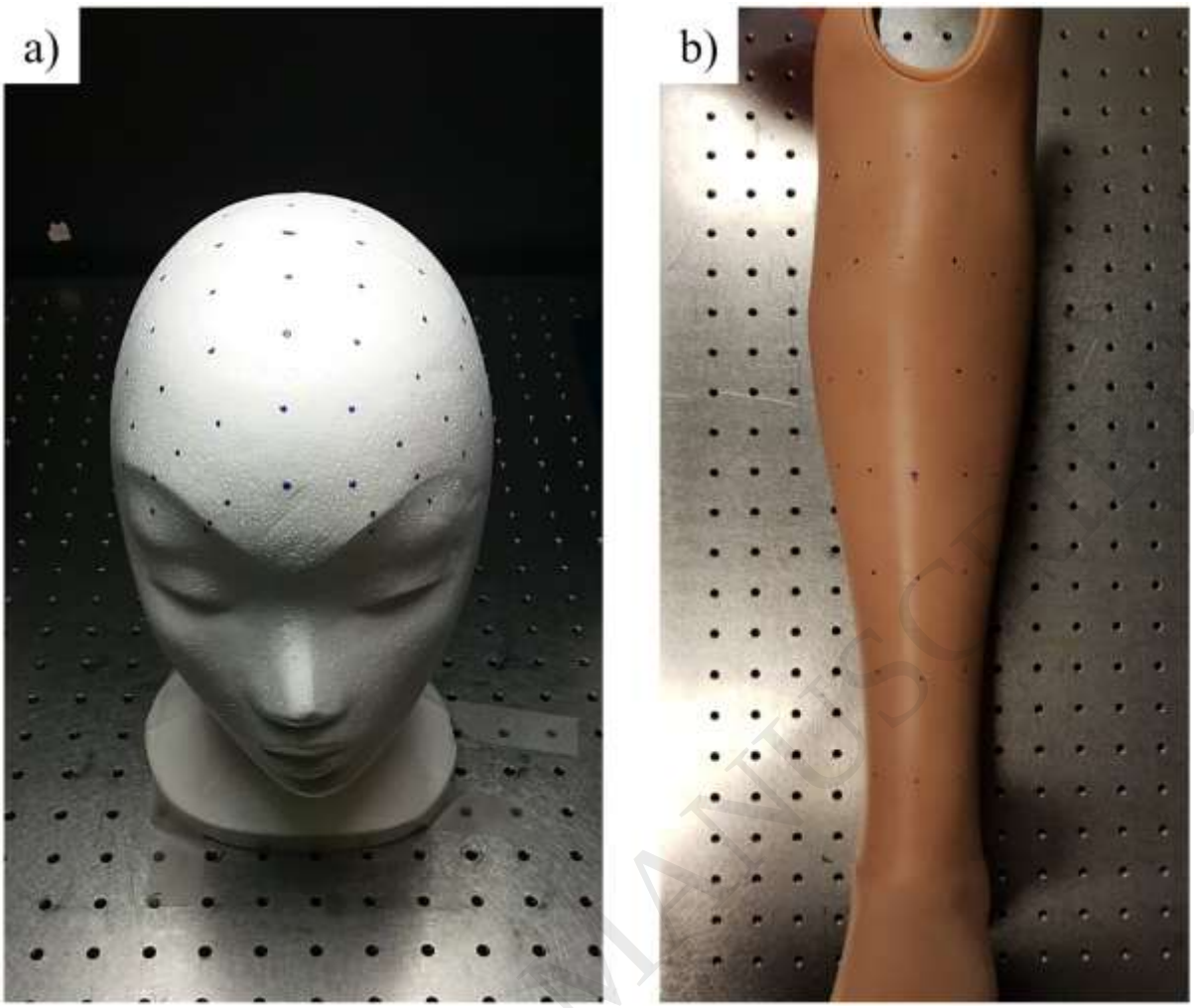


Figure 3. Comparison of a) spectral irradiance profiles of the artificial dPDT light source (left y-axis) and daylight (right y-axis), and b) normalised PpIX-weighted irradiance profiles.

