

# Skin Blood Flow Response Signal Using Time and Frequency Domain Features for Pressure Ulcer Evaluation

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**Abstract:** Pressure Ulcer (PU) is an area of the skin in which cutaneous tissue is compromised and there is progressive damage on the underlying tissue caused by blood flow obstruction due to prolonged external direct pressure. Research has shown that ischemic stress response can be evaluated using skin blood flow response (SBFR) signal features which are useful for pressure ulcer evaluation. Trends of peak reactive hyperemia (RH) were observed for three repetitive loading-unloading cycles in previous animal study to investigate tissue recovery. However, tissue recovery and tissue damage cannot be discriminated by the trends of peak RH for short recovery time.

The trends of alternative time-domain SBFR features such i.e total hyperemic response as well as frequency-domain features using Fast Fourier Transform (FFT) and Short Time Fourier Transform (STFT) i.e total power spectrum are further investigated to indicate tissue recovery. The results show that total hyperaemic response outperforms peak RH at detecting insufficient tissue recovery with 72% of samples with increasing trend in the short recovery time group compared to 57% of samples for peak RH. Total hyperemic response is effective at discriminating insufficient recovery time while other investigated features are only effective at detecting sufficient recovery time.

**Keywords:** Pressure Ulcer, Skin Blood Flow Response, Reactive Hyperemia, Time Domain Features, Frequency Domain Features, Peak of Power Spectrum, Total of Power Spectrum

## 1. Introduction

People with limited mobility such as the elderly in long-term care and home care are exposed to severe illness such as Pressure Ulcer (PU). Malaysian Registry of Intensive Care (MRIC) reported that the rate of pressure ulcer in Malaysia was 3.4 per 1000 ICU days [1] and increases year by year. PU can occur within the first two weeks for patients in ICU [2]. When skin is broken over pressure area leading to Stage 4, the cost of treating pressure ulcer can be very expensive [2].

PU is also related to mortality. Several research [2] has found that mortality rates for hospitalized patient are higher when they are subjected to pressure ulcer. Development of PU can be worsened by prolonged external pressure loading on the soft-tissues [3-5], friction and [4-7] and also shear forces [4-6]. Those factors may lead to localized ischemia [6] [8] and capillaries occlusion [9] which results in tissue damage [10-11]. Several studies have established the relationship between mechanical loading and tissue condition including reperfusion injury [12], inflammation [13], lymphatic drainage [14], impaired interstitial fluid flow and sustained swelling of cells [15]. However, many studies

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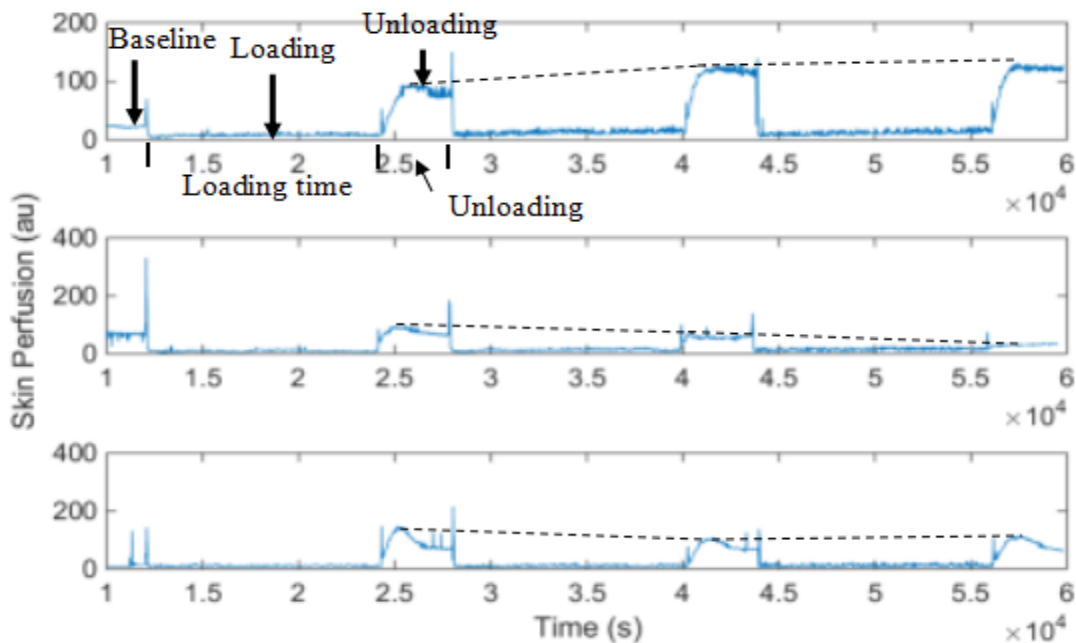
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acknowledged that the main etiology of PU is local ischemia [6] [12] [13] [16-17]. Tissue ischemia theory suggests that tissue ischemia is caused by the occlusion of blood capillaries due to external pressure that leads to ischemic damage of weight-bearing tissue [18]. Prolonged unrelieved pressure is thought to be the primary causative factor that results in decreased blood flow and tissue ischemia.

