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ORIGINAL ARTICLE

Wavelet transform based features of skin blood flow response signal for pressure ulcer evaluation

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ABSTRACT – Pressure Ulcers (PUs) are localized tissue damage that usually occur over the soft tissue of body prominence when a subject is exposed to prolonged external mechanical loading. Several studies have proposed that skin blood flow response (SBFR) can be used in PU evaluation to determine tissue ischemic accumulation due to insufficient time of tissue recovery. In previous study, twenty one Sprague Dawley rats weigh 388-481g that were divided into three different group have been used to investigate the trends of SBFR signal using time domain features like peak reactive hyperaemia (RH), time to peak RH and area under the RH curve as well as frequency domain features like peak power spectral density (PSD) and total PSD. However, the results indicate that both frequency domain features are not effective at determining individual insufficient recovery time. In this study, Continuous Wavelet Transform (CWT) based features such as average amplitude and relative amplitude based on Morlet wavelet function scale 200 are investigated. The results show that the samples representing inconsistent trend of average amplitude for metabolic frequency range are dominant in all short (3 samples) , moderate (4 samples) and prolonged groups (4 samples), while no clear pattern can be established for relative amplitude. Hence both features may not suitable at distinguishing between sufficient and insufficient recovery time due to the low percentage in number of samples.

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skin blood flow;
continuous wavelet transform;
average amplitude;
relative amplitude;
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INTRODUCTION

Pressure Ulcer (PU) is a serious health complication and frequently occurs in patients with limited mobility, such as spinal cord or bedridden patients. The cost of pressure ulcer treatment increases once the skin is broken. PU resulted from blood flow restriction which happen when a person is exposed to mechanical loading on the soft tissue due to factors like direct pressure [1–3] , shear forces [2–4] and friction [3–5] in lengthy period of time that causes the blood vessels occlusions [6] . These occlusions impede the micro-circulation in the skin [7]. Those factors also lead to blood vessels collapse [8]and localized ischemia [9, 10] which results in tissue damage [11, 12], damaged interstitial fluid flow and lymphatic waste, inflammation [5], sustained deformation of cells [13] and reperfusion injury [14]. However, local ischemia is well-known as the main cause of PU.

Researchers have proposed some techniques to assess PU and understanding the role of ischemia on tissue damage which include Skin Blood Flow Measurement [10, 15–17] Ultra-sonography [5, 18–20], bioimpedance spectrometer [20–21] and histopathology study [22]. Skin blood flow measurement using Laser Doppler Flowmetry (LDF) is considered as the best reliable non-invasive method for the PU assessment because of its ability at revealing and determining the adjustment in skin blood flow in reaction to stimulus. SBFR signal has been known as a good indicator at indicating people who are at risk towards pressure ulcer [22]. SBFR may also be useful at detecting PU since skin microcirculation has an important role at regulating blood flow to satisfy the metabolic demand of local cell [23]. Measurement of SBFR can be performed using LDF and is advantageous over conventional invasive or in vitro studies [24].

Peak hyperemia has been widely used in investigating tissue ischemic event [15-17, 25-27]. From these studies, pressure relief with sufficient recovery time can probably prevent pressure ulcer by fully reversing the tissue damages induced on weight-bearing tissues. However, it has been found that existing prevention may not be sufficient for all individuals due to individual characteristics and tolerance for pressure. It has been hypothesized that short recovery time probably gives insufficient recovery time. In previous study [17], twenty one Sprague-Dawley rats weigh 388-481g and at average age of 15.71 weeks, were split into three different group with three different recovery time; (A1-A7 in group A for short (3min), B1-B7 in group B for moderate (10min) and C1-C7 in group C for prolonged (40min) respectively) with fixed loading pressure time. Three repetitive cycles of loading-unloading were performed and each peak were extracted from every cycle from the filtered SBFR to generate the trend. Those peak RH where then joined to form a trend. Three different RH trends consisting of increasing, decreasing and inconsistent trends can be distinguished from the results to stimulate the sufficient and insufficient recovery time.

