TEMPERATURE DEPENDENCE OF LED AND ITS THEORETICAL EFFECT ON PULSE OXIMETRY

K. J. REYNOLDS, J. P. DE KOCK, L. TARASSENKO AND J. T. B. MOYLE

SUMMARY

Ambient temperature is known to affect the emission spectrum of a light-emitting diode (LED). This study has investigated the effect of changes in ambient temperature on the emission spectra of two LED with peak emission wavelengths similar to those used in pulse oximetry. There was a 5.5-nm increase in the peak wavelength for a 660-nm LED, and a 7.8-nm increase in the peak wavelength for a 950-nm LED as temperature increased from 0 to 50 °C. Using a simple theoretical model based on the Beer–Lambert law, the effect of these shifts in wavelength on pulse oximeter accuracy was examined and found to be negligible over the temperature range studied.

KEY WORDS

Equipment: pulse oximeters Monitoring: pulse oximeters.

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Table II. Electro-optical LED characteristics

<table>
<thead>
<tr>
<th>LED type</th>
<th>Wavelength (nm)</th>
<th>Output power</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLMP 7005</td>
<td>660</td>
<td>500 mcd at 50 mA</td>
</tr>
<tr>
<td>TSUS 5402</td>
<td>950</td>
<td>15 mW at 100 mA</td>
</tr>
</tbody>
</table>

A theoretical model was then used to predict the effect of these shifts on the accuracy of pulse oximeter saturation readings.

MATERIALS AND METHODS

The spectra of the LED were measured using a Czerny–Turner type monochromator. Two LED were investigated (table II): one with peak emission wavelength, \( \lambda_{\text{peak}} \), at a nominal 660 nm (R), and one with \( \lambda_{\text{peak}} \) at 950 nm (IR), these wavelengths being typical of those used in pulse oximetry. Each LED in turn was mounted in a holder in front of the spectrometer, and was modulated with a square wave signal at 1 kHz. The modulating signal had a 50 % duty cycle, and the maximum current specified on the data sheet (table II) was passed through the LED during the “on” part of the cycle. The LED in commercial pulse oximeters are pulsed typically at between 0.5 and 1.5 kHz, with a duty cycle of 2–50 % depending on the make of oximeter. A 50 % duty cycle was chosen for our experiments, as the heating effect is greatest under these conditions.

The light from the LED was focused through the input slit of the spectrometer and, by varying the angle of incidence onto a reflection grating, a range of wavelengths from 600 nm to 1000 nm was obtained. The spectrometer uses a germanium photodiode to measure the output light intensity at each wavelength. A transimpedance and lock-in amplifier completed the arrangement (fig. 1).

The holder in which the LED were mounted contained a hollow channel through which water from a temperature controlled reservoir was pumped (fig. 2). The walls of the holder were very thin in order to optimize thermal contact between the water and the LED. By adjusting the temperature of the water in the reservoir, the ambient temperature of the LED was changed. The water temperature in the reservoir was measured using a mercury-in-glass thermometer.
Wavelength (nm)

Fig. 3. Shift in emission spectrum of red LED as ambient temperature is increased from 0 °C to 50 °C in 10-°C steps. Immersed up to 10 cm. To minimize heat loss through the circuit, distances between the LED holder and the reservoir were small, and the temperature difference between water at the inlet and outlet of the reservoir was checked and found to be less than 1 °C.

The spectrum of each LED was measured at 2-nm intervals at ambient temperatures of 0, 10, 20, 30, 40 and 50 °C. The system was allowed to equilibrate for 10 min between the measurement of each spectrum.

Theoretical model to examine the effect of spectral shifts on pulse oximeter reading

As pulse oximeters are calibrated when the two LED are operating at their nominal wavelengths, it is possible that shifts in wavelength lead to inaccuracies in the oxygen saturation reading from the pulse oximeter (SpO₂). In order to estimate the error caused by a change in ambient temperature from 0 to 50 °C, we derived, as a first approximation, a simple mathematical relationship based on the Beer–Lambert law. This law relates the optical density (OD) of an absorbing (but non-scattering) solution to the concentration of absorber by

$$\text{OD} = \log_{10} \left( \frac{I_0}{I} \right) = e cd$$

where I₀ and I are the incident and transmitted light intensities respectively, through a sample of depth d, concentration c, and having an extinction coefficient e.

