ORIGINAL ARTICLE

Wearable Phototherapy Using Side Glow Fibre Optic for Homecare Neonatal Hyperbilirubinemia Treatment With Temperature Monitoring System

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ABSTRACT

Introduction: Hyperbilirubinemia is a condition in which there is too much bilirubin present in the blood. Hyperbilirubinemia is treated by using phototherapy that converts bilirubin into a simpler isomer via the photo-oxidation process. Most existing phototherapy devices are designed for inpatient hospital care and hence restrict the bonding time between mother and newborns during treatment. Thus, this study attempts to develop a portable phototherapy device based on fibre optics for hyperbilirubinemia treatment at home. **Methods:** The development process involved an electronic system for temperature monitoring and light engine system for fibre optics light source. Additionally, the mechanical system involved hooded blanket design and fibre optics strands placement. **Results:** The device is designed on hooded blanket with fiber optics strands for irradiance more than 31.06μ W/cm^2/nm, body surface area coverage of 80% and equipped with temperature monitoring that will trigger visual and audible alarm when body temperature exceeds 37.5 degree celcius. **Conclusion:** This study has successfully developed a Smart BiliWrap, a fibre optic based home care phototherapy device with temperature monitoring system.

Keywords: Neonatal hyperbilirubinemia, Wearable phototherapy device, Body surface area, Temperature monitoring system

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INTRODUCTION

An article published by The Star dated 20th November 2018 on hyperbilirubinemia stated that half of the Asian newborns develop neonatal hyperbilirubinemia at birth. This statement agrees with earlier study that reported neonatal hyperbilirubinemia affects one in two infants globally (1) as the study concluded that prevalence of neonatal jaundice in healthy term babies is 55.2%. Additionally, the crude birth rate of Malaysians in 2019 published in the latest vital statistics of Malaysia is 15 births over 1000 population (2). Looking at the crude birth rate statistics and the prevalence of hyperbilirubinemia, more research is needed to develop portable phototherapy devices to cope with the big number of cases each year. The shortage of advanced phototherapy devices that supports home treatment, simple, easy maintenance is one of the motivations for more research under this topic as current inpatient phototherapy sessions set at hospitals will isolate and limit intimate contact between newborns and their mothers (3). This makes home usage phototherapy among the best choice of designs. Recent study by Patterson et al in (26) concluded that home phototherapy could be a safe alternative to inpatient phototherapy for healthy term newborns with hyperbilirubinemia if daily checkups and 24/7 telephone support can be provided. Close monitoring of temperature of the infant is also very important (27). Hence, portable phototherapy devices, especially ones that are wearable, should be further developed.

Undoubtedly, there are many portable phototherapy devices available for home usage and were built on materials such as blankets and pads. However, most of them have uncomfortable designs and are heavy (4). On top of that, some phototherapy devices have low light intensity, and this will make phototherapy treatment sessions become longer. Prolong treatment may contribute to problems such as dehydration of neonates' skin, hypothermia, hyperthermia, rash, and a few more problems (5-6, 27).

Hence, this study came out with a prototype of a wearable phototherapy device that is suitable for home care. Research has been conducted including exploring the national Ministry of Health guideline for effective phototherapy devices in the development of this wearable phototherapy device for home care (25).

Hyperbilirubinemia or jaundice is translated as having too much bilirubin in the blood. Bilirubin is a yellow pigment by-product of red blood cells broken down by the liver before further broken in the intestines. Hyperbilirubinemia happened when the bilirubin failed to be processed and removed from the body. Consequently, it is left in the blood and causes yellow discolouration of the skin, mucous membranes, and the white of the eyes. Gradual bilirubin production in infants can lead to deafness and brain damage if it is left untreated (8). According to the Division of Family Health Development, Ministry of Health (2009), an infant suffers from hyperbilirubinemia if the concentration of bilirubin is above 85μmol/L (5mg/dL)(7).

The application of phototherapy in treating hyperbilirubinemia was introduced in the early 1950s in exchange for blood transfusion method. In a study by Lightner & Mcdonagh (9), phototherapy helps to break down bilirubin to its isomers via the photo-oxidation process. The resulting isomer is more polar and easily excreted. The broken-down bilirubin can be easily excreted by the liver through feces and urination.

