Design and implementation of a phototherapy apparatus for the treatment of neonatal jaundice of the newborn

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Abstract

We propose a designed and implemented phototherapy apparatus (DIPTA) for a safe and effective treatment of neonatal jaundice. The improvement regarding the existing apparatuses mostly used in the developing countries in general and in Cameroon in particular, has been done by replacing the fluorescent lamps by LEDs ones, adjusting the light irradiance and baby-to-light distance and pre-setting the exposure time. The DIPTA consumes low power and can be accessible to all hospitals. It can be used at any time even within the power cut period, in rural and urban zone. It can operate in the hot regions with the temperature up to 65 degree C. The operating system is easy-use and the irradiance range is from 6.68 to 25.81 $\mu\text{W}/\text{cm}^2$ within the baby-to-light distance of 20–40 cm.

Keywords Phototherapy · Irradiance · LED lamps · Baby-to-light distance · Treatment

1 Introduction

About 60% of term and 80% of pre-term babies develop jaundice in the first week of life whereas about 10% of breastfed babies are still jaundiced at 1 month [1–3]. Jaundice is noticed by the yellow coloration of the skin and the conjunctival (white color of the eyes) [4]. This yellow coloration is caused by the accumulation of bilirubin in the skin and mucous membranes. Bilirubin is mainly produced from the breakdown of red blood cells. This type of bilirubin is named unconjugated (or indirect) bilirubin which flows mostly and bound to albumin, although some is free known as unconjugated bilirubin and is able to enter the brain. Unconjugated bilirubin is metabolized in the liver to produce conjugated (or direct) bilirubin which then passes into the gut and is then largely excreted in stool. Jaundice is caused by an increased level of bilirubin in the body. This condition is known as hyperbilirubinemia which is generally harmful.

In young babies, unconjugated bilirubin can penetrate the membrane that lies between the brain and the blood

(the blood–brain barrier). Unconjugated bilirubin is potentially toxic to neural tissue (brain and spinal cord). If the unconjugated bilirubin enters into the brain, this can lead to both short-term and long-term neurological dysfunction (so-called bilirubin encephalopathy), neuromuscular tone and control, hearing and death in the worst situation [1].

There are various types of jaundice distinguishable either with the age or the origin [3–5]. Regarding the age, the jaundice can be classified as: early jaundice viewed before 24 h of the newborn life; the delayed jaundice developed after 72 h and the persistent jaundice seen after more than 3 weeks. Regarding the origin, we can get: the protentional jaundice rarely detected but needs an urgent medical care; the unconjugated bilirubin jaundice mostly diagnosed and needs a phototherapy cure.

Once jaundice is diagnosed, there is uncertainty about when and how to treat, and the widespread variation in the use of phototherapy and exchange transfusion. Depending on the level of bilirubin measured on the baby according to the standard threshold's values

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[3], the medical doctor can determine the type of treatment whether the phototherapy or the exchange transfusion. The former is more often used when the serum bilirubin level is about in the range [100, 350] $\mu\text{mol/l}$ for the age from 0 to more than 96 h while the latter is used for the values up to 100 for 0 h and 450 $\mu\text{mol/l}$ for more than 96 h life [3, 6, 7]. The normal serum bilirubin value of a neonate is in the range [0.2, 1.4] mg/dl [6, 7].

The efficacy of phototherapy depends on four main factors: the light intensity characterized by the irradiance, the spectral range characterized by the wavelength or color, the exposed skin area and the time exposition. The irradiance is the measurement of the incident beam intensity that hits the skin given by the power per unit area per wavelength. The irradiance can be increased by decreasing the distance baby-to-light [1, 3]. It is clear that the choice of the devices for the design of the phototherapy apparatus requires the consideration of all the above-mentioned factors. Most of the phototherapy apparatuses use the fluorescent or halogen lamps suspended above the patient (baby), with a fixed luminance and a timer or manual clock for the control of the timing treatment. The fluorescent lamps cannot maximize the irradiance due to their high intensity output generating a significant heat. That obliges the users to place them far from the neonate by increasing the distance baby-to-light. As a result, the irradiance is reduced and the efficacy of the curing can be negatively affected [1]. Furthermore, those lamps cannot be produced only in a narrow wavelength range desired. The phototherapy treatment with fluorescent lamps leads to the disadvantages which are not negligible. Some manufacturers succeeded to overcome such problems by designing the apparatuses with the light emitting diodes (LEDs) lamps which have been found to be more efficient and no risky [2, 8–10]. The LED lamps provide significant advantages related to the: small size used, high intensity at desired wavelengths, narrow spectrum and low cost.

