Potential application of photoplethysmography technique in evaluating microcirculatory status of STAMP patients: Preliminary report

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Abstract—Diabetes mellitus and peripheral vascular disease often lead to infections that result in lower extremity amputations. Transcutaneous oxygen pressure (TcPO₂) has been shown by many investigators to be a highly reliable means of assessing cutaneous blood supply and, thus, predicting healing potential. However, TcPO₂ measurements are time-consuming and subject to technical difficulties. For this reason, a potential application of photoplethysmography (PPG) as a method for assessing the level of cutaneous circulation was investigated by comparing PPG peak-to-peak voltages with corresponding TcPO₂ measurements. The comparisons were made at 37 locations in 20 patients with an age range of from 20 to 81 years (mean = 64.4 years). Although the two methods are intrinsically different and measure two different physiological parameters, the peak-to-peak voltages from PPG were compared with TcPO₂ measurements since TcPO₂ was reported to be the best single adjunct in determining healing potential after amputation. Linear regression analysis correlating output peak-to-peak voltages from PPG with TcPO₂ yielded a correlation coefficient of 0.60. The anatomic locations did not affect the PPG or the TcPO₂ measurement. The results of this study encourage further investigation of this technique and instrumentation as a method of assessing the level of cutaneous circulation and ultimately aid in determination of optimal amputation levels.

Key words: *amputations, cutaneous circulation, diabetes mellitus, peripheral vascular disease, photoplethysmography, transcutaneous oxygen pressure (TcPO₂).*

INTRODUCTION

Amputation of a lower extremity is often a common complication for patients suffering from peripheral vascular disease and/or diabetes. Performing the amputation at the optimal level in order to obtain primary healing and to restore function is imperative for patient care. There are numerous devices in use today that assess vascular status in order to aid surgeons to make this critical decision. Due to multiple factors that affect the rate of healing following amputations, such as the vascular status of the patient, surgical technique, health, intercurrent disease, and postoperative care, no single technique can unfailingly predict the level of amputation which will maximize healing potential as well as function (2).

Recently, Burgess *et al.* showed that transcutaneous oxygen pressure (TcPO₂) is one of the most effective means of determining optimal levels of amputation (2). TcPO₂ is recorded by a heated sensor which is placed on the surface of the skin using an airtight seal. Heating the skin induces hyperemia and largely eliminates the sympathetic reactivity of the cutaneous vasculature (8). Therefore, the amount of oxygen penetrating the skin directly corresponds with the amount of oxygen in the cutaneous circulation. This methodology is supported by many groups who have performed studies on the effectiveness of this technique (3,4,7,8,9,10). The authors reported that the transcutaneous PO₂ (TcPO₂) was found to be more consistent with healing rates in below-knee amputations when compared to Doppler pressures at the ankle for diabetic patients (8). This correlation is also seen in evaluating pre- and postoperative comparisons of ankle blood pressure and

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TcPO₂ in nondiabetic patients (10). Christensen *et al.* showed that a TcPO₂ reading of 20 mmHg or less usually resulted in necrosis of the stump and consequently, TcPO₂ readings of 30 mmHg or above resulted in uncomplicated healing (4). However, this scale is not applicable 100 percent of the time. Cases have been reported in which TcPO₂ readings of zero have resulted in healing of the stump (8).

The photoplethysmograph (PPG) is another technique which may be used to evaluate healing potential by measuring pulsatile cutaneous blood flow. The PPG consists of an infrared light-emitting diode (LED) and receiver, a power source, and a strip-chart recorder. The phototransistor responds to light reflected from the cutaneous vascular bed (1). The signal is then fed into the recorder and a hard copy is obtained. The PPG, therefore, is a direct measurement of pulsatility of the cutaneous vascular bed. This technique also has been used as a means of assessing the healing potential of ulcers in the skin (1). Although the study was qualitative, it was found that healing ulcers demonstrated good pulsatile waveforms in cutaneous blood within the immediate vicinity of the ulcer. If the ulcer did not display evidence of healing, cutaneous blood flow around the ulcer was seen to be nonpulsatile (6).

In comparing the two methodologies, PPG measures direct subcutaneous presence of red blood cells, which in turn provide oxygen to the skin. Although TcPO₂ has been shown as an effective means of determining the optimal level of amputation, the calibration and data collection is excessively delicate and time-consuming. On the other hand, a PPG reading requires approximately one-tenth of the time that is required for TcPO₂. For this reason, a comparison between the PPG and TcPO₂ was made as a preliminary study.

METHOD

Twenty patients were randomly selected and tested while visiting the STAMP Service, VA Medical Center, Long Beach, CA, for a possible amputation of the lower extremity. The patients' ages ranged from 20 to 81 years (with a mean age of 64.4 years) and all were diabetic. Thirty-seven measurements were obtained from 19 males and 1 female. The points tested were as follows: 21 dorsum of foot, 9 calf, and 5 thigh while in the supine position. The test sites were chosen according to the requested sites for TcPO₂ measurements by STAMP physicians.

The pulsatility of the subcutaneous circulation was measured using a photoplethysmography device (PPG

model 13, Meda Sonics, Mountain View, CA) with a two-channel strip-chart recorder (model R12B, Meda Sonics). For calibration of the PPG system, a wave function generator (model 112, Wavetek, San Diego, CA), a digital voltmeter, and an oscilloscope were used. The testing setup is shown in **Figure 1**.

