

Construction and characterization of a phototherapy radiometer for optical radiation measurements

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It is necessary to measure the irradiance levels to evaluate the effective dose delivered to the neonate from phototherapy devices. For such purpose, a broadband phototherapy radiometer has been used for measuring these phototherapy irradiance doses of plurality types of phototherapy sources. A phototherapy radiometer has been designed and during the construction its optical characteristics has been tested in collaboration between the National Institute of Standards in Egypt (NIS) and Department of Research And Development, Medical Engineering Group (MEG) Company. The most parameters required to characterize the performance of radiometer are the responsivity and uniformity. Then the present radiometer has been compared to other two available portable phototherapy radiometers in irradiance levels measurement. The calibration has been settled and the expanded uncertainties has been calculated according to the Guide to the expression of uncertainty in measurement (GUM) at coverage factor $k = 2$. The designed radiometer has responsivity range 415-495 nm with FWHM 35 nm which covers the phototherapy blue band. The radiometer results output summarized as; quantum efficiency is 84%, the uniformity 72% and measuring irradiance range 100-2500 $\mu\text{W}\cdot\text{cm}^{-2}$.

Keywords: Phototherapy radiometers, Irradiance spectral responsivity, Uniformity, Calibration

1 Introduction

The effectiveness of neonatal jaundice treatment depends directly on the amount of energy emitted by light expressed by irradiance in $\mu\text{W}\cdot\text{cm}^{-2}$. Performance evaluation of phototherapy devices depends on accurate measurements of the irradiance levels doses in the blue phototherapy spectrum and its distribution over the irradiated surface area using optical phototherapy radiometer. The radiometer is used for calibration of irradiance of phototherapy sources and also for spectrally weighted measurements like phototherapy dose¹⁻³.

Irradiance (E) is a measurement of optical power falls onto a surface area. Because the irradiance is quantified as $\mu\text{W}\cdot\text{cm}^{-2}$ within the effective wavelength range for efficacy; it is also referred to as spectral irradiance and is expressed⁴ as $\mu\text{W}\cdot\text{cm}^{-2}\cdot\text{nm}^{-1}$. According to the BS EN 60601-2-2009 the total irradiance for bilirubin is equal to the evaluated irradiance in the range 400 nm to 550 nm and give by integration:

$$E_{bi} = \int_{400\text{nm}}^{550\text{nm}} E_{\lambda}(\lambda) d\lambda \quad \dots (1)$$

where $E_{\lambda}(\lambda)$ is the measured irradiance at an individual wavelength (λ).

These values and their distribution on the effective surface area can be determined by measurements with a radiometer whose detectors have a limited spectral sensitivity to the infant phototherapy. In the integral method the total irradiance for bilirubin E_{bi} is measured with a radiometer whose spectral sensitivity has been adjusted to the total irradiance in the wavelength range⁵ between 400-500 nm.

Any radiometer consists of mainly a combination of a sensor, a band-pass filter, and electronics. The filter focuses the radiation to a proper range after separation of spectral components. The sensor responds to the radiant power passed through the band-pass filter. The output signal was amplified by the electronics and converted to digital counts with meaningful unit⁶⁻⁸.

The performance of optical radiometer is characterized by its responsivity, uniformity and calibration. In all cases the detectors, national industry or the imported, are all under test and compared with a standard detector of known spectral responsivity traceable to primary cryogenic radiometer⁷⁻⁹.

In this article, the performance and the uncertainty of the present radiometer was investigated by

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comparing to other available phototherapy radiometers and the construction was prepared in cooperation between the National Institute of Standards (NIS) at Egypt, and Medical Engineering Group (MEG) Company.

2 Materials and Method

2.1 Construction of radiometer

The radiation sensor is simply a silicon detector sensor which converts the light signal to appropriate electrical signal. The sensor covered by a band-pass filter and diffuser, the sensor signal paths through a USB data wire to the control board. The band-pass filter has a maximum spectral wavelength at 450 nm and 80 nm for the full width and half maximum (FWHM), while the photodiode has spectral sensitivity at the range 380 - 1100 nm.

The detector connected to an electronic control board to produce readings in $\mu\text{W}\cdot\text{cm}^{-2}$. The above configuration present in a case (the detector head) 25 mm in thickness and the effective irradiated surface area of the detector is 20 mm. The radiometer construction description is illustrated in Fig. 1.

2.2 Function description

The main function of the control board is reading the electronic signal from the radiation sensor. This sensor connected through a USB socket J5, then the microcontroller converts this value using the calibration equation to calculate the irradiance value. The user can change the displayed units on the screen through the units' button.

