

Assessment of a low-cost LED vein detection method

Initial proof of concept

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Abstract: Venepuncture is one of the most common invasive procedures in medical healthcare worldwide, however failure rates are still relatively high, particularly for paediatric, geriatric, darker skinned, and obese patients. Visualisation of the veins has been shown to decrease failure rates and can be achieved through trans-illumination, near infrared reflectance, or sonography. However, these techniques are either not reliable or very expensive, resulting in them not being commonly used in the clinical workplace. This paper develops a proof of concept low-cost LED vein detection device using photocurrent generated by LEDs in reverse bias. The prototype uses two emitting LEDs and one detecting LED to identify the location of a vein via trans-illumination and reflectance. Various light intensities and wavelengths of the LEDs are tested in regard to resolution, noise, and signal peaks. A balance between system noise and resolution is identified for each LED in relation to the emitted intensity. No significant difference was observed in relative peak height when different wavelengths were used to identify the same superficial veins. The initial proof of concept proves the LED vein detection method and provides the foundation for further low-cost LED vein detection devices to be developed.

Keywords: Venipuncture, Trans-illumination, Medical Imaging, Low-cost.

1. INTRODUCTION

Venepuncture is one of the most common invasive procedures in medical healthcare worldwide, with over 90 % of admitted hospital patients requiring this procedure to be performed (Juric et al., 2014). Although this procedure is very common, failure rates as high as 30-50% are reported, particularly in paediatric, geriatric, darker skinned, and obese patients (Balter et al., 2015; Fukuroku et al., 2016).

Difficult peripheral Venous Access (DiVA) is a medical situation in which the veins are non-visible and non-palpable, thus requiring a highly experienced clinician and technical aids for successful venepuncture (Sou et al., 2017). Patients with DiVA may undergo multiple painful attempts to gain peripheral venous access, with each failed attempt comprising the patient's confidence and trust in the nursing staff (Fukuroku et al., 2016; Sou et al., 2017), and heightening their anxiety, leading to further potential complications (Walsh, 2008).

Currently, localisation of a vein is performed via palpation and viewing the intended puncture site. A tourniquet is also commonly used to improve visualisation through engorgement of the veins. Once a vein is located, its location is memorised, and the site sterilised with alcohol wipes. This procedure is strongly dependent on clinician skill and is not always successful. Consequently, a number of imaging tools have been developed in an attempt to improve vascular visibility. Specifically, trans-illumination (Cuper et al., 2011; Mullani, 2011; Paul Dryden, 2005), near infrared reflectance (NIR) (AccuVein, 2012; Juric et al., 2014; Shahzad et al., 2014) or

sonography (Fukuroku et al., 2016; Gottlieb et al., 2017) imaging are the most common techniques to improve vascular visibility.

Trans-illumination involves placing a light source (commonly 580-640 nm (Cuper et al., 2011; Mullani, 2011; Paul Dryden, 2005)) beside or underneath the vein, and, due to the deoxygenated haemoglobin in the blood absorbing more light than the surrounding tissue, the veins appear darker to the clinician. However, this procedure does not generate a strong contrast between vein and tissue, and direct contact with patient skin is required for effective visibility, thus requiring disinfection after each use (Shahzad et al., 2014).

NIR systems use a near infrared red light source, an infrared sensitive camera, and image processing unit to visualise the veins. The processed IR image is then shown on a screen or re-projected onto the patient themselves. The procedure of NIR is shown to be one of the most promising approaches for improving venepuncture success rates (Juric et al., 2014; Shahzad et al., 2014), however, due to these systems costing over 2,000 USD they are rarely accessible and used for regular clinical use. Similarly, sonography can be used for needle placement, however, due to the high complexity and costs of such devices, they are also rarely used regularly in the clinical setting for venepuncture assistance.