A study by Vreman, Wong, & Stevenson shows, a phototherapy treatment would be most effective when using blue light at 450 to 470 nm wavelength (10). In addition, the American Academy of Pediatrics stated that high intensity phototherapy with spectral irradiance higher than 30μ W/cm²/nm is the most effective irradiance in lowering bilirubin (12). Irradiance is the number of photons exposed to the body surface area per square cm. High irradiance indicates higher efficacy of the device. Irradiance value above 30μ W/cm²/nm falls within the "plateau region" in which higher irradiance would not contribute to higher degradation of bilirubin. Besides, higher exposure of phototherapy to the body surface area, rather helps with reduction of bilirubin (15). Other than that, studies also add that intermittent treatment is better than long and continuous phototherapy in bilirubin reduction (10, 26-27).

Al-Alaiyan in his research explained that phototherapy can be divided into two which is conventional phototherapy and fiber optic phototherapy (13). Most fiber optic photo therapies have an irradiance up to 35μ W/cm²/nm (10,14). Romagnoli et al. measured bilirubin reduction per hour in fiber optic and conventional phototherapy and bilirubin levels are at 1.14 ± 0.73 and 12 ± 0.73 respectively (16). In special or severe cases of neonatal hyperbilirubinemia, a combination of conventional and fiber optic phototherapy is applied (17). Therefore, the irradiance is the total of both light sources.

Blue light emitting diode phototherapy devices has emerged as a new way of phototherapy. Additionally, consideration on the selection of fiber optic and the type of light in phototherapy design will greatly influence bilirubin degradation. Blue light emitting diodes (blue LED) is more efficient compared to conventional light (18). This is due to its narrow spectral light intensity which overlaps with the bilirubin absorption spectrum which is at 470 ± 60 nm (19, 24). In the context of producing a wearable phototherapy device, the blue LED light is the most preferred light source for fiber optics as it has the widest exposure, produces low heat and is durable thus, safe to be put very close to neonates, has the longest life span, and has the lowest energy consumption (20-21).

A typical session of phototherapy for term newborns aged 24-48 hours takes three to four hours with 30 minutes of break time for feeding and diaper changing. A long break should be avoided as it may raise the bilirubin level again. After four to six hours of intermittent or continuous phototherapy session, the bilirubin levels will be tested to ensure that the treatment is working. Once the bilirubin level reaches below 5 mg/dL, the phototherapy session will be stopped (22-23).

MATERIALS AND METHODS

Development of Smart BiliWrap Prototype

This study developed Smart BiliWrap, a wearable phototherapy device based on fibre optic strands on blankets as shown in Figure 1. The blanket hosts the light source of the phototherapy device and produces light intensity which complies with the American Academy of Pediatrics guideline. The blanket is also designed to allow blue light projection over body surface area to reach 80% coverage.

The development of Smart Bili Wrap was started by designing the blanket and followed by the process of selecting the best diameter of fibre optics.

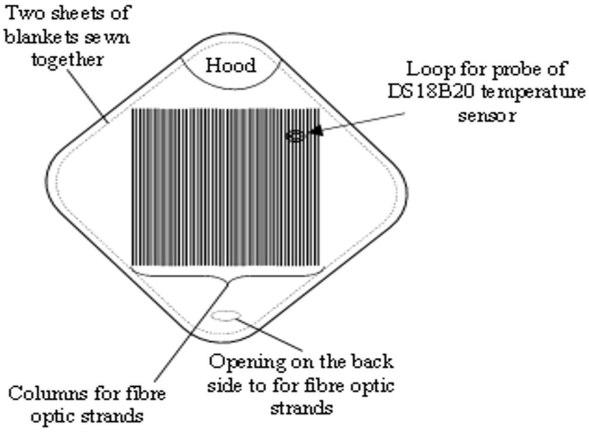

Figure 1 : Overall diagram of the Smart BiliWrap features.

A 100% Cotton material hooded blanket was chosen to host the fibre optic source. Cotton material is chosen for the blanket as it is thin and breathable to baby skin to reduce potential of skin rashes in neonates. Effective phototherapy devices are characterized by the ability to produce 80% light exposure to the body surface area of the neonates (10). Hence, by using a blanket, fiber optics strands emitting blue light can be easily sewn on the blanket and it can be wrapped around the body to receive direct emission of blue light during phototherapy. The blanket is aimed to be able to cover ventral and dorsal surfaces of the neonates as well.

