Evaluation of the irradiance levels delivered by non-conventional phototherapy devices for intensive Jaundice treatment

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Abstract The main purpose of this research is to evaluate irradiance levels delivered by non-conventional phototherapy devices. This evaluation can help to save energy, achieve better treatment and improves available intensive phototherapy quality in use in several hospitals in Egypt. The irradiated energy and uniformity of non-conventional phototherapy devices (n=36) were evaluated at nine hospitals in Egypt. These devices were categorized as three groups including: bilibeds with LEDs, bilibed with fluorescent lamps and bilisphere. The irradiance levels were measured using a phototherapy radiometer. The results show that the irradiance levels ranged from 20.3 to 93.1μW.cm⁻².nm⁻¹ and the LEDs bilibed devices produce average irradiance levels approximately double of those results from bilisphere with fluorescent lamps. Otherwise, the bilibed with fluorescent lamps (present about 30% of the non-conventional phototherapy devices studied) is not adequate for intensive phototherapy. Any assessment of the irradiance energy of the phototherapy devices using a suitable calibrated sensor (radiometer) is mandatory in developing countries. The phototherapy devices that produces an adequate and accurate irradiance levels would increase the degradation rate of bilirubin in the blood and hence minimize the necessity to blood transfusion substitution. LEDs bilibeds produce sufficient electromagnetic energy for jaundice treatment. It can be used alone for intensive treatment better than the bilibed with fluorescent lamps and the bilisphere.

1. Introduction
Rademetry is the field of metrology related to the physical measurement of the optical energy properties of electromagnetic radiation, including visible light [1]. Many branches of life are depending on light energy especially in medication. Phototherapy is one of the well established techniques in the treatment of many human disorders such as neonatal Jaundice. Various phototherapy systems are available to provide treatment for neonatal jaundice. Neonatal jaundice appear as yellowing skin within the first month of life due to increasing of yellow pigment (bilirubin) just beneath the skin [2] and [3]. The blue spectrum of light (450 - 495 nm) is commonly used for jaundice phototherapy because at this band, light energy transmitted through skin and well absorbed by bilirubin. After the photoisomarization, it easy for bilirubin molecules to be excreted with urine [4] and [5].
Many factors affect the efficiency of phototherapy such as the type of light sources, the spectral range of the radiation, the irradiance levels emitted from the phototherapy source used and the exposed area of skin [6][7]. The American pediatrics recommended that the intensive irradiance level for bilirubin is more than 30μW.cm⁻².nm⁻¹ [8][9]. The intensive phototherapy is recommended at high bilirubin levels which ought to be reduced as fast as possible. In this case, exposing more infant's skin area to uniform phototherapy is essential [10][11][12]. In order to measure the irradiance levels of blue light phototherapy devices, expressed in W/m², special phototherapy radiometer sensors are used. These types of radiometers have special characterization that their spectral responsivity is within the phototherapy band range, 400-500nm [13]. The infant’s surface area can be increased by either placing bilibed, that may contains a group of special blue fluorescent lamps or include a blue light emitting diode LEDs sources, under the infants with the conventional phototherapy apparatus above or expose the infant inside the bilisphere phototherapy [4,9,12].

Utilization the intensive phototherapy treatments has dramatically effect on the reduction need to exchange blood transfusions. The exchange blood transfusion is still regularly performed in the developing countries, due to lack of the awareness to the importance of making sure of the irradiance delivered from the phototherapy devices [14]. As a result of this lack of awareness, phototherapy devices is not regularly evaluated for their irradiance values. The aim of this study is to verify and evaluate irradiance levels and therefore the uniformity distribution of light delivered by non-conventional phototherapy devices to improve intensive phototherapy available and currently in use in several hospitals in Egypt.

2. Material and methods

2.1. Non-conventional phototherapy devices studies

Non-conventional phototherapy devices obtained for the study from the Egyptian hospitals are classified into three types: a) Group (A) contains 16 bilibed devices each contains more than 300 blue LEDs sources covered with thin sheet of transparence Perspex and have highly transparent mattresses where the baby is laid on, b) Group (B) contains 11 bilibed devices each contains three 20W special blue fluorescent lamps arranged on one plan and covered with a thin transparence Perspex sheet, and c) nine bilisphere devices included in group (C) each consists of two sets each contains eight special blue 20W fluorescent lamps arranged in a half circle way, positioned face to face and parallel with a transparent web bed in between the two sets. Each set has an acrylic plate cover the lamp banks.