TcPO₂ measurements were made using a commercially available device (**Figure 1**) (Transcom Oxygen Monitor 807, Novamatrix Medical System, Inc., Wallingford, CT). The low point was calibrated using zero solution at 45 degrees Celsius every time a new electrode was installed. The high point of the device was calibrated with the electrode at 45 degrees Celsius in the room at atmospheric pressure before each use.

While the patient was in supine position, a point was selected on the dorsum of the foot, calf, or thigh, that was suggested by STAMP physicians. The skin was shaved and cleaned and the infrared transducer of the PPG was then attached to the designated location by using double-sided tape. The strip-chart was started at 25 cm/min, and the peak-to-peak voltages from the PPG were recorded until the pulse wave output was consistent. The gain on the PPG device was set to maximum for greatest sensitivity and the gain on the strip-chart was kept constant throughout the study. The procedure required approximately 20 seconds to complete for each location. The pulse wave was then followed by an input of 10 mV peak-to-peak sine wave at 60 Hz from the function generator for scaling of the PPG voltage for comparison with the corresponding TcPO₂ measurement (**Figure 2**). The peak-to-peak voltage of the sine wave was verified using a digital voltmeter and oscilloscope.

A new TcPO₂ electrode was prepared using a two-step method. First, zero solution was applied while the electrode temperature was 45 degrees Celsius and the device was calibrated to zero mmHg. Second, the electrode was wiped free of any solution and calibrated to 156 mmHg (atmospheric pressure) in room air at 45 degrees Celsius. An adhesive ring was applied to the electrode along with contact gel and the sensor was placed on the same position as the one where the PPG was previously taken. Tape was used to secure the sensor and to avoid any air leaks. After 10 minutes, the temperature of the electrode was reduced to 44 degrees Celsius. The TcPO₂ reading usually stabilized approximately 10 minutes after the change in temperature.

Voltages of the PPG pulse signal were obtained by measuring the peak-to-peak amplitude of the signal from a single anatomical point in three separate places to get an overall average amplitude. This amplitude was then

Figure 1.

Diagrammatic scheme of the equipment setup. The peak-to-peak voltage from PPG output is compared to a corresponding TcPO₂ reading taken at the same location.

scaled to the 10 mV amplitude of the sine wave in order to obtain average peak-to-peak PPG voltage. This process yields a voltage which was then compared to the TcPO₂ measurements. Special attention was given to ensure the repeatability of the procedure for each patient.

Statistical comparisons were made using the IBM-RS1 statistics program. The measurements at different anatomical locations were compared to determine if the TcPO₂

and PPG measurements showed a dependence with respect to the anatomical locations. This was accomplished using one-way analysis of variance for the TcPO₂ and PPG independently of each other and thus, the only variable was the anatomical location. Thereafter, regression analysis was used to obtain the best fit and also to correlate TcPO₂ and PPG measurement.

Figure 2.

Three peak-to-peak measurements are averaged from one 20-second span of PPG readout and compared to output from function generator.

RESULTS

The results indicate that the anatomical location does not have an effect on both the $TcPO_2$ ($p > 0.29$) and PPG ($p > 0.23$) measurements (**Figure 3**). A regression analysis showed the relationship between the peak-to-peak voltage output from the PPG and the $TcPO_2$ was ($y = 12.8 \times x^{0.55}$) with a correlation of $r = 0.6$ (**Figure 4**). A higher correlation was not expected because the two methods are intrinsically different.

DISCUSSION

Many investigators have reported $TcPO_2$ to be the most reliable indicator for determining healing potential after amputation (3,7,8,9,10). This methodology, however, is not ideal in its assessment of cutaneous blood supply. Using $TcPO_2$ measurements can result in the following inadequacies: 1) the measurement is localized, and to the extent that the ischemia may vary over the limb, one value for transcutaneous oxygen tension may not be representative of the overall degree of ischemia; 2) healing was observed in stumps at which the previous $TcPO_2$ reading was zero (8); 3) $TcPO_2$ readings have been found to vary as much as 11 mm when measured at similar locations on the same patient within a 24-hour period (5); and, 4) the

procedure requires approximately 20 minutes to obtain just one $TcPO_2$ reading.

Using photoplethysmography to evaluate healing potential seems to possess two basic advantages over $TcPO_2$. First, the actual pulsatility of cutaneous circulation can be obtained. Second, the PPG measures the amount of red blood cells directly by the use of reflected infrared light. The $TcPO_2$ assesses microcirculatory status indirectly, by measuring transcutaneous oxygen tension. Further, the PPG only requires one-tenth of the time to complete the measurement. As with $TcPO_2$, PPG values are also localized to a specific area.

The PPG comparison was made with the $TcPO_2$ measurement since this methodology has been reported as the best single adjunct in assessing the healing potential after an amputation. A direct high correlation was not expected due to their intrinsic differences. The data clearly indicate that with a proper implementation of this device, the PPG technique can be a valuable adjunct in assessing the healing potential after an amputation. This preliminary study necessitates further development of the instrumentation and also a prospective clinical evaluation of photoplethysmography techniques to evaluate healing potential following lower extremity amputation.

Figure 3.

A graph showing comparison between TcPO₂ and the peak-to-peak voltage from PPG with respect to specific anatomical location.

PPG vs. TcPO₂

Figure 4.

Scattergram showing the peak-to-peak voltage from the PPG output to TcPO₂.

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