The interface circuit contains 4 LEDs and 2 buttons; one button to ON the device and the other for change the units of the displayed data on the LCD, two LEDs to obtain the displayed units ($\mu\text{W}\cdot\text{cm}^{-2}$) and ($\mu\text{W}\cdot\text{cm}^{-2}\cdot\text{nm}^{-1}$), Low battery indicator LED and charging indicator LED.

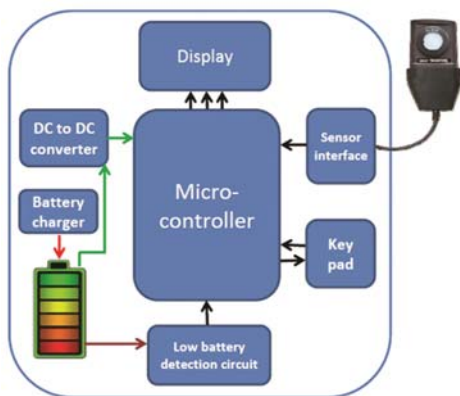


Fig. 1 — Block diagram of the fabricated radiometer

2.3 Spectral responsivity characterization

The performance of the constructed radiometer under spectral range illumination was investigated by responsivity measurements. The NIS responsivity system based on single monochromator from NEWPORT model 77700 which is illuminated by high intensity quartz tungsten halogen (QTH) lamp as a tunable light source. The reference and test detectors were aligned at the exit aperture of the monochromator and the output data was recorded.

The spectral irradiance response of the manufactured radiometer was determined at selected spectral range 400-500 nm and the irradiance readings was recorded each 5 nm increment performed by selection options in extension monochromator program. The HAMAMATSU photodiode model S2281 calibrated at NIST for spectral responsivity from 200-1100 nm each 5 nm was used as reference detector and its response readings was compared to that of the manufactured radiometer. The integrated responsivity was calculated relative to the reference responsivity obtained from its calibration certificate.

2.4 Uniformity measurements

The variation in responsivity as a function of position across the detecting surface is known as spatial uniformity. A stable optical power source with lens to provide a light spot size of 2 mm diameter was used as the light source and the output signal of each segment of the detector was obtained.

The spatial uniformity distribution was obtained by moving the detector by step of 2 mm in both directions X and Y. The measured active surface area size of manufactured detector was 20×20 mm. The scans were continued in the reverse direction and average readings were recorded^{10,11}.

2.5 Accuracy and uncertainty repeatability

The comparison in irradiance measurements and calibration was established between a national manufactured radiometer code (RM 916) and two other available radiometers responses in blue spectral range. The two radiometers are phototherapy radiometer from FULKE biomedical model DALE40 of the spectral response from 429-473 nm with maximum response at 453 nm and the hyperbilirubinemia radiometer ILT74 from international light technologies with 425-475 nm spectral response and maximum response at 455 nm. The reference radiometer used for the calibration was the UDT-S480 with 268-BLUE detector with spectral response from 420-475 nm and maximum response at

440 nm. The source used for illumination in calibration setup was a QTH lamp source with blue bandpass filter with maximum spectral peak at 450 nm.

3 Results and Discussion

3.1 Spectral responsivity and quantum efficiency evaluation

The responsivity spectrum of the RM 916 radiometer is shown in Fig. 2 as a function of the relative responsivity A/W versus wavelengths. It is found that its spectrum response from 415-490 nm with maximum response peak located at 445 nm.

The maximum relative responsivity value was 0.293 A/W with standard uncertainty 0.145%.

The quantum efficiency (*QE*) of silicon-based photodiodes generally has been produced in such a way that their internal QE is close to unity especially in the visible region of electromagnetic spectra. The quantum efficiency computed as a function of wavelength according to the equation:

$$QE = R \times 1.24 / \lambda \quad \dots (2)$$

where *R* is the detector responsivity, the λ is the wavelength interval, and the factor $1.24/\lambda$ ($= hc/\lambda$, where *h* is the Planck constant and *c* is the speed of light). According to this equation the calculated QE for the RM 916 radiometer¹² was 84%.

3.2 Uniformity measurements

The result of the uniformity response measurements of the RM 916 radiometer is shown in Fig. 3. The spatial uniformity is measured at 460 nm corresponding to the maximum peak of the used source.

Uniformity measurement data analyzed using 3D surface pictorial. The pictorial is created by normalizing the data where zero represents the "no response" measurement and one represents the highest response measurement. The normalized data is then presented with a 3D surface pictorial by plotting the X position versus the Y position versus the normalized response¹³.