2.2. Irradiance measurements setup

According to British Standards specification, the effective surface area is defined as the interested treatment area which is irradiated by the phototherapy energy and is recommended as standard sized surface of 60 × 30 cm. The irradiance levels were measured all over the irradiated area at different specified positions [4] and [15]. In this study, the irradiation area was the transparent sheet covering the LEDs or lamps in bilibed devices while the area was the web bed fixed in the bilisphere devices. In Group (A), the irradiation area had an elliptical shape with diameters 45 × 24 cm divided to eleven marked positions for irradiance measurements. The irradiation area of the Group (B) was 40 × 28 cm and irradiance levels were measured at nine points. Finally, the irradiance measurement of the upper and lower sets of the third Group (C) devices is performed using fifteen demarcated points along the 60 × 30 cm of the web bed between the two sets. The irradiance of the upper and lower lamp sets can be assessed by exposing the radiometer sensor upward or downward. The mean of the fifteen upper and lower points were calculated [10].

The irradiance levels \(E\) were measured using a radiometer model UDT-S480, from GAMMA scientific Inc., equipped with a detector of type 268BLUE contains 450 nm band pass filter and cosine diffuser. The sensitivity range is 425 to 479 nm with the maximum peak sensitivity at 450 nm. The irradiance levels that measured at each position were repeated n times for average and standard deviation calculations.

The uniformity of irradiance levels \(E\) is calculated as follows:
Uniformity = \frac{E_{\text{min}}}{E_{\text{max}}} \quad (1)

where, the $E_{\text{min}}$ is the minimum irradiance level and the $E_{\text{max}}$ is the maximum irradiance level. The uniformity results were compared to the British Standard requirements to evaluate the phototherapy devices.

2.3. Statistical Analysis
The irradiance and uniformity parameters of the phototherapy devices were analyzed using the statistical SPSS program. The independent sample T test was used followed by the 2-tailed Student’s t-test in order to compare the irradiance and uniformity values of non-conventional phototherapy devices to the recommended standard values. The significance level $P \leq 0.05$ was applied in all statistical tests.

3. Results

3.1. The irradiance measurements
The spectral irradiance at each position ($E_{ij}$) of the thirty six non-conventional phototherapy devices under study are measured and calculated according to the following equation:

$$E_{ij} = \frac{\int_{400}^{500} E(\lambda) d\lambda}{\text{Radiometer}_{\text{FWHM}}} = \frac{E_{\text{total}}}{\text{Radiometer}_{\text{FWHM}}} \quad (2)$$

where,

$E_{ij}$: the spectral irradiance from non-conventional phototherapy devices in $\mu \text{W.cm}^{-2}\text{.nm}^{-1}$ at each measurement position along the effective surface area.

$E(\lambda)$: irradiance at each wavelength from non-conventional phototherapy devices in $\mu \text{W.cm}^{-2}$.

$E_{\text{total}}$: Total irradiance from non-conventional phototherapy devices in $\mu \text{W.cm}^{-2}$.

$\text{Radiometer}_{\text{FWHM}}$: Spectral sensitivity range in (nm) of the phototherapy radiometer using its full width at half maximum (FWHM).

Figure 1, 2 and 3 reveals a measurements comparison between the non-conventional phototherapy devices groups (A), (B), and (C), predominantly in the required spectrum (400 nm - 500 nm). These comparisons include the mean irradiance levels in $\mu \text{W.cm}^{-2}\text{.nm}^{-1}$ along the 15 measurement positions of the irradiated surface area. A comparison of measurement of their non-uniformity as well were introduced. Measurements showed that group (A), bilibed devices based on LEDs, exhibits highest irradiance and uniformity and can be used in intensive cases in bilirubin photodegradation compared to that of the group (B) and (C), both are based on fluorescent tubes.

Table 1 shows all evaluation characteristics combined with the thirty six studied non-conventional phototherapy devices. On the other hand, Figure 4 presents samples of the three phototherapy groups to verify the non-uniformity calculation according to differences in irradiance values at different positions (central and peripherals) at the central line of the irradiated surface area treatment area. Each group follows its own uniformity trend. As shown, group (A) produces the best uniformity while group (B) is on the contrary of it. Group (C) lies in the middle and also produce reasonable uniformity.
Figure 1. Average irradiance and uniformity of each sample in Group (A).

Figure 2. Average irradiance and uniformity of each sample in Group (B).

Figure 3. Average irradiance and uniformity of each sample Group (C).
Table 1 Characteristics of the studied 36 phototherapy devices. Spectral irradiance measured in μW.cm⁻².nm⁻¹ while the uniformity is unit less.

| Phototherapy Device Groups | Number | Spectrum | Spectral Irradiance Range (Mean ± SD) | Uniformity (Mean) | % of devices fulfill intensive irradiance level (>30) | % of devices fulfill Uniformity (>0.4) |
|---------------------------|--------|----------|--------------------------------------|-------------------|--------------------------------------------------|-------------------------------------|
|                           |        | Total Range (nm) | FWHM (nm) | Maximum Peak (nm) |                     |                           |                                     |
| LEDs Bilibed (Group [A])  | 16     | 425-510 | 23 | 460 | 40-90 | 68.6±16.7 | 0.71 | 16/16 (100%) | 16/16 (100%) |
| Fluorescent lamps Bilibed (Group [B]) | 11 | 350-580 | 95 | 455 | 20-28 | 23.8±2.5 | 0.39 | 0/11 (0%) | 0/11 (0%) |
| Bilisphere (Group [C])    | 9      | 350-580 | 95 | 455 | 32-45 | 33.6±6.6 | 0.66 | 9/9 (100%) | 9/9 (100%) |

Figure 4. The irradiance levels at each position at the central line of the treatment area for the three groups [A], [B] and [C].