PU detection and prevention have been a concern in healthcare system for many years. There are several recommendations to reduce the occurrence of PU that will minimize patient discomfort and suffering [19]. One method of PU prevention includes frequent repositioning of patient. There are only a few published studies related to optimal repositioning schedules. The gold standard [2] of PU repositioning of patients is two hours repositioning [4] [13] to relieve lengthy pressure and to prevent complications. However, 43% respondents did not agree on the effectiveness of the two hours repositioning in the hospital care [2] [20] and several studies suggest that critically ill patients should be repositioned more often [21]. In order to resolve the optimal duration of the repositioning, the relationship between the repositioning duration and tissue condition is under active investigation. In evaluating the tissue conditions, the skin blood flow response (SBFR) signal and their trends over several repetitive loading-unloading cycles have been studied [22].

The studies of SBFR have presented an understanding of the role of tissue ischemia on the development of pressure ulcers [22-24]. Compared to other parameters of SBFR, peak reactive hyperemia (RH) is the most extensively used [6] [22] [25-30] to investigate the severity of tissue ischemia.

In the previous animal study [22], twenty-one male Sprague-Dawley rats per group were grown and divided into three different recovery time; short (3min), moderate (10 min) and prolonged (40 min). The loading pressure and loading duration were fixed (50mmHg and 10 min). The experiment was conducted for three repetitive loading-unloading time cycles. Extractions of peak RH for each cycle were performed from filtered SBFR to form the trend. During the three different unloading cycles, three peak RH trends were observed which include increasing trend, decreasing trend and inconsistent trends (Figure 1 and Table 1). An increasing trend is characterized when peak RH is increasing cycle by cycle and decreasing trend is characterized when peak RH is decreasing cycle by cycle. An inconsistent trend is characterized by lower or higher peak RH of the second cycle compared with the first and third peak RH.



**Fig. 1 - Filtered SBFR signals which indicate the three different trends for three repetitive loading-unloading cycles (a). Increasing trend , (b). Decreasing trend, and (c). Inconsistent trend**

The results from previous study indicate that the number of samples with increasing trend of peak RH decreases when the recovery time increases [22]. The results support the hypothesis that the number samples with inconsistent trend for peak RH increase when the recovery time increases. Note that it is impossible to obtain a flat trend in real experimental data and inconsistent trend instead of a flat trend. The increasing trend indicates that the samples did not get sufficient recovery time to recover from the tissue damage while the inconsistent trend shows that the weight-bearing tissue recovers before the next cycle [22]. However, the tissue recovery cannot be discriminated effectively for short recovery time (4 out of 7 samples or 57%) as observed in Table 1 associated with previous study [22]. A good discrimination is when at least 5 out of 7 or 72% samples show a specific trend.

**Table 1 – Peak RH Trends in Three Different Groups**

| Peak RH Trends | Short<br>(3 minutes) | Moderate<br>(10 minutes) | Prolonged<br>(40 minutes) |
|----------------|----------------------|--------------------------|---------------------------|
| Increasing     | 4 (57%)              | 2                        | 1                         |
| Decreasing     | 1                    | 1                        | 1                         |
| Inconsistent   | 2                    | 4                        | 5(72%)                    |

Reactive hyperemia has been conventionally quantified using time-domain parameters such as peak hyperemia, time to peak hyperemia and total hyperemic response [17] [18] [29]. These parameters provide a description of the response but may exhibit large inter- and intrasubject variations [17] [18] [25]. Time to peak hyperemia is proposed to reveal the vascular resistance [6] [31]. Total hyperemic response was measured by taking the area under the curve of the hyperemic response. It was evaluated within the time when the blood flow to return to baseline levels after pressure released. Total hyperemic response has been suggested since it is considered as a required distribution for metabolic repayment caused by tissue ischemia [6][32].

Other than time-domain analysis, RH has also been investigated using frequency analysis include Fast Fourier Transform (FFT) and Short Time Fourier Transform (STFT). FFT and STFT have been used to investigate the contributions of control mechanism system of Blood Flow Oscillations (BFO) [6] [33]. The power or mean amplitude is usually used to assess the activity of corresponding blood flow control mechanisms [17] [18] [34]. The periodic blood flow oscillations of skin blood flow can be quantified by FFT indicating the energy of the SBFR signals at given frequencies [6] [35]. The dissemination of the power spectrum [36] or energy of the SBFR signal is provided by FFT and STFT. Due to the similarity between BFO and SBF, the FFT and STFT may also be applied to SBFR.