The relative percentages uniformity value 72% for the test detector along the 50% of central active area. The standard uncertainty due to repeatability was calculated and the result is 0.59% at coverage factor *k* = 2. The other relative uniformities of portable radiometers within the same central active area are in between 52% and 85% for radiometers with models ILT74 and DALE40, respectively.

3.3 Measurement range and uncertainty

The manufactured phototherapy radiometer was compared to other portable phototherapy radiometers models ILT74 and DALE40 for their irradiance ranges response. The result indicates that the manufactured radiometer can record irradiance readings in the range of 100-2500 $\mu\text{W}\cdot\text{cm}^{-2}$ from light sources. The other two portable radiometers ILT74 and DALE40 can record 100-7000 $\mu\text{W}\cdot\text{cm}^{-2}$ and 1-1999 $\mu\text{W}\cdot\text{cm}^{-2}$, respectively.

The resolution of the manufactured radiometer is 0.1 $\mu\text{W}\cdot\text{cm}^{-2}$, which is the same as ILT74 while the resolution of DALE40 is 1.0 $\mu\text{W}\cdot\text{cm}^{-2}$. At a distance of 50 cm from source emitting blue band, the three radiometers record 1268 $\mu\text{W}\cdot\text{cm}^{-2}$, 1263 $\mu\text{W}\cdot\text{cm}^{-2}$ and 1310 $\mu\text{W}\cdot\text{cm}^{-2}$ for the constructed radiometer and both ILT74 and DALE40, respectively. The relative standard uncertainty of these records is 2%.

The three radiometers was calibrated against the UDT radiometer model S480 readout connected to detector model 268-BLUE as a reference radiometer, calibrated and traceable directly to NIS reference

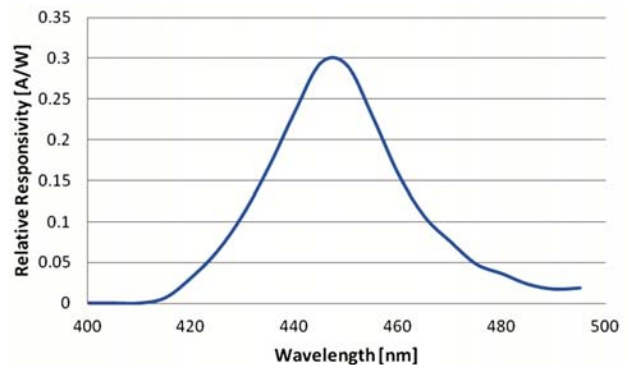


Fig. 2 — Typical RM 916 radiometer' responsivity curve shows A/W relative responsivity as a function of wavelength.

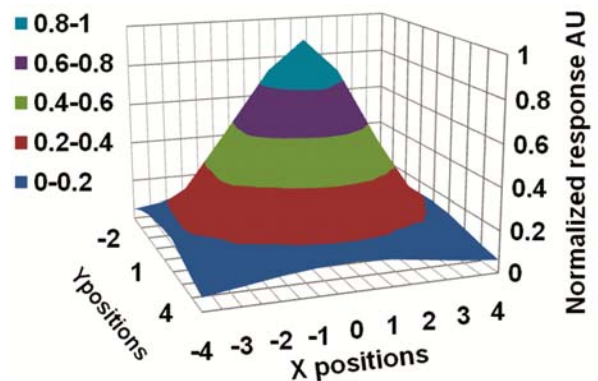


Fig. 3 — Spatial uniformity of the manufactured radiometer 3D display.

silicon trap detector. The expanded uncertainty was 5.8% for manufactured radiometer, 5.2% for ILT74 and 7.6 for DALE40. We don't check the angular sensitivity of fabricated measuring head due to shortage in measuring tools.

4 Conclusions

The new designed radiometer constructed from a silicon detector sensor which converts the light signal to appropriate electrical signal, the sensor covered by a band-path filter and diffuser, the sensor signal pass through a USB data wire to the control board. It has responsivity range 415-495 nm and 35 nm FWHM which covers the phototherapy blue band. The QE is 84%, uniformity 72% and measuring in irradiance range 100-2500 $\mu\text{W}\cdot\text{cm}^{-2}$. The designed radiometer characteristics compared with two radiometers will establish from two other manufactures used in the same purpose. The comparison results were very close to each other. It can be used to measure the irradiance level of wide variety of blue phototherapy source.

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