3.2. Statistical analysis
The irradiance readings for the two groups (A) and (C) devices were higher in their values than that obtained for the intensive phototherapy (>30μW.cm⁻².nm⁻¹) (p= 0.061 and p= 0.055 respectively). For the Group (B) (represent about 30% of total 36 devices), the mean irradiance readings (23.8 μW.cm⁻².nm⁻¹± 0.036) were significantly lower than that obtained for the intensive phototherapy and hence lower than those of the two groups (A) and (C) (p=0.022).
On the other hand, the mean value of uniformity of Group (B) is 0.39 ± 0.022 whereas the other mean value for groups (A) and (C) together is 0.8 ± 0.06 which already meet the standards (uniformity > 0.4). The sig. (2-tailed) (p-value) for Group (B) is less than 0.05 thresholds for the Levene’s test (p=0.015), and therefore there is really the difference between the calculated mean and the recommended value. This significant difference indicates that Group (B) is low in uniformity and doesn’t achieve the BS standards requirements.

4. Discussion
As noticed from these results, the Group (A) produces the best uniformity and highest mean total irradiance, while the mean total irradiance of Group (C) is approximately half the value of that produced by the group (A). On the other hand, the Group (B) produces the lowest level in both irradiance and uniformity. The total irradiance of this group is approximately one third of the value produced by Group (A). The mean irradiance results from samples of groups (A) and (C) highly match the required intensive phototherapy levels (>30 μW.cm⁻².nm⁻¹) for treatment of the intensive hyperbilirubinemia [16], while the Group (B) produces irradiance level below the required for intensive phototherapy with low uniformity. The evaluation of the output irradiance levels must be confirmed regularly as a quality assurance process [14].

According to the British standards for testing the performance of phototherapy devices [15], the uniformity must be greater than 0.4. The results show that Group (B) has the mismatch uniformity and thus it does not fulfill the requirements. To explain the inadequacy of Group (B), as mentioned before the irradiance measurements were recorded at the transparent sheet which is close to the fluorescent lamps covering them. This result was expected due to the high difference of irradiance levels as a result of the closeness to fluorescent lamps. The irradiance levels are high in the middle position of lamp compared to those at the peripheral sides [17][18]. These high differences lead to significant decrement in the uniformity value because uniformity is directly related to the ratio between the maximum and minimum irradiance levels. The uniformity depends mainly on how the sources, LEDs or fluorescent lamps, distribute in phototherapy devices and consequently the interference of irradiated areas on the exposure area matrix [16][19].

As for Group (C), although it produces an intensive irradiance level and has high uniformity, it has the problem of power lamps consuming and more heat output to the infant. These reasons lead to a non-comfort in jaundice treatment.

So the Group (A) is better in use for its advantage of producing high irradiance matches to the phototherapy intensive level, low heat output, long life time, low power consuming [20] and high uniformity irradiance levels that are produced as a result of a large number of LEDs and well design distribution along the bilibed surface area [21].

5. Conclusion
The phototherapy devices studied in this research are bilibed contained LEDs (Group (A)), bilibed contained blue fluorescent lamps (Group (B)) and bilisphere (Group (C)) illuminated also by blue fluorescent lamps. As shown from the results, the irradiance levels of Group (C) were approximately half of those produced by Group (A), and the irradiance level obtained from Group (B) was approximately 35% of that obtained by group (A) despite the insufficiency of acceptable uniformity (0.39). In this case this phototherapy group device (B) will not be able to give equivalent irradiance treatment along the infant body surface. So it may be reconstructed and combined with a conventional phototherapy to produce a proper irradiance dose.

Group (A) can be used in conjugation with conventional phototherapy, this situation gives double sided treatment that increases the irradiated area. The exposure area is going to be accumulated in the same way as using the cylindrical arrangement lamps in Group (C) with more benefits including decreasing in heat upon the infant body and electrical consumption and an increase in the comfortable ventilation and treatment.
Finally, intensive phototherapy can be achieved effectively and economically by using double-sided irradiation. This can be done easily by using two phototherapy luminaire opposite to each other to treat the baby in between. Also, this technique of treatment saves a lot of money and time.

The continuous and regular monitoring of the irradiance level is mandatory to achieve better results from phototherapy service. Also, schedule lamp replacement is another solution if the irradiance readings are not suitable for phototherapy purpose. This ought to be considered as a method for quality confirmation to accredit these devices to convey intensive phototherapy and hence contributes significantly to reduce the exchange blood transfusion rates.

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