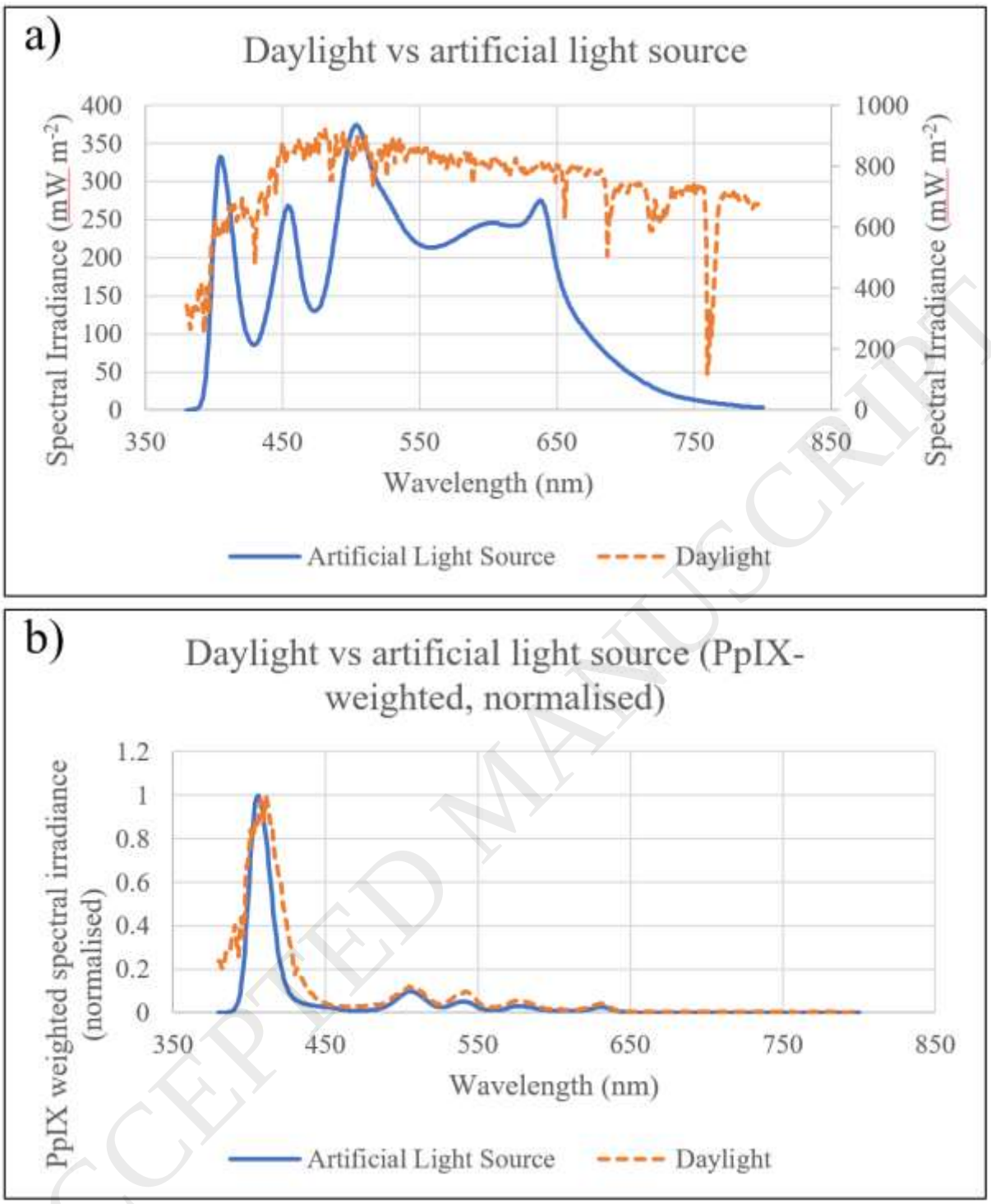


Figure 4. Irradiance uniformity map on a flat surface for a) unoptimised dPDT light source, b) optimised dPDT light source, and c) Aktilite CL-128. Each cell represents a 50 x 50 mm measurement area. A colour scale is shown on the right-hand side.