In Cameroon, the statistics show that within 20 months, in Central Hospital of Yaounde, 5.55% of the newborns develop the unconjugated bilirubin jaundice hence need a quick medical care [5]. However, many hospitals in urban and rural zone do not have enough phototherapy apparatuses to solve the situation. More to that, the existing apparatuses are designed with the fluorescent lamps. The medical users face obstacles of accessing to the imported apparatus devices which are expensive and difficult to repair. Even though, when they are used, they cannot be repaired in case of breakdown. There is no doubt that there is still a need in our country to easily access to an apparatus that can: be low cost, consume low power, operate at desired wavelengths, provide high irradiance to a considerable skin surface.

The aim of our project is to contribute to overcome the existing problems by proposing a design and implementation of a phototherapy apparatus (DIPTA) that: can be used for two levels newborn jaundice treatment over the country; is able to satisfy the standard curing conditions as well as the existing apparatuses; is cheap and also be easily used in developing countries which more often have the power cut problems. The designed apparatus can be used under the standard power or the solar power then can overcome the failure problems generally frequent in our country. Furthermore, this apparatus is mandatory, especially in developing countries such as Cameroon where a little hospital get phototherapy apparatuses for neonatal jaundice curing. The DIPTA usable in urban zone and in rural zone is a great interest to prevent grave and irreversible damages and often death of the innocent neonatal babies.

2 Basic principles of jaundice treatment

It is important that the medical staff knows the factors that influence the hyperbilirubinemia in order to be able to identify the suspicious cases at the early stage. Babies who are more likely to develop significant hyperbilirubinemia can have: gestational age under 38 weeks, previous siblings who needed phototherapy treatment (PT) for jaundice and visible jaundice in the first 24 h of their life. The medical doctors should examine jaundice at any time within 72 h not only by the visual inspection, but also by measuring the serum bilirubin level for the babies with suspected jaundice. The serum bilirubin level can be measured by a transcutaneous bilirubinometer or a serum bilirubin. The results should be checked with the thresholds bilirubin values presented in Table 1 according to [3].

Once the jaundice is confirmed, an urgent treatment should be done according to the bilirubin results measurements. From Table 1, it can be seen that PT is needed when the bilirubin level reaches the range [100, 350] $\mu\text{mol/l}$ for the age 0 to more than 96 h.

There are two types of phototherapy treatment:

- The standard phototherapy treatment (SPT), the bilirubin level is $\leq 300 \mu\text{mol/l}$ and the rate of the bilirubin should be reduced at about 25% within 24 h;
- The intensive phototherapy treatment (IPT), the bilirubin level is $> 300 \mu\text{mol/l}$ and the rate of the bilirubin should be reduced at about 50% within 24 h.

The principle of the PT consists of lying the baby under the blue light (radiation) within a limited period according to the level of jaundice [5, 11]. The degree of absorption depends on the wavelength of the light [5, 11]. The

Table 1 Threshold values of serum bilirubin level against baby age with action to be taken [3]

Age (h)	Bilirubin	Measurement	(BM) ($\mu\text{mol/l}$)	
0			> 100	> 100
6	> 100	> 112	> 125	> 150
12	> 100	> 125	> 150	> 200
18	> 100	> 137	> 175	> 250
24	> 100	> 150	> 200	> 300
30	> 112	> 162	> 212	> 350
36	> 125	> 175	> 225	> 400
42	> 137	> 187	> 237	> 450
48	> 150	> 200	> 250	> 450
54	> 162	> 212	> 262	> 450
60	> 175	> 225	> 275	> 450
66	> 187	> 237	> 287	> 450
72	> 200	> 250	> 300	> 450
78		> 262	> 312	> 450
84		> 275	> 325	> 450
90		> 287	> 337	> 450
96+		> 300	> 350	> 450
Action	Repeat BM in 6–12 H	Consider PT and repeat BM in 6 H	Start PT	Exchange transfusion

absorption wavelength range is generally between 380 and 490 nm, centered at 459 nm [11]. The blue radiation for jaundice curing transforms the bilirubin in the skin of the baby and eliminates it through the urine and feces.

The success of the treatment depends on the wavelength light (420–490 nm), the distance between the radiation source and the baby (baby-to-light distance: 20–40 cm), and the exposed skin surface. The distance baby-to-light should be minimized to maximizing the irradiance [1, 5]. For IPT, an additional source light should be used below the baby. The standard values of irradiance for SPT are about $10 \mu\text{W}/\text{cm}^2/\text{nm}$ whereas for IPT there are $\geq 30 \mu\text{W}/\text{cm}^2/\text{nm}$ in the 430–490 nm for largest skin area [11]. The indications of the PT are referred to the standard values of the bilirubin levels [3].