Alternatively, standard low-cost Light Emitting Diodes (LEDs) are able to act as both an emitter and detector using relatively simple low-cost electronics (O'Toole et al., 2008; Radovan Stojanovic et al., 2013). This paper looks into using principles of trans-illumination and reflectance with standard

LEDs to develop an initial proof of concept LED vein detection device. In particular, the influence of wavelength and light intensity are investigated in regard to signal noise and strength.

2. METHODS

2.1 LED as a detector

When an LED is operated in reverse bias and is excited by an external light source a current is generated, dependent on the light intensity (photoelectric effect). Each LED commonly has a band of peak *excitation* wavelengths slightly shorter than their peak *emission* wavelength (Dietz et al., 2003; R. Stojanovic et al., 2007; Radovan Stojanovic et al., 2013). The photocurrent generated by the LED is typically small (approx. 30 μ A), and its behaviour can be simply modelled as a capacitor (LED capacitance) in parallel with a current source (Dietz et al., 2003), see Fig. 1. As a result, the discharge time of a reverse biased LED is directly proportional to the external light intensity.

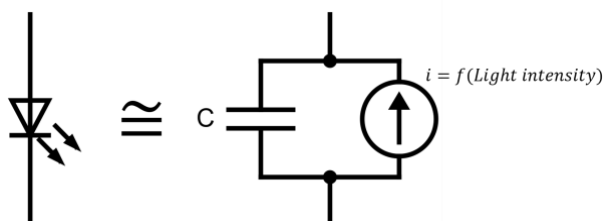


Fig. 1. Simple model for LED in reverse bias.

Although LEDs are not optimised to be light detectors, they provide an inexpensive and widely accessible alternative to dedicated photodiodes (O'Toole et al., 2008). In addition, their ability to both emit and detect light enables potentially more compact future versions of the device. Therefore, the use of only a single type of LED will be the focus of this paper.

2.2 Initial prototype design

To maintain system simplicity, reduce component costs, and provide an initial proof of concept, the system was designed and operated as follows (see Fig. 2):

1. Two 3 mm LEDs, either side of the detecting LED, were excited trans-illuminating the surrounding tissue and in particular, the tissue directly below the detecting LED. In parallel, the detecting LED's (reverse biased LED) internal capacitance is charged to 5 V (logic level of the microcontroller used).
2. The detecting LED is then switched to be a digital input and time to reach logic 0 (internal capacitance discharge time) measured. Note the microcontroller used has a logic 0 threshold of 2.1 V (Atmel, 2015).
3. This process is then repeated to provide a continuous measurement of the detected light intensity.

The prototype uses the same type of 3 mm LEDs for both the emitting and detecting LEDs. An Arduino Nano v2.3 was used as the microcontroller. The final prototype can be seen in Fig. 2.

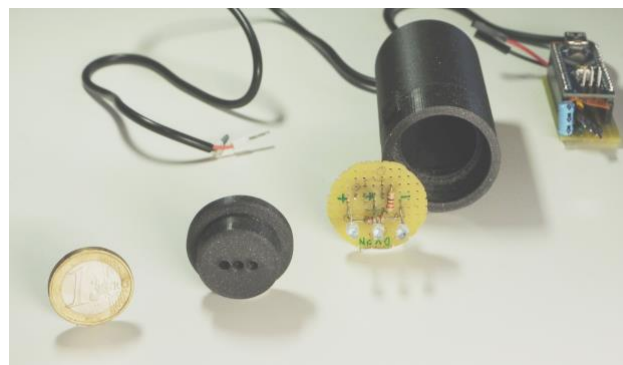


Fig. 2. From left to right: 1 Euro coin, sensor/LED alignment head, LED-module, system casing and custom Arduino Nano module.



Fig. 3. Example experimental setup with positioning guide on the back of the hand.

2.2 Experimental setup

To assess the ability of the LED vein detection prototype to detect a vein it was tested on the back of the hand. A positioning scale was placed on the back of the hand to provide a guide when moving the LED vein detector across the skin surface, as seen in Fig. 3. During this procedure no tourniquet was used.