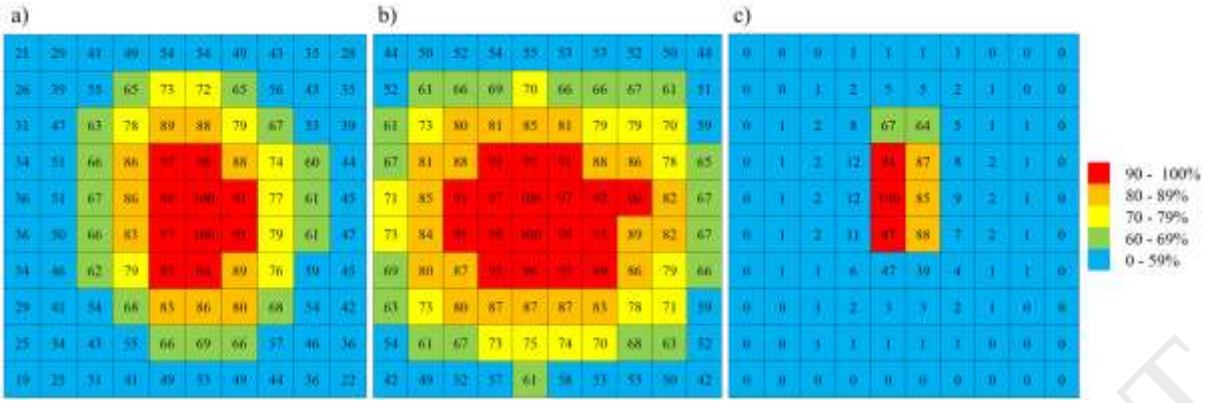


Figure 5. Irradiance uniformity map on a model head for a) unoptimised dPDT light source, b) optimised dPDT light source, and c) Aktilite CL-128. Each cell represents a 25 x 25 mm measurement area. A colour scale is shown on the right-hand side.

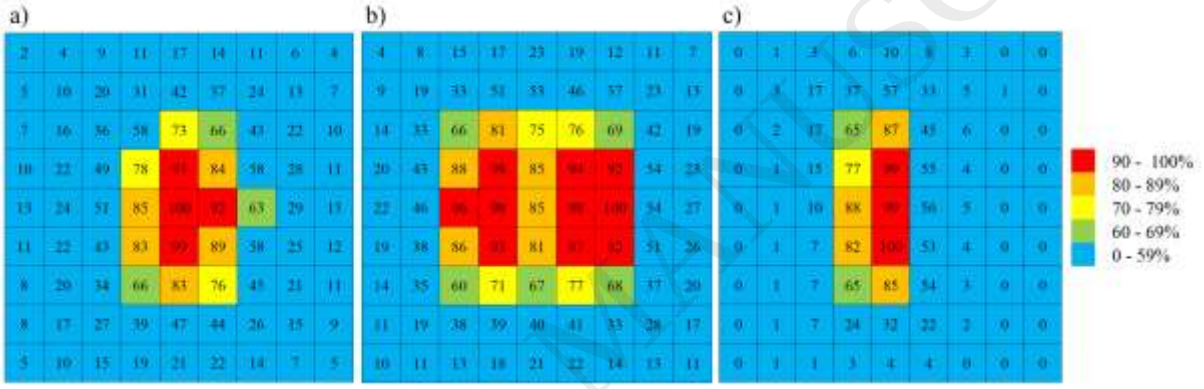


Figure 6. Irradiance uniformity map on a model leg for a) unoptimised dPDT light source, b) optimised dPDT light source, and c) Aktilite CL-128. Each cell represents a 25 x 50 mm measurement area. A colour scale is shown on the right-hand side.