In this study, the feature extraction of SBFR signal features which include both time and frequency domain features have been performed and the trends of selected SBFR signal features are compared with peak RH in [22] and the following hypotheses are tested. Trends of SBFR signal features such as time to peak, total hyperemic response, peak of power spectrum and total power spectrum can be used in discriminating tissue conditions effectively.

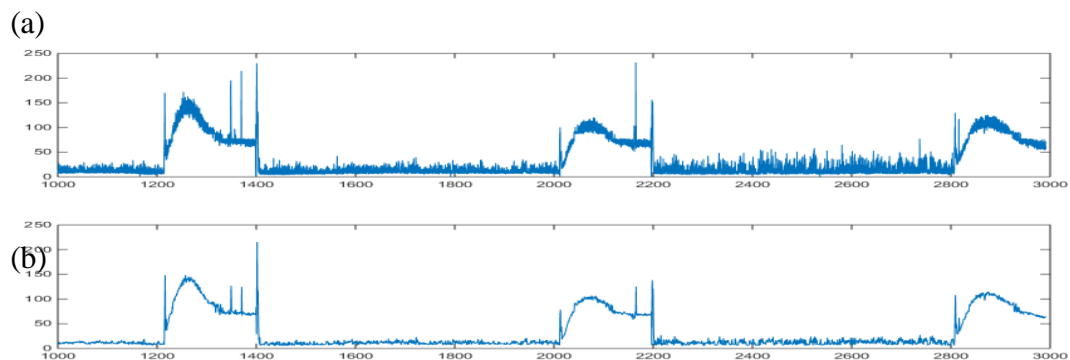
## 2. Method

### 2.1 Pre-processing SBFR data

Measurement of SBFR data was performed on twenty-one male anesthetized Sprague-Dawley rats of 15-16 week old weighing 388-481 g in the previous study [22] using a non-invasive Laser Doppler Flowmetry (LDF) probe (Probe 407, Perimed AB, Sweden) with LDF system (PF 5001, Perimed AB, Sweden).

### 2.2 Post-processing and filtering

As the regulatory mechanism of reactive hyperemia is thought to be local [17] [18] [36-37], the SBFR signals were filtered to contain only endothelial, neurogenic and myogenic oscillations. The filtering process consisting of 4th order low-pass Butterworth filtering [35] with a cut-off frequency of 0.74 Hz to eliminate the effects of respiration and cardiac activities as well as noise. The filtering was implemented using MATLAB software (version 8.5.0; The Mathworks, Inc).



**Fig. 2 - (a) Unfiltered SBFR signal; (b) Filtered SBFR signal;**

### 2.3 Data Segmentation

Manual segmentation of filtered SBFR data for all three repetitive loading-unloading cycles was performed to extract only the unloading data during experiment as shown in Fig.3.

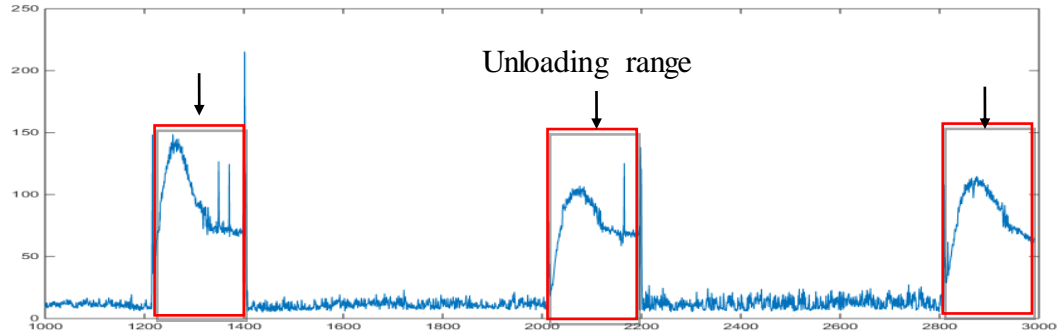


Fig. 3- Segmentation of unloading data range for short recovery time

## 3. Features extraction

### 3.1 Time domain features

In the previous animal study [22], peak RH for each cycle were extracted. Peak RH was represented as the highest blood flow value after the pressure released and values were expressed as  $P_{max}$ . In the present study, time domain features other than peak RH were identified such as time to peak hyperemia and total hyperemic response. Time to peak hyperemia,  $T_{peak}$  and total hyperemic response,  $Total_{hyperemicresponse}$  for each cycle were extracted for each cycle to form the trend.