Using this setup, the influence of the light intensity of the trans-illuminating LEDs (I_e) and the wavelength of the LEDs were investigated. In particular, the LED detector discharge times across the hand were measured for different light intensities (forward current), I_e , of the emitting LEDs (875 nm), and six different wavelength LEDs (see Table 1). Specifically focusing on the influence on the signal peaks (over a vein) and resolution (in relation to the timing of the microcontroller used). Note, the forward current through the emitting LEDs was controlled via an external power supply.

Table 1. Properties of the LEDs investigated.

Wavelength (nm)	Rated Intensity, I_e
588	5000 mcd
611	7800 mcd
632	5000 mcd
660	4500 mcd
850	30 mW/sr
875	30 mW/sr

3. RESULTS

3.1 Signal conversion

As each LED used had different electrical properties in terms of capacitance and luminosity, direct comparison of the discharge times was not possible. Therefore, for fair comparison of the received signal, a relation of the measured light intensity (I_r) and discharge time (t_d) was determined for each LED tested. This was done by placing one emitting LED directly in front of the detecting LED in a light impermeable tube. The intensity of the emitting LED (I_e) was then varied. With the assumption that approximately all of the emitted light (I_e) fell onto the receiving LED, a relationship between discharge time (t_d) and received light intensity (I_r) was determined for each LED. An example relationship can be seen in Fig. 4.

3.2 Influence of trans-illuminating LED intensity

The measured discharge time and associated light intensity (I_r) was measured for various trans-illumination LED intensities (I_e), see Fig. 6 for reference, on the back of the hand is shown in the top of Fig. 5. For further comparison, the signals were normalised based on their *baseline* value, where the *baseline* value is the average measured intensity when on tissue and ‘not over a vein’ (subjectively determined retrospectively). Fig. 5 shows that the absolute peak difference in the received signal, I_r , is dependent on the emitting LED

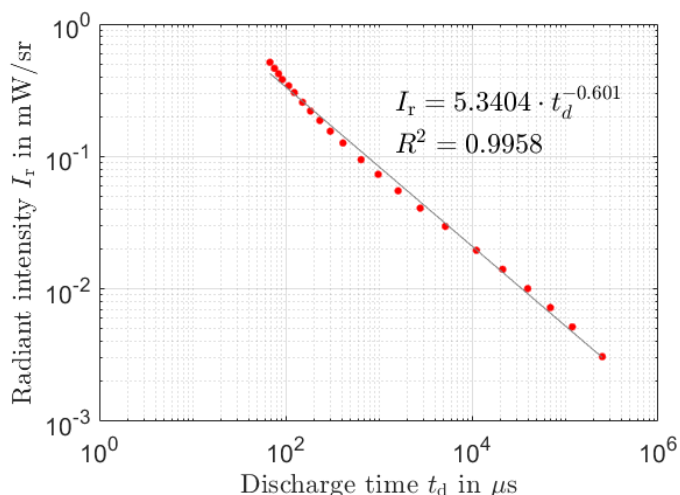


Fig. 4. Example relationship between radiant intensity received and discharge time for an 875 nm LED.

intensity, I_e . However, the normalised peak difference is similar for all emitted intensities. Note, only four of the seven emission intensities were plotted to improve interpretability of the figure. Furthermore, the resolution decreases for higher emitting LED intensities due to the limited microcontroller timing resolution (8 μ s). Conversely, the variation at a single point (noise) within the measured values was seen to decrease with higher emitting LED intensities.