3 Material and method

3.1 Lamp devices

The phototherapy apparatus is mainly based on the lamps devices that can differ depending on the type of the PTA. We can distinguish the halogen lamps, the fluorescent lamps and the LEDs. All types of lamps do not have the same light efficiency that is important for the choice of the treatment.

Table 2 presents various types of lamps with their life-time and light efficiency levels for comparison. One can see that LED lamps are the best because of their high life-time, high light efficiency and little heat production. It is observed that the halogen and fluorescent lamps require more energy than the LED lamps for the same efficiency. The LEDs are highly monochromatic devices. They can emit a pure color in a tiny region of wavelength. The emitted light is identified by a wavelength peak in the emission zone. Because LED can use little power, the consumed power in the phototherapy apparatus (PTA) designed with LED can be minimized.

In Cameroon in particular in Yaounde, the few PTA are designed with the fluorescent lamps which consume power between 60 and 120 W. Their lifetime is about 2000 H. Most of the hospitals do not get the phototherapy apparatuses. In addition, those having these apparatuses face a great problem to repair them. They only present one level efficiency of treatment either for SPT or ITP and the curing time is increased in case of IPT. This procedure is a bit risky once the radiation can damage the skin of the patient. Our DIPTA is designed in order to improve the curing function, reduce energy consumed, resist to high temperatures and be low costly.

3.2 Prototype of DIPTA

The synopsis scheme of the apparatus consisting of four main moduli is presented in the Fig. 1. The first is the supply modulus composed of the photovoltaic section for the use of solar energy in case of power cut and the alternative

Table 2 Comparison of various types of lamps used in PTA [5, 12]

Types of lamps	Halogen	Fluorescent	LED
Operating lifetime (H)	2000	9000	40,000
Produced heat	25% of the light is produced against 65% of the heat	55% of the light is produced against 45% of the heat	80% of the light is produced against 20% of the heat
Mean light efficiency (lm/W)	Lamps of 12 V: 22 Lamps of 230 V: 16	70 (with the peak at 105)	(80, 200)

Fig. 1 Synopsis scheme of the designed and implemented phototherapy apparatus. *AC: Alternative current, DC: direct current

current (AC) power sector. The second is the supply modulus with the battery where the commands are used to supply the system. The third modulus is the timer system used to set the treatment timing and the fourth is the pilot LED modulus used for the irradiation phase.

Our phototherapy apparatus has two power supplies: the main one which is delivered by the AC voltage of 220 V and the frequency of 50 Hz and the second one is a photovoltaic panel of (12 V, 50 Wc). A rescue power supply battery is added. It is necessary to convert the alternative current delivered from the sector to the direct current in order to feed the LED. The battery is also charged continuously. The switch is used to control the microcontroller, the LED and the screen. The procedure is as follow: the LEDs are controlled by a microcontroller through an appropriated pilot. A keyboard is used to schedule the time of a treatment session; the task of the microcontroller is to analyze the input information and send the timing of the treatment session to the screen. The switch assists of choosing the type of treatment either SPT or IPT through the light intensity which is examined by the microcontroller type ATmega 2560.

The whole procedure can be completed through an algorithm in which the input data are introduced by the switch allowing the choice of the light intensity level and a keyboard determining the timing of the curing session. The command job is done by the microcontroller to control the LED pilot and LED. Then, the output data are the degree of the luminosity and the timing to be used for the exposition related to the curing.

Due to the fact that the standard values of the luminosity of LED in terms of irradiance are known, it is important to determine the power of the LED as a function of irradiance. The formula is given as [5]:

$$I_r = \alpha P. \quad (1)$$

where $P = UI$ and $\alpha = \frac{\eta}{K_{555} v(\lambda) S}$. U and I are the voltage and current through the LEDs, η in lm/W is the luminosity efficiency defined as the ratio between the visual energy flux

efficient for the human eye per unit time (θ_v) and the flux energy emitted (θ_e) by the lamps ($\eta = \frac{\theta_v}{\theta_e}$), K_{555} in lm/W is the conversion factor, $v(\lambda)$ is relative efficient luminosity (eye sensibility) and S is the illuminated surface. The unit of irradiance is $\mu\text{W}/\text{cm}^2/\text{nm}$.

The irradiance is proportional to the luminosity flux E in lm/m^2 by the formula,

$$I_r = \frac{E}{K_{555} v(\lambda)}, \quad (2)$$

where

$$E = K_{555} v(\lambda). \quad (3)$$

With $K_{555} = 683 \text{ lm/W}$ and $v(\lambda) = 0.038$ at 450 nm, U and I are known and it remains to determine the current I .