### 3.2 Frequency domain features

Frequency domain features including FFT have been utilized in investigating the activities of the regulatory mechanism of skin blood flow [6][18]. Time series signal can be decomposed into a finite number of periodic oscillations with different frequencies and phases which reveals the power spectrum. The FFT is defined as

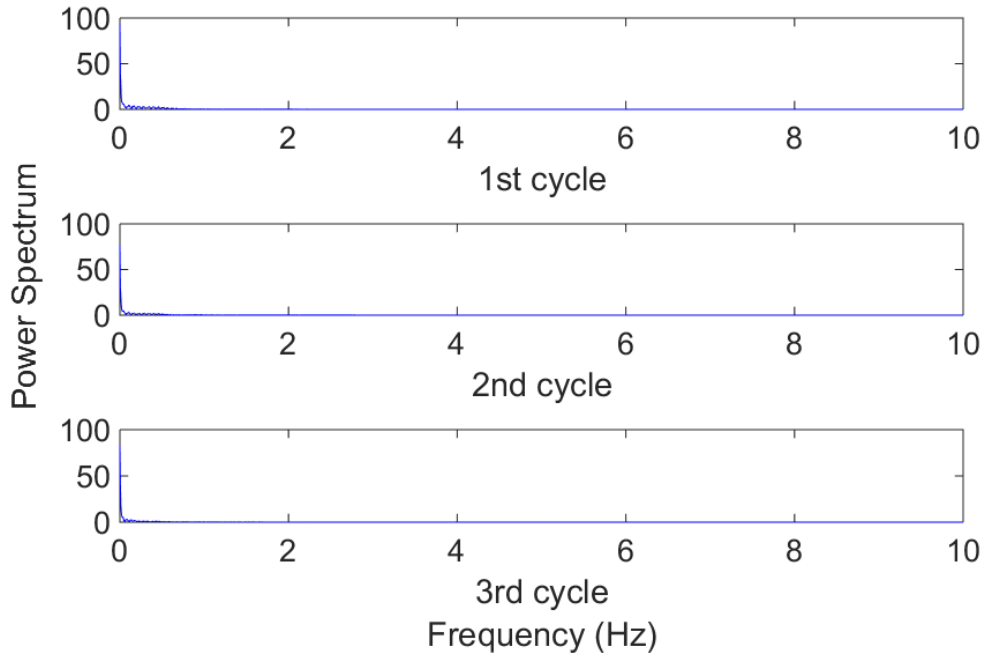
$$X_k = \sum_{n=1}^N x_k e^{\frac{-2\pi jkn}{N}} \quad (1)$$

where  $X_k$  is the discrete SBFR signal sequence,  $N$  is data length and  $k$  is the discrete frequency.

The revealed power spectrum  $P_k$  from time domain signal is defined as

$$P_k = \frac{|X_k|^2}{N} \quad (2)$$

The FFT power spectrum with a sampling frequency of 20 Hz is shown in Figure 5.



**Fig. 5- Example of power spectrum result of filtered SBFR signal for each cycle**

Subsequently, total power spectrum  $Sum P_n$  of the hyperemic response can be defined as

$$Sum P_n = \frac{1}{N} \sum_{k=1}^K |X_k|^2 \quad (3)$$

FFT was applied to the segmented data to yield the estimated power spectrum. In this study, short, moderate and prolonged recovery time are selected as  $K = 1800$ ,  $K = 6000$ , and  $K = 24000$  respectively. SBFR signal is nonstationary and changes continuously overtime. Hence the signal is broken up into short-time segments and FFT is applied on each segment. This approach is termed as Short-Time Fourier Transform (STFT) [18]. STFT evaluates the frequency changes of a signal over time. The SBFR signal is segmented into blocks of finite length and each Fourier Transform of each block is measured [38]. The results can be improved by overlapping the block and each block is multiplied by a window that is tapered at its ends. Using STFT, the spectrograms were computed using Matlab to obtain spectral densities using Equation (4) [39].

$$P_{sp}(t, \omega) = |S_t(\omega)|^2 = \left| \frac{1}{\sqrt{2\pi}} \int e^{-i\omega\tau} s(\tau)h(\tau - t) d\tau \right|^2 \quad (4)$$

Spectrogram displays the magnitude square of STFT,  $S_t(\omega)$ . A 128-second Hanning window  $h(\square)$  was selected to ensure good time resolution of SBFR signal  $s(\square)$  [18] [39], where  $\omega$  represents the frequency range, and  $t$  represents the time interval of interests. The example of spectrogram for filtered SBFR signal is shown in Fig. 6. The results show that power spectrum is higher during reactive hyperemia.