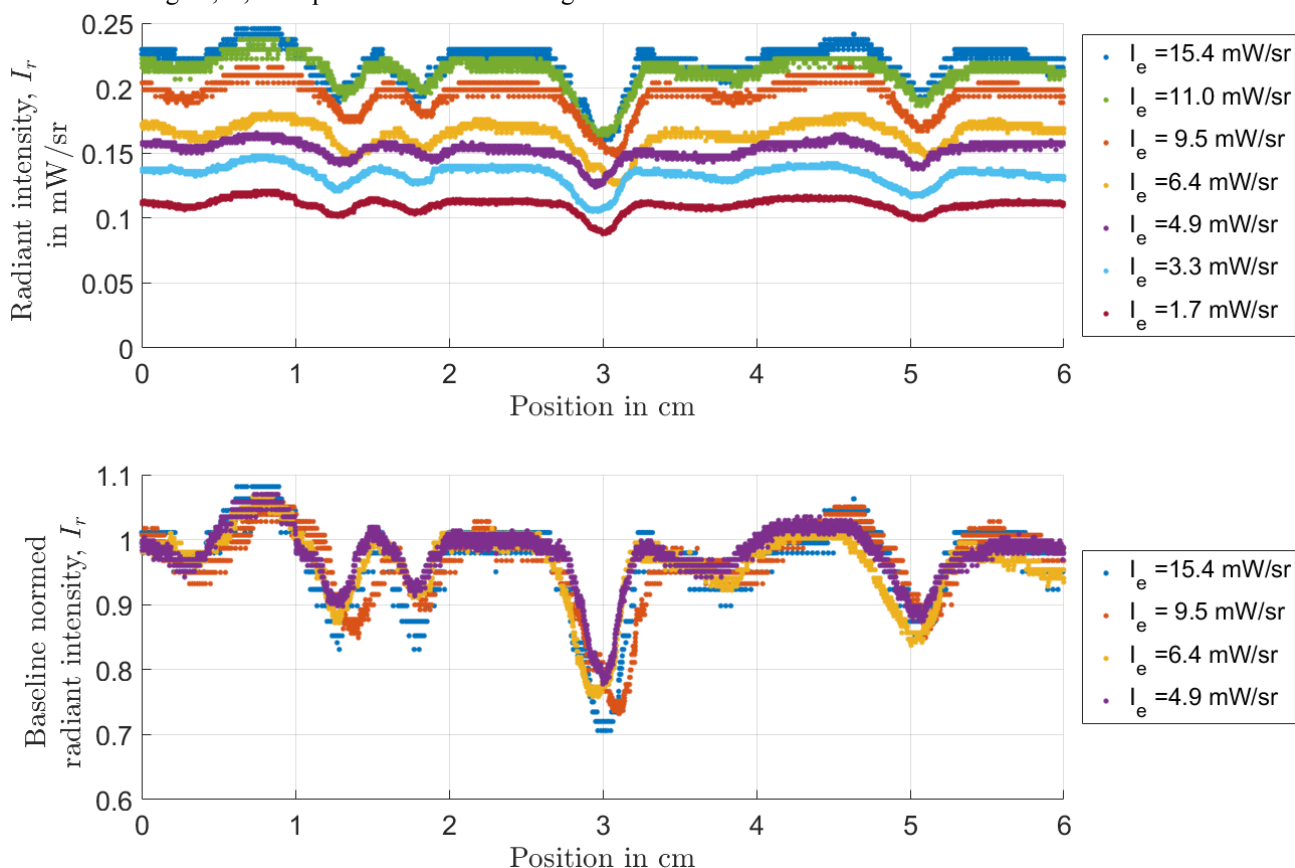


Fig. 5. The observed relationship between emitting LED radiant intensity, I_e , and measured radiant intensity, I_r . (Top) The absolute change in measured radiant intensity, I_r , across the back of the hand for seven different emitting LED radiant intensities, I_e . (Bottom). The same measurements normalised based on the average reading ‘off vein’ (baseline value).

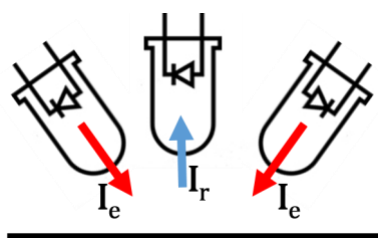


Fig. 6. Schematic of the LED light intensities received, I_r , and emitted, I_e .

