A METHOD FOR COMPUTING THE RADIANT ENERGY DENSITY IN THE CONVENTIONAL PHOTOTHERAPY OF THE NEWBORN

Heitor S. Lopes [1], Nelson O. Osaku [2]

[1] Bioinformatics Lab./CPGEI, Federal University of Technology – Paraná (UTFPR)
Av. 7 de setembro, 3165 80230-901 Curitiba, Brazil
[2] University Hospital, West of Paraná State University, Cascavel, Brazil
e-mail: hslopes@pesquisador.cnpq.br

Abstract: The phototherapy with conventional fluorescent lamps is the most widely used method for treatment of the neonatal hyperbilirubinemia. Not only spectral irradiance measurements are important to warrant efficacy of treatment, but also the radiant energy density. A method for computing the radiant energy density is proposed. We explain the transformation of spectral irradiance into irradiance using the normalized spectral response of a clinical radiometer. Next, it is shown how the radiant energy density can be computed from successive discrete measurements of irradiance. Finally, we discuss the clinical implications of this methodology.

Key-words: Phototherapy, Radiant energy density, Irradiance, Optical measurements, Hyperbilirubinemia.

Introduction

The hyperbilirubinemia of the newborn is observed in 80% of the preterm and 60% of the term newborns (corresponding to those born before and after the 37th gestation week, respectively). The high level of total serum bilirubin (TSB), related to the non-conjugated fraction, is the main cause of this clinical condition. In most cases, its physiological consequences disappear by itself after some days of life without affecting the newborn's health. However, it is estimated that around 3 to 6% of these cases require clinical care [1,2], since hyperbilirubinemia can lead patient to a serious encephalopathy known as kernicterus [3]. It has a high morbity and survivors of this pathology can present serious problems, like coreoathetosis, deafness, and mental impairment [4,5]. Despite of the advancement of medicine, kernicterus, as consequence of unmanaged hyperbilirubinemia of the newborn, is still an issue of current concern [3,6].

The main method for the prevention and treatment of the newborn's hyperbilirubinemia is the phototherapy [2,7]. This method was proved efficient a half century ago, and much progress has been done in this area, especially towards the study of the spectral irradiance with different type and number of lamps in the phototherapy equipments [2,8]. Also, it was demonstrated that phototherapy turns out to be inefficient if patient is submitted to a spectral irradiance lower than 4 μW/cm^2/nm [2,9,10]. As a consequence, measurements of spectral irradiance of phototherapy unites using clinical radiometers was suggested to be routine for the clinical engineer.

Around three decades ago, it was suggested that, once the radiant energy density (or simply, the accumulated dose) can be measured, it could be possible to predict the average decreasing of blood concentration of bilirubin in the first 24 hours of conventional phototherapy [11,12]. However, not much research about this specific subject has been done, in the quest for a predictive model relating the decrement of bilirubin to the phototherapy parameters. Possibly, the reason for this is not only the lack of a clear procedure for obtaining the dose, but also the belief that monitoring irradiance is enough to ensure the efficacy of phototherapy. Only recently a dose-response model for the phototherapy of the newborn has appeared [14].

Therefore, the objective of this work is to present a methodology for obtaining the radiant energy density, departing from successive measurements of spectral irradiance in the clinical setting.

Computation of the Radiant Energy Density

Derived Units of the SI – Before explaining the method for obtaining radiant energy density (RED) based on the spectral irradiance, it is worth to present and comment some derived units of the SI (International System of Units). There are two systems for measuring optical quantities: the radiometric and the photometric systems.

The radiometric related system considers the whole electromagnetic spectrum evenly, while the photometric system considers only a narrow band of the visible spectrum. In fact, the photometric system is based on the normalized curve of the human visual response, with peak of luminous efficiency at 555 nm [15,16]. There is no constant that relates quantities in both systems.

Although radiant energy (Q, in joules) is not a derived SI unit, it is of crucial importance for this study. Radiant energy is defined as the product of radiant flux by the exposition time. Frequently, this quantity of referred as the total dose received by a patient under phototherapy [13,14].