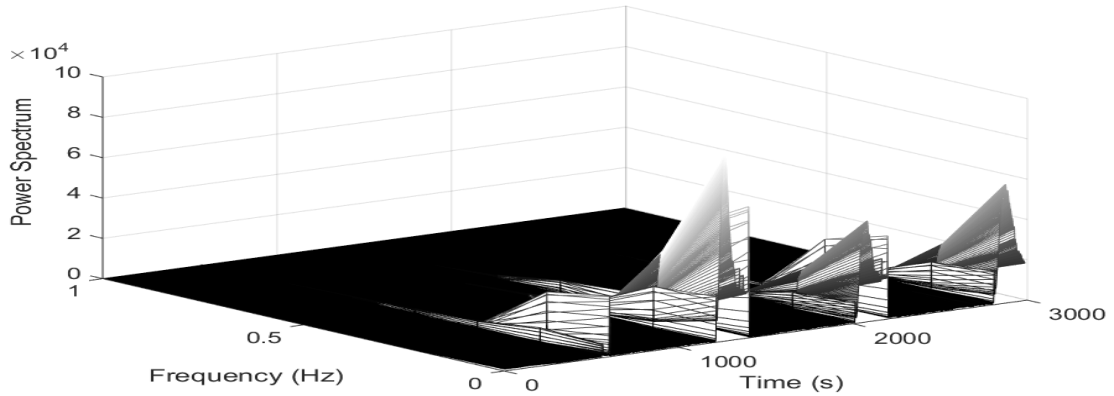


Fig. 6 - Example of spectrogram of filtered SBFR signal for three repetitive loading-unloading cycles.

The example of power spectrum using STFT results for SBFR signals can be obtained as shown in Fig. 7.

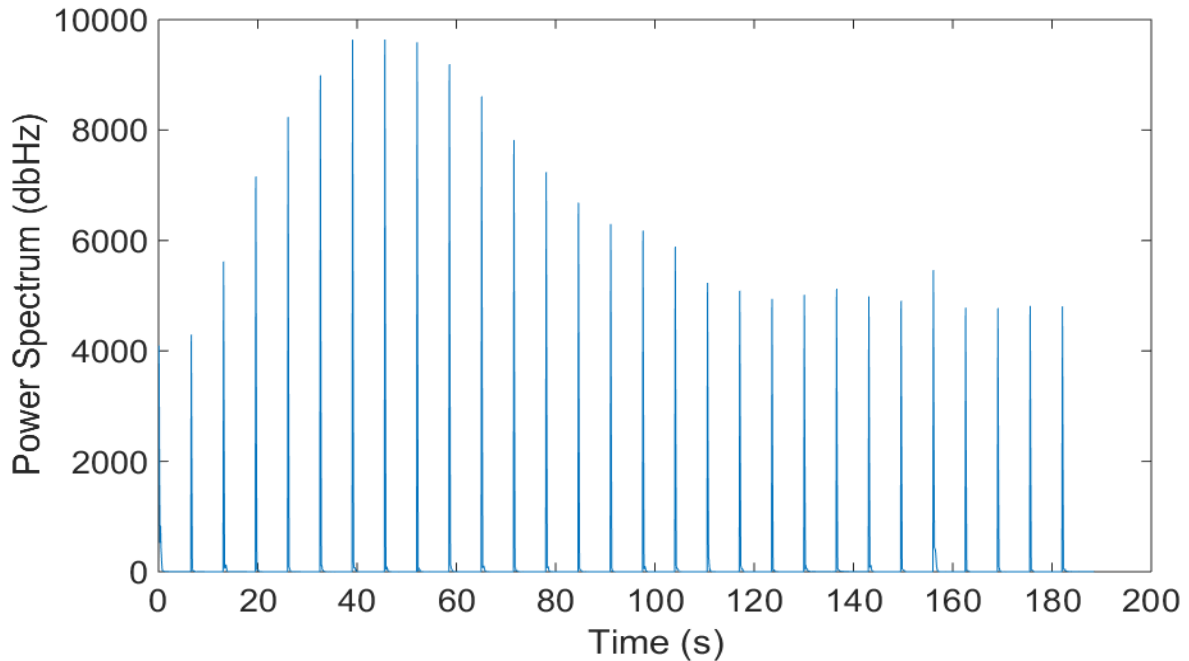


Fig.7- Example of power spectrum using STFT graph of filtered SBFR signal for the first cycle

Subsequently, total power spectrum applied the hyperemic response can be defined as

$$Sum P_{sp}(t, w) = \sum_k \left| \frac{1}{\sqrt{2\pi}} \int e^{-iwt} s(\tau)h(\tau - t) d\tau \right|^2 \quad (5)$$

STFT was applied to these segmented data to yield the estimated power spectrum. In this study, k for short, moderate and prolonged recovery time are selected as k = 23, k=75, and k=311 respectively.