Thus, for further analysis the standard deviation of the normalised baseline value at 2.5 cm (high frequency noise) is compared with the received light intensity, see Fig. 7. Note, it assumed that the low frequency fluctuations in the signal at other positions along the hand are a result of underlying venous structures. In addition, the minimum step size (resolution) in the baseline normed intensity is also plotted against the received light intensity in Fig. 7. For this LED (875 nm), it can be seen that there is a point (0.14 mW/sr) in which the minimum step size is approximately equal to the expected 'noise'.

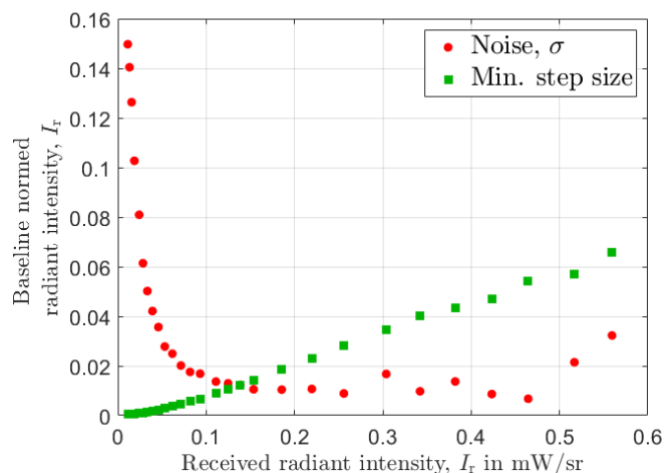


Fig. 7. Relationship between received light intensity, the minimum step size, and noise measured for an 875 nm LED.

3.3 Influence of LED wavelength

The measured discharge time and associated detected light intensity was measured for six different wavelength LEDs on the back of the hand (five times per LED). The intensity of the trans-illuminating LEDs was adjusted such that the noise and minimum step size were equal, as shown in Fig. 7. The baseline normalised peak heights were then compared for four different prominent veins on the back of the hand (varying in size and depth), as seen in Fig. 3 and through a thermal imaging camera in Fig. 8 (FLIR Systems Inc., T420, Wilsonville, OR, USA).

The mean and standard deviation of the peak heights for each of the different wavelength LEDs tested is shown Fig. 9. Here it can be seen that each of the different wavelength LEDs generate a relatively consistent sized peaks in all of the five tests performed. However, no obvious trend in peak height could be seen when using a different wavelength LED.

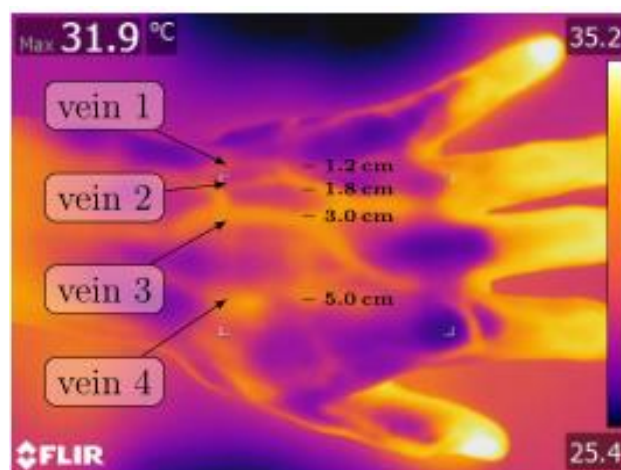


Fig. 8. The four prominent veins, whose absorption peaks were compared for the six different wavelength LEDs tested, seen through a thermal imaging camera (FLIR Systems Inc., T420, Wilsonville, OR, USA).