2 pieces of similar blanket were sewn together around the same edges to have a hollow space in between the two blanket layers. Small vertical columns were sewn on the blanket so that it can be the compartments of the fiber optic strands. The number and the dimensions of the columns are based on the targeted irradiance following the formula for irradiance of each column. The formula of irradiance, *E* for a wavelength of a column surface is as Eq. (1).

$$E = P/(L\lambda) \qquad (1)$$

Where *P* is power dissipated from column surface area, *L* is surface area of the column, and λ is the wavelength of the blue LED light. The formula requires variables for power dissipated from column surface area, *P* and surface area of the column, *L*. Then, the irradiance formula is expanded to find the necessary variables for *P* and *L*. Refer to Eq. (2) and Eq. (3) for the formula.

$$P = (P_{max}/N_T).\, N_C \qquad (2)$$

Where P_{max} is the maximum power dissipation of the light engine, NT is the total number of fiber optic strands, and NC is the number of fiber optic strands in one column.

$$L = l - w \quad \text{Eq.} \quad (3)$$

Where *l* is the length of the column and *w* is the width of the column. Referring to the Eq. (2) and Eq. (3), the dimension of column and the number of fiber optic strands are very crucial in calculating the irradiance. Hence, the dimension of the column as well as the number of fiber strands to be used in this study are pre-determined during the design phase.

First, Eq. (3) is solved by estimating the possible length and width of the column. Estimation could be done by measuring the area of the blanket which will be used to host the fiber optic strands capable of exposing 80% of neonates body surface area. From the measurements, the overall blanket area is 70cmx50cm. To increase blue light emission, the number of columns available to host the fiber optics must be increased. From 50 cm blanket width, a total of 25 columns containing fibre optics strand were sewn.

The electrical system of the wearable phototherapy device is designed by integrating a few components including microcontroller, temperature sensor, switches and LCD screen. The Arduino Uno Rev 3 microcontroller which has 14 I/O digital pins is used and powered up using a 9V battery which is connected to the external power supply jack. The temperature sensor type DS18B20 is a single wire digital temperature sensor that measures up to 125 °C with a precision of ±0.5 °C. The function of the temperature sensor is to read the body temperature of the newborn. This sensor requires a 4.7 kΩ resistor from the DATA to VCC. 1602 LCD screen is also included to display the output signal by receiving a real-time input from the temperature sensor and displaying the inputs as programmed. The 1602 LCD screen displays real-time temperature which allows monitoring to be done by parents. Then, there is a buzzer that serves as an audible alarm when the body temperature exceeds 37.5 ^{o}C. Altogether, the components form a monitoring system for the wearable phototherapy device to meet the

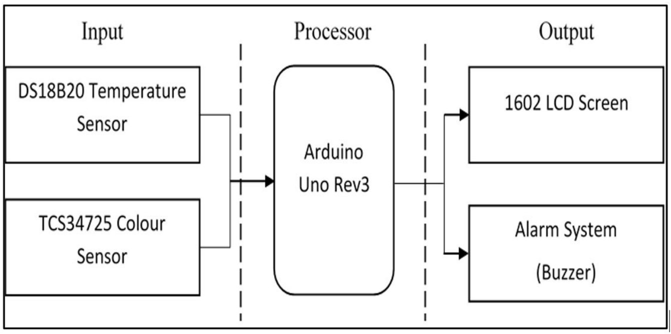

Figure 2 : Electronic components of Smart BiliWrap system.

home-based phototherapy system features. The block diagram of the whole monitoring system is shown in Figure 2.

The electrical part of the wearable phototherapy device also includes a light engine to light up the side glow fibre optics. The light engine is AC powered. The blue LED light is a 25W blue light with wavelength of 400 - 500 nm, is used to photo oxidize bilirubin and then degrade it. The PMMA based fiber optic strands were slid through every column on the blanket. The PMMA material makes it optically clear, lightweight and flexible. Then, the light engine is connected to the fiber optic strands at the bottom-end of the fiber optic strands and the probe of the DS18B20 temperature sensor was inserted into the loop made on the blanket.