#### 4. Data Analysis and Results

The time and frequency domain analyses are presented in this section.

##### 4.1 Time Domain Analysis

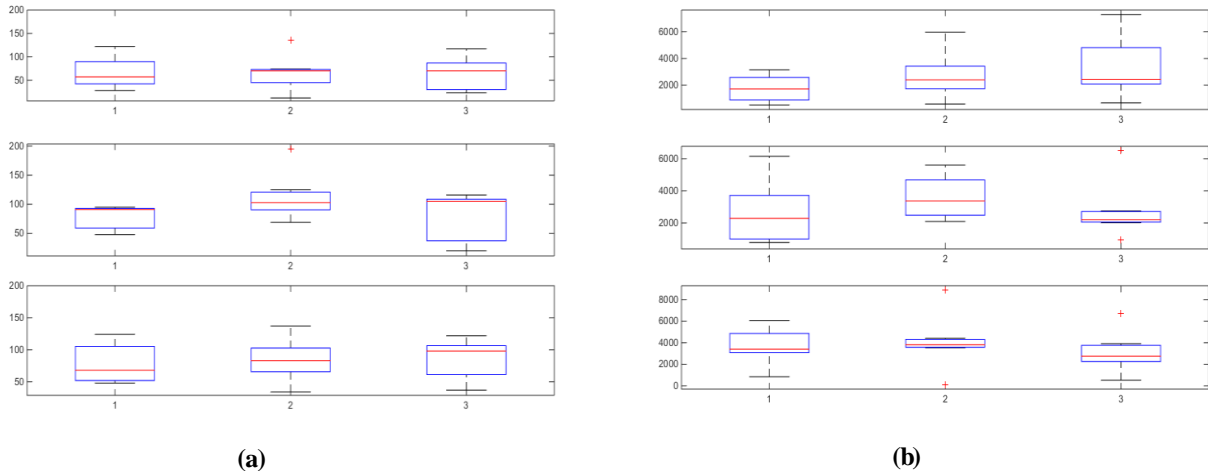
The results of time domain analysis are presented in Table 2-3 and Figure 8.

**Table 2 – Time to Peak Trends in Three Groups**

| Time to Peak Trends | Short (3 minutes) | Moderate (10 minutes) | Prolonged (40 minutes) |
|---------------------|-------------------|-----------------------|------------------------|
| Increasing          | 2 (29%)           | 2                     | 1                      |
| Decreasing          | 1                 | 1                     | -                      |
| Inconsistent        | 4                 | 4                     | 6 (85%)                |

**Table 3 – Total Hyperemic Response Trends in Three Groups**

| Total Hyperemic response Trends | Short (3 minutes) | Moderate (10 minutes) | Prolonged (40 minutes) |
|---------------------------------|-------------------|-----------------------|------------------------|
| Increasing                      | 5(72%)            | 1                     | 1                      |
| Decreasing                      | -                 | 2                     | 2                      |
| Inconsistent                    | 2                 | 4                     | 4(57%)                 |



**Fig. 8- (a) Time to peak extraction (b) Total hyperemic response in each group for each cycle for short recovery time, moderate recovery time and prolonged recovery time. The box lines represent the lower quartile, median and upper quartile values. Outliers are data with values beyond the ends of the whiskers.**

The results in Table 2 show that the time to peak hyperemia can detect sufficient recovery time as well as such that 85% of sample formed the inconsistent trend in prolonged recovery time (Group C) However the feature cannot be used in detect insufficient recovery time because the number of sample with the inconsistent trend in short recovery time (Group A) is merely 57%. From Table 3, the results indicate that total hyperemic response is better at detecting short or insufficient recovery time (72%) compared to time to peak RH. Fig. 8 shows the distribution of data of time to peak and total hyperemic response features. Outliers in Figure 8 are value that lies at abnormal distance from other values (outside 1.5 times the interquartile range above the upper quartile and below the lower quartile).