The luminosity flux can be also expressed as a function of the distance between the radiation source and the baby (baby-to-light distance: d) as follow:

$$E = \frac{I_c}{d^2} \quad (4)$$

where I_c is the luminosity intensity in candela.

To minimize the consumed energy, we chose to monitor the LEDs in PWM (pulse width modulation) mode. This is quite interesting for the high temperature countries. We also use the enriched MOSFET channel N working at zero temperature charge polarization point for optimum thermal stability.

The optimum characteristics of the LED are summarized in Table 3 [5]. The diffusion angle is 50° for the LED of 460 nm wavelength peak and the luminosity flux of 60 lm or 50 lm. The number of LED differs with the power and the consumed current.

The LEDs $3.2 \times 2.8 \text{ mm}$ SMD LED with ceramic substrate were used in this work and purchased from the Kingbright Electronic Europe company, under the part number KT-3228QB10ZS-RV blue.

Table 3 Optimum characteristics of LED at peak wavelength of 460 nm [7]

Wavelength (nm)	Luminosity flux (lm)	Power (W)	Consumed current (mA)	Supply voltage (V)	Diffusion angle	Number of LED
460	60	1.05	310	3.4	50°	6
460	50	1.26	370	3.4	50°	7

4 Results and discussion

Our DIPTA for neonatal jaundice treatment is shown in Fig. 2. It is composed of four main parts: three boxes made in wood containing, respectively, the LEDs, the electronic circuit, the switch + LCD screen and a frame holding a LED box.

The LED characteristics are following:

- Luminosity flux: 13 lm per LED;
- Diffusion angle: 120°;
- Number of LED: 13;
- Power supply voltage: 2.8–3.6 V;
- Maximum current intensity: 350 mA.

We have chosen to park the LEDs in wood box after taping in order to protect the LEDs from mechanical shock when transporting. The LEDs may be damaged if the boxes are dropped or receive a strong impact against them, so precautions must be taken to prevent any damage. The boxes are not water resistant and therefore must be kept away from water and moisture. The dimensions of the LEDs are 3.2 mm × 2.8 mm × 0.8 mm.

The properties of the designed apparatus are:

- Power energy: 14 W;
- Main supply voltage: (220–230) V;
- Solar panel: 12 V;
- Frequency: 50 Hz;
- Irradiance: (6.68–25.81) $\mu\text{W}/\text{cm}^2$;

Fig. 2 Designed and implemented phototherapy apparatus (DIPTA) for neonatal jaundice curing

- wavelength: (440–470) nm with a peak at 458 ± 1 nm;
- Operating temperature: 0–65 °C;
- Height: 180 cm.

Note that the values of the wavelength related to the spectral distribution and the brightness given above for the LEDs used in this work can be found in the datasheet of the supplier Kingbright electronic Europe [13]. The solar energy supply has been done following the practical principles of solar power supply and the use of solar panels in the houses.

The designed prototype has a higher brightness with two extrema levels of irradiance $6.68 \mu\text{W}/\text{cm}^2$ and $25.81 \mu\text{W}/\text{cm}^2$. It consumes a power energy of 14 W and allows to set the timing treatment. The type and timing of the PT can be read on the LCD screen. It is worth noting that the regulators were used to regulate the input voltage leading to the stability of our system and the fluctuations of the light for LEDs supplying could be avoided.

The designed apparatus cost is about 300,000 XAF equivalent to USD 508.55. Note that this price is cheap compared to that of the available apparatuses using LED lamps in Cameroon which are imported and almost cost 1,500,000 XAF equivalent to USD 2542.74 per unit. In addition, the halogen lamps apparatus for phototherapy treatment almost costs 500,000 XAF equivalent to USD 847.58. So, considering that the price given above for our design apparatus is that of the prototype, it is clear that the final product will be less expensive since it can be produced in series and the price of the imported components could be reduced.

A LCD display DIGITAL LUX METER with one silicon photo diode with filter (resolution of 1 Lux, accuracy of 4%) was used to determine the luminosity flux and deduce the irradiance. The irradiance train versus the distance baby-to-light is shown in Fig. 3. It is clearly seen that the irradiance is decreasing by increasing the distance baby-to-light as underlined in Refs. [1, 14]. At the highest distance ($d = 40$ cm), the irradiance is about $8.63 \mu\text{W}/\text{cm}^2$ whereas it corresponds to $13.49 \mu\text{W}/\text{cm}^2$ at $d = 30$ cm. These values correspond to the recommended values for SPT [14, 15]. Thus, our DIPTA can be used for SPT between 30 and 40 cm. At the lowest distance ($d = 20$ cm), the irradiance corresponds to $25.81 \mu\text{W}/\text{cm}^2$ and decreases to $18.30 \mu\text{W}/\text{cm}^2$ at 25 cm. Knowing that the minimum required value for the IPT is $30 \mu\text{W}/\text{cm}^2$ [14–16], we think that this DIPTA can be used for IPT at these distances if the curing timing is slightly increased considering the chosen distance.