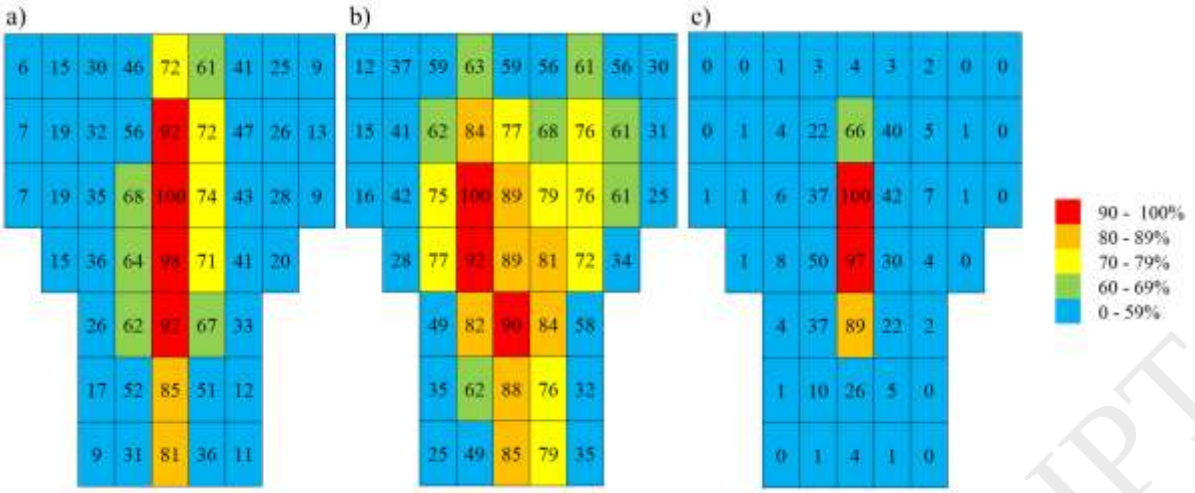
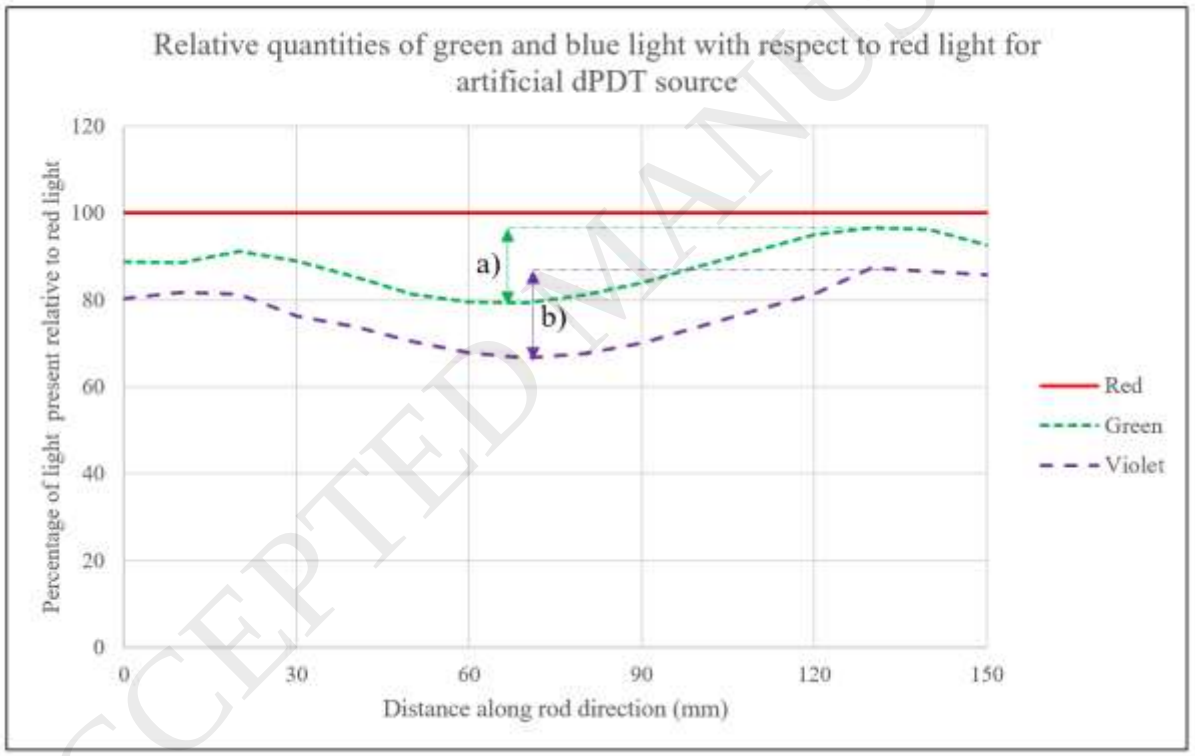


Figure 7. Wavelength uniformity of the artificial dPDT light source. Maximum relative change in a) green and b) violet light are indicated



Tables

Table 1. CoV, expressed as a percentage of the standard deviation divided by the mean, for each light source on each measurement surface for standard and large treatment areas

	Flat surface		Head		Leg	
Area dimensions (mm)	50 x 100	300 x 300	50 x 100	125 x 125	50 x 100	75 x 250
Unoptimised light source	1.6	15	17	29	20	21
Optimised light source	0.9	7.2	6.8	14	4.8	11
Aktilite	1.6	140	13	75	40	65