## 4.2 Frequency Domain Analysis

### 4.2.1 FFT Analysis

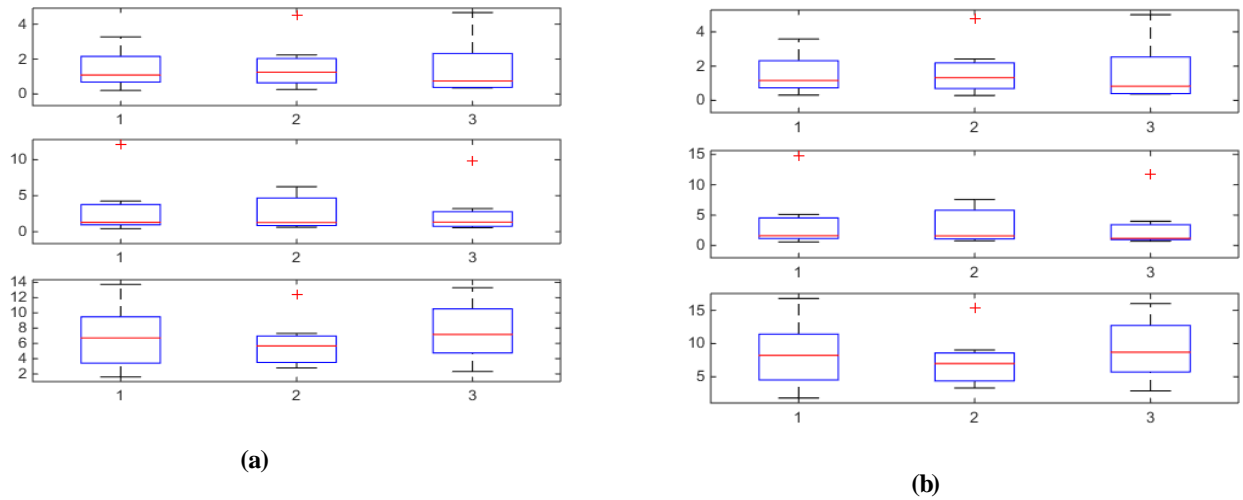
The results of frequency domain analysis using FFT are presented in Table 4-5 and Figure 9.

**Table 4– Peak of Power Spectrum Trends in Three Groups**

| Peak of Power Spectrum Trends | Short (3 minutes) | Moderate (10 minutes) | Prolonged (40 minutes) |
|-------------------------------|-------------------|-----------------------|------------------------|
| Increasing                    | 3 (43%)           | 2                     | 2                      |
| Decreasing                    | 3                 | 3                     | 2                      |
| Inconsistent                  | 1                 | 2                     | 3 (43%)                |

**Table 5 – Total Power Spectrum Trends in Three Groups**

| Total Power Spectrum Trends | Short (3 minutes) | Moderate (10 minutes) | Prolonged (40 minutes) |
|-----------------------------|-------------------|-----------------------|------------------------|
| Increasing                  | 2 (29%)           | 2                     | 2                      |
| Decreasing                  | 3                 | 3                     | 2                      |
| Inconsistent                | 2                 | 2                     | 3(43%)                 |



**Fig. 9- (a) Peak of Power Spectrum extraction (b) Total Power Spectrum in each group for each cycle for short recovery time, moderate recovery time and prolonged recovery time. The box lines represent the lower quartile, median and upper quartile values. Outliers are data with values beyond the ends of the whiskers.**

The results show that 43% of sample show inconsistent trend in prolonged recovery time for both peak power spectrum and total power spectrum of FFT analysis. However, peak power spectrum of FFT analysis gives the same percentage (43%) in decreasing and increasing trend for short recovery time. The results also show that 43% from number of sample in short recovery time for total power spectrum of FFT. Hence, peak power spectrum and total power spectrum of FFT are unable to distinguish between sufficient and insufficient recovery time (less than 57% or 5/7) Fig. 9 shows the distribution of data of peak of power spectrum and total power spectrum features using FFT analysis.

**4.2.2 STFT Analysis**

The results of frequency domain analysis using STFT are presented in Table 6-7 and Figure 10. The results show that 72% of sample in prolonged recovery time (Group C) forms the inconsistent trend for both peak power spectrum and total power spectrum. However, the result also shows that only 29% of sample in short recovery time group (group A) is associated with increasing trend while 72% of sample in prolonged recovery time group (group C) is associated with inconsistent trends for both peak power spectrum and total power spectrum. Hence, both peak power spectrum and total power spectrum of STFT is able to distinguish the sufficient recovery time, but it is unable to detect the insufficient recovery time. Fig. 10 show the distribution of data of peak of power spectrum and total power spectrum features using STFT analysis.