Increasing trend is defined as each peak RH level increase cycle to cycle, while decreasing trend is defined as each peak RH decrease cycle to cycle. Furthermore, inconsistent trend is defined by a relatively flat trend with lower or higher

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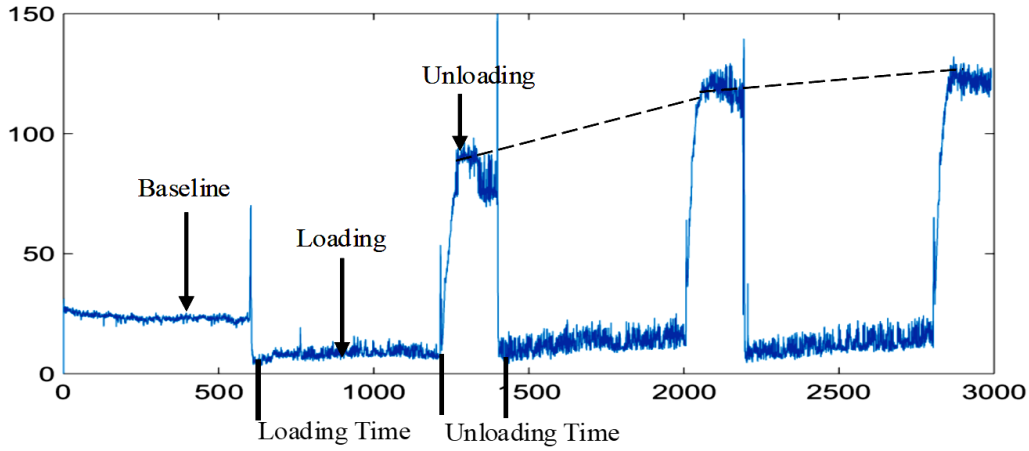
peak RH in the second cycle in comparison with the peak RH of first and third cycle since it is impossible to observe a flat trend. Example of the three trends can been shown in Figure 1.



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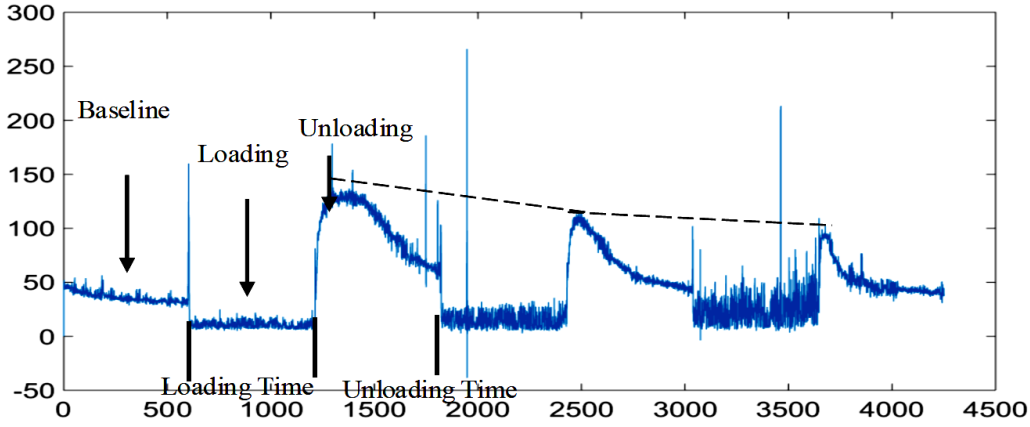