For a solution containing n absorbers:

$$\text{total absorption} = \sum_{i=1}^{n} e_i c_i d_i$$

The ratio of the absorption at two wavelengths, 1 and 2, is:

$$\frac{R}{IR} = \beta = \frac{\sum_{i=1}^{n} e_i c_i d_i}{\sum_{i=1}^{n} e_{i0} c_i d_i}$$

With two species of haemoglobin, oxygenated (subscript o) and reduced (subscript r), occupying the same depth, this becomes:

$$\beta = \frac{e_{10} c_{10} + e_{1r} c_{1r}}{e_{20} c_{20} + e_{2r} c_{2r}}$$

(1)

If we define the saturation of a species i as $$S_i = \left( \frac{c_i}{c} \right)$$, where c is the total haemoglobin concentration, then we have:

$$\beta = \frac{S_{o1} e_{11} + S_{o10}}{S_{r1} e_{11} + S_{r10}}$$

Now $$S_r = 1 - S_o$$. Substituting into (1) and rearranging gives:

$$S_o = \frac{S_{p0} e_{11} - \beta e_{2r}}{e_{1r} - e_{10} + \beta (e_{20} - e_{2r})}$$

(2)

which is the theoretical relationship for the oxygen saturation of blood when scattering is neglected. It should be remembered that SpO₂ is expressed normally as a percentage, and equation (2) should therefore be multiplied by 100%.

Calculation of the effective extinction coefficients

While LED have narrow-band spectral outputs, they cannot be considered to be monochromatic. It is preferable, therefore, to compute “effective extinction coefficients” for oxyhaemoglobin (HbO₂) and deoxyhaemoglobin (Hb), taking into account the spectral distribution, rather than using the values of extinction coefficients at the peak emission wavelengths. The effective extinction coefficients are computed by summing the products of the normalized LED intensity value and the extinction coefficient every 2 nm over the whole spectrum. That is:

$$e^{\text{eff}} = \sum_{\lambda} I(\lambda) e(\lambda)$$
The extinction coefficients, $\varepsilon(\lambda)$, of HbO$_2$ and Hb were obtained previously at 2-nm intervals using a Shimadzu UV-160 double beam scanning spectrophotometer [6].

**RESULTS**

The measured spectra for the red and infra-red LED, respectively, are shown in figures 3 and 4. Each spectrum has been normalized by setting the sum of the intensity values, $I(\lambda)$, measured at 2-nm intervals, equal to 1. The results in figure 3 show a steady increase in peak emission wavelength of the red LED as temperature is increased from 0 to 50 °C, with an overall shift of 5.5 nm. Figure 4 shows a shift of the infra-red spectrum of 7.8 nm in the same direction for the same increase in temperature.

![Shift in emission spectrum of infra-red LED as ambient temperature is increased from 0 °C to 50 °C in 10-°C steps.](image)

From figures 3 and 4, the half-intensity spectral bandwidths may be measured to be 25 nm for the red LED and 55 nm for the infra-red LED, although the spectral bandwidth did not change significantly with either LED. The effective extinction coefficients of HbO$_2$ and Hb at each temperature were evaluated using the method described. These values (table III) were substituted into equation (2), and the values of $S_{\text{PO}_2}$ calculated from this equation were plotted against the $R/IR$ ratio at 0 and 50 °C (fig. 5).

**DISCUSSION**

A shift of 5.5 nm in red LED peak wavelength, and of 7.8 nm in infra-red LED peak wavelength caused negligible change in the value of $S_{\text{PO}_2}$.