When a given quantity is normalized according to a spectral response curve, the corresponding unit is divided by nm (10^{-9} m). This transformation does not change the nature of the quantity, only its amplitude. For instance, spectral irradiance is given in W/m^2.nm. For quantities representing densities, values are divided by their area of influence, such as radiant energy density (J/m^2). For a concise list of derived quantities of the SI related to photometric measurements, see table 1

In this work, the RED effectively delivered to the newborn during phototherapy was obtained by computation, according to the procedure explained in the next session.

Table 1: Derived quantities of the SI for radiometric measurements

Quantity	Symbol	Unity
Radiant flux	P, Φ	W (watt)
Irradiance	E	W/m^2 (watt per square meter)
Radiant Intensity	I	W/sr (watt per steradian)
Radiance	L	W/(m^2 sr) (watt per square meter steradian)

Transformation of Spectral Irradiance into Irradiance – The first step is transforming spectral irradiance (E_e) into irradiance (E), considering the wavelength (λ) and the spectral response curve of the optical device. Let E be the irradiance (in W/m^2), E_e the spectral irradiance (in W/m^2.nm), λ the wavelength, and $s(\lambda)$ the normalized spectral response curve of the optical system. The relationship between E and E_e is given by Equation 1

$$E = \int_{-\infty}^{+\infty} E_e . s(\lambda) . d\lambda \qquad (1)$$

In Equation 1, considering E_e constant, the integral of the spectral response curve corresponds to the area under the curve.

Figure 1 shows a typical spectral response curve of the optical elements of a clinical radiometer, including optical filters, diffuser and optical sensor. This curve represents the response of a real-world radiometer, previously used by [14,17]. Observe that the peak of optical transmittance is around 450 nm, and a bandwidth similar to the optimal photodegradation of bilirubin (400-500 nm).

The spectral response curve can be obtained theoretically, by considering the spectral curves of optical transmittance of filters and diffuser and the sensitivity of the sensor.

Another way of obtaining this curve is experimentally, by using a calibrated light source (with known spectral curve) and a set of band-pass filters with very narrow bandwidth (less than 10 nm).

In general, the radiometer manufacturer can supply the spectral response curve of the equipment.

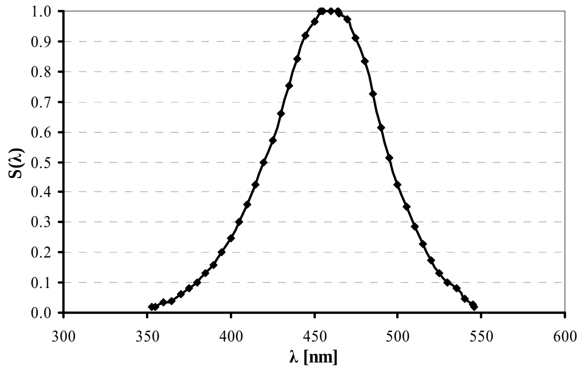

Figure 1: Normalized spectral response curve of a radiometer.

For the curve shown in Figure 1, the integral of Equation 1 is approximated by numerical integration, yielding the value of 84.0707 [17]. Renaming this constant to R, Equation 1 is promptly simplified to:

$$E = E_e . R \qquad (2)$$

Radiant Energy Density Computation using Irradiance – Considering Q the radiant energy (in joules), t the exposition time (in seconds), $E(t)$ a function that describes how irradiance varies along time, and Φ the radiant flux[1] (in watts), Equations 3 and 4 define the relationship between these quantities.