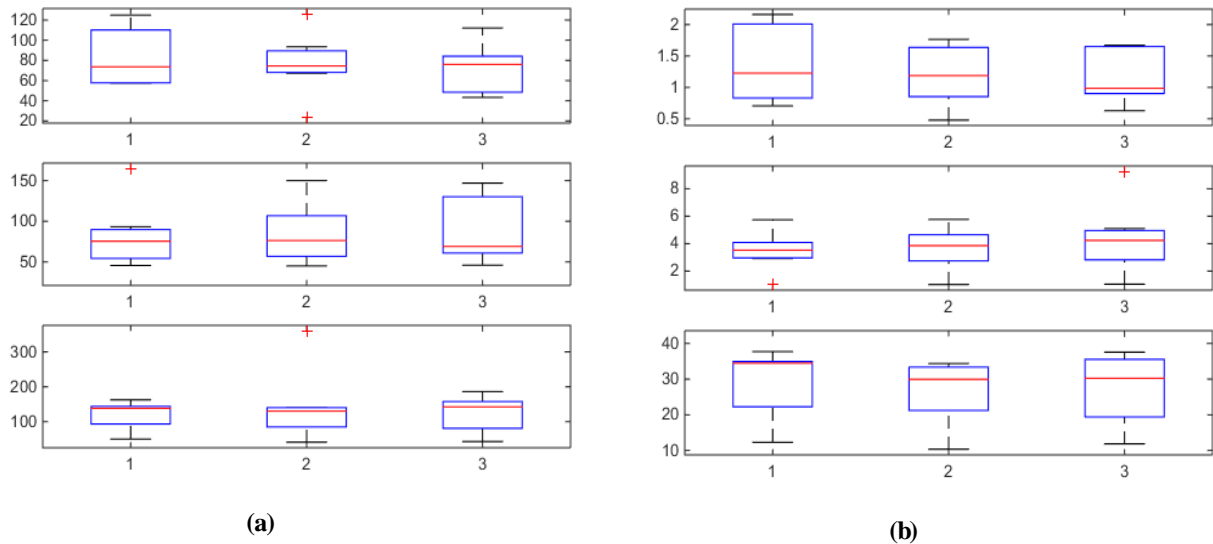
**Table 6 – Peak of Power Spectrum Trends in Three Groups**

| Peak of Power Spectrum Trends | Short (3 minutes) | Moderate (10 minutes) | Prolonged (40 minutes) |
|-------------------------------|-------------------|-----------------------|------------------------|
| Increasing                    | 2 (29%)           | 2                     | 1                      |
| Decreasing                    | 2                 | 1                     | 1                      |
| Inconsistent                  | 3                 | 4                     | 5(72%)                 |

**Table 7 – Total Power Spectrum Trends in Three Groups**

| Peak RH Trends | Short (3 minutes) | Moderate (10 minutes) | Prolonged (40 minutes) |
|----------------|-------------------|-----------------------|------------------------|
| Increasing     | 2 (29%)           | 2                     | -                      |
| Decreasing     | 2                 | -                     | 2                      |
| Inconsistent   | 3                 | 5                     | 5(72%)                 |





**Fig. 10 - (a) Peak of Power Spectrum extraction (b) Total Power Spectrum in each group for each cycle for short recovery time, moderate recovery time and prolonged recovery time. The box lines represent the lower quartile, median and upper quartile values. Outliers are data with values beyond the ends of the whiskers.**

## 5. Discussion and Conclusion

Previous studies have investigated the time domain features of SBFR response [6] [8] [29] in detecting PU, however, only Yapp [21] investigated the trends of peak RH. The results show that the number of samples with increasing trend is decreasing when the recovery time is increasing which can be seen from the first row of Table 3-7. The results also show that as the recovery time increase, the number of sample with inconsistent trend increases which can be seen in the third row of Table 3-7. It applies to all extracted features which include time domain and frequency domain features. The results of other time domain features also support the hypothesis in previous study [22]. Total hyperemic response can discriminate between sufficient and insufficient recovery time.

Abnormalities of SBFR signal can be evaluated using power spectrum in frequency domain. Higher peak of power spectrum show that higher disturbance to the activities during the metabolic repayment of tissue damage. As the recovery time increase, peak of power spectrum and total power spectrum decrease. However, the trend of peak power spectrum and total power spectrum using FFT cannot be used to detect both sufficient and insufficient recovery time. STFT provided us more information on both time and frequency localization it can be used to distinguish the trend clearly than FFT. Results show that power spectrum increase during reactive hyperemia. However, the value of power spectrum does not correlate with the peak RH value. The trend of peak power spectrum and total power spectrum using STFT can be used to detect sufficient recovery time but cannot detect the insufficient recovery time. Although STFT results are better compared to FFT, it indicates that the trends cannot be determined clearly in short recovery time. A larger window size might be required to distinguish the trend smoothly in determining the optimum recovery time. Therefore, alternative frequency domain analysis in evaluating tissue recovery time for pressure ulcer detection need to further study in determining the best feature that is able to detect both sufficient and recovery time.

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