**Table III. Effective extinction coefficients of oxyhaemoglobin (HbO$_2$) and reduced haemoglobin (Hb)**

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Red</th>
<th></th>
<th></th>
<th></th>
<th>Infra-red</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HbO$_2$</td>
<td>Hb</td>
<td>HbO$_2$</td>
<td>Hb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_{10}$</td>
<td>$\varepsilon_{1r}$</td>
<td>$\varepsilon_{10}$</td>
<td>$\varepsilon_{1r}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.123</td>
<td>0.856</td>
<td>0.274</td>
<td>0.153</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.122</td>
<td>0.849</td>
<td>0.273</td>
<td>0.151</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.121</td>
<td>0.845</td>
<td>0.271</td>
<td>0.148</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.119</td>
<td>0.832</td>
<td>0.269</td>
<td>0.145</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.118</td>
<td>0.823</td>
<td>0.267</td>
<td>0.141</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.117</td>
<td>0.811</td>
<td>0.265</td>
<td>0.139</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

![Pulse oximeter saturation reading ($S_{\text{PO}_2}$) plotted against red/infra-red ratio ($R/IR$) according to equation (2), at ambient temperatures of 0 °C and 50 °C. Equation (2) was derived using the Beer–Lambert law.](image)
calculated from equation (2) (fig. 5). Thus, to a first approximation, a change in the ambient temperature of the LED from 0 to 50 °C should not affect the accuracy of pulse oximeter readings.

The temperature dependence of the energy gap of semiconductors is well documented [3, 4]. The standard deviation of the energy gap at room temperature is approximately 0.1 % [7], and for a given change in temperature, the uncertainty in the magnitude of the wavelength shift is of the same order of magnitude. This spread of values for wavelength shift is small enough not to affect our conclusion. In contrast, there is a variation of up to ±15 nm in the peak wavelength of different LED of the same type, because of production tolerances. This problem is overcome in commercial pulse oximeters by the inclusion of a coding resistor in the probe connector which allows the oximeter to select a calibration curve appropriate to the wavelengths of the LED in that particular probe [8].

It should be remembered that the relationship between $S_{PO}$ and $R/IR$, $\beta$, given in equation (2), was derived using the Beer–Lambert law. However, it is well-known that whole blood does not behave as a simple absorbing substance, and that light is scattered repeatedly by the red blood cells [9]. Thus equation (2) is only an approximation and pulse oximeters are usually calibrated empirically using data obtained by inducing hypoxia in healthy volunteers. Nonetheless, the model based on equation (2) does give a good indication of the effect of changes in extinction coefficients on the estimation of $S_{PO}$. It is unlikely, therefore, that the shift of LED emission spectra with ambient temperature affects the pulse oximeter reading in most clinical situations.

Other factors, however, may cause inaccuracies in $S_{PO}$ readings at extreme temperatures. In states of extreme cold, for example, there is a generalized cutaneous vasoconstriction and reduced blood flow, while in hot temperatures vasodilatation occurs and blood flow is increased. These effects are particularly marked in the extremities of the body, for example in the finger. Vasoconstriction of the peripheral vascular bed induced by cold exposure may reduce significantly the amplitude of the a.c. signals received by the pulse oximeter [10]. While there is little conclusive evidence on the effects of perfusion on pulse oximetry, the failure of any signal to be detected in states of low perfusion has been noted on several occasions [11–15].

The reduced amplitude of the a.c. signals occurring during cold exposure causes the pulse oximeter to be more sensitive to motion artefacts, for example those caused by shivering or coughing. These artefacts may cause the pulse oximeter to give an erroneous value of $S_{PO}$ [16].

Further consequences of exposure of the body to cold temperatures include a reduced oxygen uptake by the cold skin, and a cold induced shift to the left of the $HbO_2$ dissociation curve. This causes the oxygen saturation of the blood to increase, especially in the extremities of the body which are at a lesser temperature than the core temperature. Thus the oxygen saturation measured across the finger by a pulse oximeter may not give a correct indication of the oxygen saturation of the blood in the main body circulation, even though it may be giving a correct value for the saturation of the blood in the finger.

We conclude that inaccuracies in pulse oximeter readings in extreme temperatures are far more likely to be caused by changes in peripheral perfusion, rather than a result of the temperature dependence of the light sources in the pulse oximeter probe.

REFERENCES
7. Thurmond CD. The standard thermodynamic functions for the formation of electrons and holes in Ge, Si, GaAs, and GaP. Journal of the Electrochemical Society 1975; 122: 1133–1141.