$$\Phi = \frac{dQ}{dt} \qquad (3)$$

$$E = \frac{d\Phi}{dA} \qquad (4)$$

The radiant energy density Q_d, given in J/m^2, is defined as the incremental variation of the radiant energy by the area:

$$Q_d = \frac{dQ}{dA} \qquad (5)$$

Thus, the radiant energy can be obtained by integrating both sides of Equation 3:

$$Q = \int \Phi . dt \qquad (6)$$

Next, isolating $d\Phi$ in Equation 4 and integrating both sides, and considering the area as a constant, it is obtained:

$$\Phi = E . A \qquad (7)$$

[1] Radiant flux is also known as radiant power

Due to the several factors that influence the light sources in the phototherapy, *E* is, in fact, a function of time and, therefore:

$$Q = A.\int E(t).dt \qquad (8)$$

Combining Equations 8 and 6, simplifying and setting the integration limits, one can achieve an Equation to obtain the radiant energy density:

$$Q_d = \int_0^t E(t).dt \qquad (9)$$

Observing Equation 9, two working hypotheses emerge when considering real-world measurements:

a) Irradiance *E* is constant and does not vary with time. As mentioned before, this hypothesis is not valid but for short periods of time [10,17,18]. If this was the case, Equation 9 could be easily simplified to Equation 10, where *t* would be the total exposition time under constant irradiance:

$$Q_d = E.t \qquad (10)$$

b) Irradiance *E* does vary with time. This hypothesis is the most probable, since there are many sources of perturbation for the effective irradiance that reaches the patient (such as the variation of the power supply voltage or the temperature of the lamps). Also, it should be considered that in the clinical setting newborns should be disturbed as few as possible. Therefore, irradiance measurements are most probably done at *n* sparse moments, not necessarily equidistant. That is, $E(t_0), E(t_1),..., E(t_{n-1})$, as shown in Figure 2.

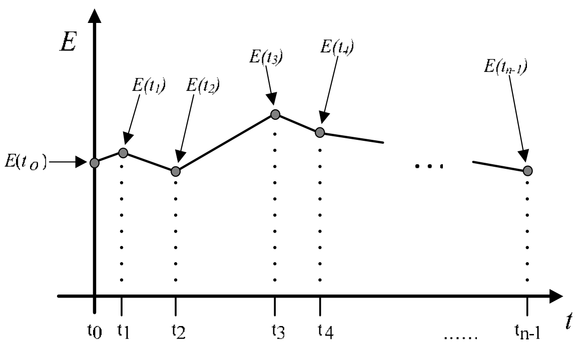

Figure 2: Variation of irradiance along time for uneven discrete measurements.

According to Equation 9, the time integration of irradiance is equivalent to the area under the curve of Figure 2. The easiest way to compute such area is taking the average value between two successive measurements and multiplying by the time elapsed between them, and then summing up all these products along all *n-1* measurements (this is known as the Simpson's rule). Therefore, this area, equivalent to Q_d, can be written as in Equation 11, the discrete version of Equation 9:

$$Q_d = \sum_{i=1}^{n-1}\left[\frac{E(t_i)+E(t_{i-1})}{2}\right].\left[t_i - t_{i-1}\right] \qquad (11)$$

Once the transformation of the spectral irradiance, commonly measured by most clinical radiometers, into irradiance was already detailed, by using Equation 11, the radiant energy density can be easily obtained.

Discussion and Conclusions

Since long ago [18], it is recommended that fluorescent lamps used in the phototherapy of the newborn have to be changed after 100 hours of use, approximately.

However, this procedure is not strictly followed everywhere, specially in countries under development. This is due both, to the cost and to the lack of means to effectively evaluate the efficacy of the lamps. Also, it must be taken into account that some low-quality fluorescent lamps deteriorate faster than expected, even under normal conditions of use [10,17,19]. These facts strongly suggest the need for a continuous monitoring of irradiance in the phototherapy of the newborn.

The availability of a predictive dose-response model for the conventional phototherapy of the newborn [14] has important practical implications. It can effectively contribute to improve the clinical management of hyperbilirubinemia, minimizing risks and discomfort for the newborn under treatment.

Therefore, the methodology proposed in this work can be useful not only for research purposes, but also for enabling phototherapy to achieve its efficacy in the treatment of the hyperbilirubinemia of the newborn.

Acknowledgement

H.S. Lopes acknowledges the financial support by the Brazilian National Research Council (CNPq) under research grant 305720/04-0.

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