Our aim was achieved by obtaining the improvement of the following devices:

- The fluorescent lamps were replaced by the LED lamps. The blue light LED with a wavelength in the range

Fig. 3 Train of irradiance as a function of baby-to-light distance. Full squares are the measured data points and the vertical lines are uncertainties bars

440–470 nm with a peak at 458 nm is used. It is known that the appropriated wavelength range for PT is 425–475 nm [8, 10, 14]. Thus, our chosen range is within the ideal range and is suitable for this type of treatment. The difference wavelength peak is 1 nm comparing to the peak of 460 nm in Ref. [2]. The wavelength range in that reference is 460–475 nm which is narrower than ours.

- The exposition intensity is adjustable. The secondary switch is used to monitor the irradiation intensity in order to choose the appropriated one depending on the level of jaundice. It is used also to set the timing exposition. The medical staff can adjust a minimum irradiance at $8.63 \mu\text{W}/\text{cm}^2$ or a maximum at $25.81 \mu\text{W}/\text{cm}^2$ in the wavelength range of 440–470 nm regarding the jaundice degree. The recommended values are 8–15 and ≥ 30 in $\mu\text{W}/\text{cm}^2/\text{nm}$, in the wavelength range of 430–490 nm respectively, for SPT and IPT [5, 11].
- The time of irradiation can be pre-set to avoid mistakes and carelessness and the corrections can be done without affecting the patient or the treatment efficacy.

In fact, the LEDs were selected to emit a narrow wavelength of blue light with a dominant peak at 458 ± 1 nm. The device provides the ability to cater the treatment by allowing to the caregiver to choose a low irradiance of $8.68 \mu\text{W}/\text{cm}^2$ or high irradiance of $25.81 \mu\text{W}/\text{cm}^2$. In addition, this designed phototherapy apparatus provides to the users more functions such as the adjustment of the light intensity, the possibility of setting the timing of the exposition, the suitable wavelength range with the rather good centered peak. This system reduced considerably the side effects of the PT. Knowing that the fluorescent lamp

provides a wavelength peak at 435 nm whereas the blue LED lamp provides a wavelength peak at 460 nm [2], in addition to others features, one can understand that our DIPTA with a centered wavelength at 458 ± 1 nm is more suitable comparing to the existing ones in our country.

The advantages are related to the fact that our apparatus can be used at any time even within the power cut period, in rural and urban zone. It is inexpensive, consumes low power and can be accessible to all hospitals. With the operating temperature up to 65 degree C, it can also be used in high temperature environment such as in the North and far-North regions.

5 Conclusion

The phototherapy is one of the most common interventions with a well-established efficacy and safety for the curing of the pre-term and term babies with neonatal jaundice. The application of this type of treatment requires enough knowledge of the basic principles of jaundice treatment. The suspected level of bilirubin in the infant is $\leq 300 \mu\text{mol/l}$ for standard phototherapy treatment and $> 300 \mu\text{mol/l}$ for the intensive phototherapy treatment. This treatment requires an appropriated phototherapy apparatus that can provide the blue light within the recommended wavelength range (430–490 nm) centered at about 460 nm. The need of that device is highly important so that we have designed and implemented our apparatus named DIPTA whose characteristics and properties are good for the use in the curing of the neonatal jaundice. The LEDs lamps of the luminosity Flux of 13 lm each was used to design our DIPTA. The prototype of the DIPTA and its working principle was described. Our designed apparatus can be used in the rural and urban zone and in the hot regions. It is cheap and consumes low energy, it can also be used within the power cut time. This designed phototherapy device provides to the caregivers' functions of: adjustment of the light irradiance, setting of the exposure time, the suitable wavelength range with the peak centered at 458 ± 1 nm, the timing treatment can be interrupted without risk if any mistake or in case of breast-feeding; the adjustable baby-to-light distance, the operating system with easy-used human machine interface. To conclude, a better design of the phototherapy apparatus with a rather good efficacy and safety characteristics is necessary to improve the jaundice hyperbilirubinemia diseases. We wish to improve the apparatus such as it can be used in normal conditions for the intensive phototherapy treatment.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interests.

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