Finally, the Smart BiliWrap phototherapy is ready for testing. The probe is brought to the human body and the 1602 LCD screen is monitored to check the outputs displayed. Then, the temperature also induced to become higher than 37.5 ^{o}C to test the alarm system.

RESULT

Irradiance

In this study, fiber optic strands with diameter of 0.5 mm which is the thinnest fiber optic strand available in the market were used. Considering that the strand will wrap around the neonates, thin fibre optics is preferable as to ensure comfortability. 20 fiber strands were inserted into each column. On the other hand, the P_{max} as in Eq. (2) is known from the specification of the light engine. The power dissipated from the light engine which is represented by the P_{max} is 25W. Naturally, the P for irradiance formula can be solved and the P in this study is 1W.

Finally, irradiance can be calculated as its L, P, and wavelength of the blue LED light, λ are known. In this study, the wavelength of the blue LED light used is 460 nm. By using the values that have been gathered, the irradiance of blue LED light from each column is evaluated as E = 31.06μ W/cm^2/nm. The design of the blanket is as shown in Figure 1.

Test Result

The Smart BiliWrap system was tested according to steps stated in the Materials and Method section. The system was run whilst at the same time the surrounding temperature is monitored.

Figure 3a shows the fully functional BiliWrap system that emits blue lights from fiber optics source in the range of 400-500nm for hyperbilirubinemia treatment. Irradiance of the BiliWrap system is 31.06μ W/cm^2/nm projected at 80% body surface area of the newborns.

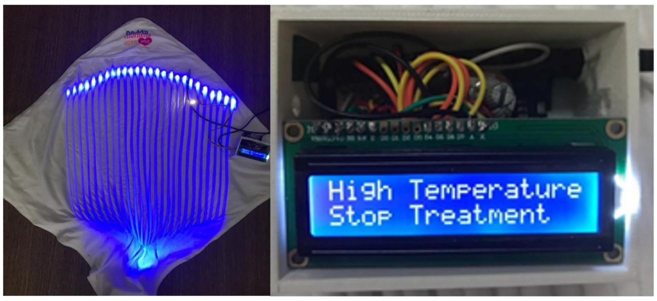

Figure 3a and 3b : Prototype of the operational Smart Biliwrap system during testing.

Right after the system is run, the temperature monitoring system displays the detected temperature in real time through the 1602 LCD screen. When the surrounding temperature is increased beyond 37.5 ^{o}C, the 1602 LCD screen displays 'high temperature' warning and commands asking users to 'Stop Treatment'. The 1602 LCD screen display during high temperature is as shown in Fig. 3a and 3b.

DISCUSSION

Smart BiliWrap is designed as a home care phototherapy device to allow treatment's flexibility and comfortability. The system consists of a hooded blanket, a temperature monitoring panel and a fiber optic light engine with a total weight of 900 grams. The overall size and weight are compact and make it portable to be carried around. Commonly, newborns are wrapped in a blanket to keep them warm and are carried in their mother's arms during breastfeeding. Therefore, Smart BiliWrap has all the features that encourage bonding between mother and newborn while undergoing treatment at home.

In terms of electrical design, the Smart BiliWrap is already equipped with temperature sensors and

LCD monitor, and could be improvised in the future by adding a vital sign monitor as well. Additionally, this prototype is not equipped with a timer. In future, a time can be introduced and an algorithm could be added to control the duration of the phototherapy treatment.

All these points make Smart BiliWrap suitable to be applied as a homecare phototherapy device to treat hyperbilirubinemia at home. Concurrently, serum bilirubin level monitoring can be done by visiting nearest healthcare centers without the need for the newborn to be admitted to hospital.

CONCLUSION

In conclusion, Smart BiliWrap provides effective phototherapy from blue light in the range of 460 to 500 nm wavelength delivered at an irradiance of 30 to 35 μW/cm²/nm and projected up to 80% BSA of neonates. Smart BiliWrap uses side glow fiber optic strands that project blue LED light at wavelengths of 460 to 470 nm, at an irradiance of 31.06μ W/cm²/nm. Meanwhile, the Smart BiliWrap blanket covers both dorsal and ventral sides of neonates.

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