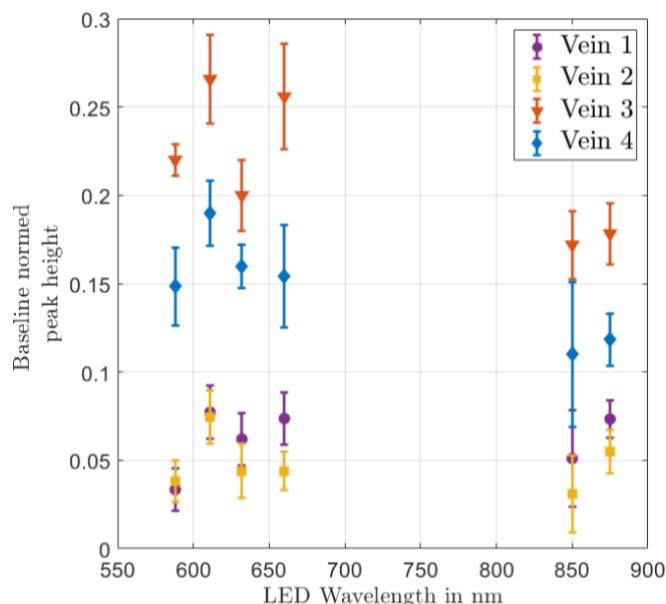


Fig. 9. Relationship between the baseline normed peak height and the wavelength of the LEDs used for four different veins on the back of the hand.

4. DISCUSSION

4.1 System performance

From Fig. 5 it can be seen that the initial LED vein detection prototype is able to easily detect superficial veins on the back of the hand, with relative changes in the received light intensity (I_r) of greater than 10%. This drop in the reflected LED light is likely due to trans-illuminating light being absorbed by the deoxygenated haemoglobin present in the veins, as seen in the trans-illuminated and near infrared reflectance vein visualizers. In contrast, the tissue scatters and reflects more of the trans-illuminating light back to the light sensing LED, leading to a higher measured light intensity when on the tissue. In addition, the relative change observed when over a superficial vein is considerably larger than the 'noise' observed when the sensor is held stationary on the hand.

Conversion of the discharge times into received light intensity from the emission relationship was shown to be necessary to fairly compare all of the LEDs tested. An exponential relationship was fitted for all of the LEDs tested, with all equations having an $R_2 > 0.95$. However, this relationship is assuming that light emitted from the LED is proportional to the forward current as stated on the respective LED datasheet, and that all of the emitted light reaches the sensor LED. Thus, the relationship determined does not perfectly represent 'actual' amount of light received in relation to the LED discharge time. However, the relationship determined for a single LED was seen to be consistent in repeated tests and within multiple versions of the same LED model. Thus, providing a relatively reliable characterisation of the LED sensor.

4.1 Influence of trans-illuminating LED intensity

After normalisation of the changes in measured light intensity, the trans-illuminating LED intensity was shown to have no considerable influence on the relative change in measured light intensity (Fig. 5). As the emitted light intensity increases it would be expected that there is a larger relative difference in measured light intensity, due to more light being reflected and absorbed by the skin and vein, respectively. However, this relationship was not observed and may be the result of the skin above the vein also reflecting more light when the emitting LED intensity is increased, as a result, the relative change in measured light intensity is the same.

However, the trans-illumination LED intensity was shown to influence the 'noise' seen in the measurement and the amount of discretisation, as a result of system limitations. As the initial prototype uses an Arduino Nano with a 16 MHz clock, and accounting for code execution time, the system was only able to measure to a resolution of 8 μ s. Therefore, discharge times of the LED and their respective light intensities (high) were only able to be distinguished into steps of this size, as seen by the larger steps present when higher light intensities are used in Fig. 5. Thus, as a result of the microcontroller used, the system had a limited resolution of measured light intensity which is apparent at high received light intensities.

Conversely, the relative variation in the measured light intensity on a single point, assumed to be system 'noise' was seen to decrease exponentially with increased received light intensity (Fig. 7.). This is likely the result of the LED sensor measuring light intensities much higher than the background light intensities, and similarly, lower measured light intensities are more influenced by background light sources. Therefore, to reduce the influence of the background light the trans-illuminating LED intensity should be above 0.1 mW/Sr.

4.3 Influence of LED wavelength

The LED wavelengths investigated were designed to cover the range of typically available commercial LEDs. From the six different LEDs tested, no obvious trend between wavelength and relative peak size when 'on the vein' could be observed (Fig. 9). Conversely, previous studies have shown wavelength to be directly related to penetration depth up until approximately 900 nm (Barolet, 2008; Goh et al., 2017; Taroni

et al., 2003). However, this lack of trend may be due to the veins being investigated being all relatively superficial (Fig. 3 and 8). Thus, lying directly below the epidermis at a depth at which all of the wavelengths tested were able to reach. Therefore, the resulting relative change in peak height was similar.

Additionally, the relative peak height can be seen to be consistently ordered and of approximately similar magnitude (excluding veins 3 and 4) across the wavelengths tested. As the relative peak height is expected to be related to both the depth and size of the veins, the consistent peak heights supports the idea in which all of the wavelengths were able to adequately reach the depths of all of the veins investigated.

A slight decrease in the peak signal height is observed in veins 3 and 4 (the most superficial veins) when the wavelengths above 800 nm was used (Fig. 9). This is likely a result of the absorption coefficient for deoxygenated haemoglobin decreasing as the wavelength increases (Barolet, 2008; Taroni et al., 2003). Thus, the relative change in measured light intensity decreases for the higher wavelengths (> 800 nm).

Within the repeated measurements of one wavelength LED on a single vein, the variation in the peak size can be seen to be relatively consistent, with a maximum relative peak size variation of 5 % (Fig. 9). Therefore, showing the repeatability of the initial LED vein detection prototype is sufficient for reliable superficial vein detection.

4.4 Limitations and future work

Although attempts were made to buy similar 3 mm LEDs and characterise the LED behaviour as a sensor and emitter, variations in the LED construction were still present. In particular, each type of LED had a different field of view (FOV) and diffusor, factors which were not able to be controlled in the purchasing of commercial LEDs. These differences in optical properties can change the trans-illumination and LED light sensor's most sensitive direction. In addition, the response to different intensities of external light will likely vary with different diffusors. However, as setup always used the same type of LED for both the emitter and receiver, and the behaviour of the LED was first characterised in a tube impermeable to light, the influence of these factors were minimised.

For the application of real-time detection of veins further investigation is needed. Specifically, the identification of the baseline value (currently determined subjectively and retrospectively). Future work will look into a calibration procedure on various points of the tissue to estimate this value. In addition, the identification and removal of the underlying high frequency noise needs to be further considered through potential low-pass filtering methods.

The initial LED vein detection prototype proved to be functional and able to reliably detect veins in a simple experimental setup on the back of a hand. However, as seen by many other vein visualisation devices, many other factors such as skin colour (Sabri et al., 2013), temperature (Lenhardt et al., 2002), and the use of a tourniquet (Simundic et al., 2018)

influence the visibility of veins. Thus, future work of this device will focus on generalising its ability to identify veins on individuals with different skin colour and temperature through the use of a calibration procedure.

The initial LED vein detection prototype costs <10 € (including Arduino and housing). Although the prototype is not complete, the fundamental components were shown to be significantly cheaper than those used in current vein visualisation devices. Future work will look into creating an array of LEDs for 2D vein localisation on the surface of the skin. In addition, attempts will be made to identify vein width and depth based on the measured peaks in the signal, and potentially the use of multiple wavelength LEDs. Lastly, a faster microcontroller with dedicated Analog circuitry or FPGA may prove useful in increasing the resolution at higher reflected light intensities, and thus, further reducing the influence of background noise.

6. CONCLUSIONS

A vein detection proof of concept device was built using only standard low-cost LEDs and the photoelectric effect of an LED in reverse bias. The LED vein detection prototype uses two emitting LEDs and one detecting LED to identify the location of a vein via trans-illumination and reflectance. A balance between system noise and resolution was identified for each LED in relation to intensity. No significant difference was observed in relative peak height when different wavelengths were used to identify the same vein. The initial proof of concept provides the foundation for further low-cost LED vein detection devices to be developed.

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