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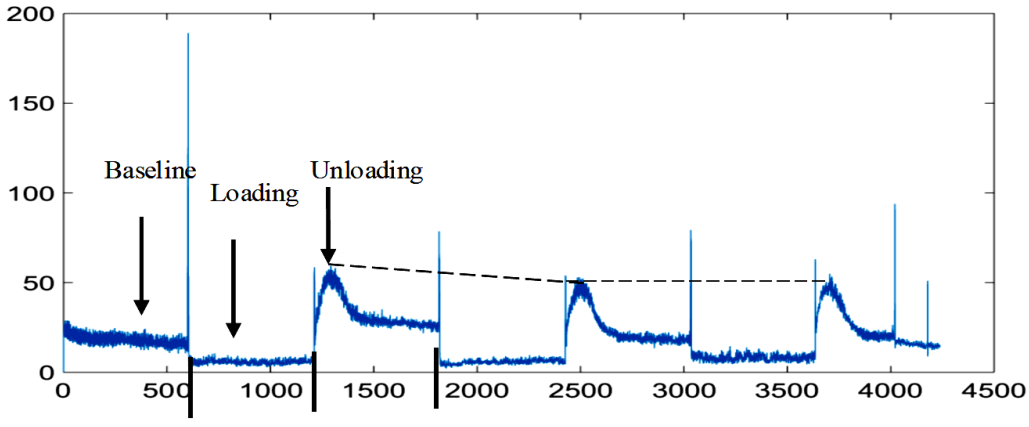


(c)

Figure 1. Examples of filtered SBFR signal trends of three group of rats which include (a) increasing, (b) decreasing and (c) inconsistent trend

The results from the study [17] summarized in Table 1 indicate that the number of samples with increasing RH trend decrease when the recovery time increase (increasing RH trend decrease from 4 samples to 2 samples to 1 sample when the recovery time increase from 3 minutes to 10 minutes to 40 minutes) which support the hypothesis that longer recovery time (40 minutes) allow the tissue to have sufficient time to recover. The result also shows that the number of samples

with inconsistent trend is highest (72% or 5/7) with prolonged recovery time. However, the number of samples exhibiting the increasing trend for short recovery time is relatively small (57% or 4/7 samples) to be considered as effective.

Table 1. Peak RH trends in three groups

Peak RH Trends	Recovery Time		
	Group A	Group B	Group C
Increasing	4(57%)	2	1
Decreasing	1	1	1
Inconsistent	2	4	5 (72%)

Other than peak RH, trends of time to peak and area under the curve of hyperaemic response have also been investigated [10, 28] and are summarized in Table 2 and Table 3 respectively. Area under curve is considered as a proportion of the need for metabolic reimbursement following tissue ischemia. Area under the curve has been determined as total hyperaemia with respect to baseline. The result indicates that these features are not effective due to both trends not fulfilling the requirement of 72% or 5/7 samples simultaneously.

Table 2. Time to peak trends in three groups

Time to peak Trends	Recovery Time		
	Group A	Group B	Group C
Increasing	2(28%)	2	1
Decreasing	1	1	-
Inconsistent	4	4	6 (85%)

Table 3. Area under the curve trends in three groups

Area under the curve Trends	Recovery Time		
	Group A	Group B	Group C
Increasing	5(72%)	1	1
Decreasing	1	2	2
Inconsistent	2	4	4 (57%)

In addition to time-domain analysis, RH has also been investigated using frequency domain analysis [28]. Maximum Peak PSD and Total PSD within frequency range of 0-10 Hz using Fast Fourier Transform (FFT) were computed [6, 28]. The results also indicated that these features are not suitable at detecting sufficient and insufficient recovery time due to lower percentages of the trends compared to requirement as observed in Table 4 and 5.

Table 4. Peak PSD trends in three groups

Peak PSD Trends	Recovery Time		
	Group A	Group B	Group C
Increasing	3(43%)	2	1
Decreasing	3	3	2
Inconsistent	1	2	4(57%)

Table 5. Total PSD trends trends in three groups

Total PSD Trends	Recovery Time		
	Group A	Group B	Group C
Increasing	3(43%)	2	3
Decreasing	3	1	2
Inconsistent	1	4	3 (43%)

Fourier Transform can reveal power spectral density of the whole signal, but it is impossible to find when a particular event has taken. In the previous study [29 - 31], Wavelet Transform (WT) based features have been proposed as a practical non-invasive investigative tool to access pressure ulcer risk and soft tissue viability. It is found that WT is capable to

describe any type of signals both in time and frequency domain simultaneously compared to FFT. In this study, analysis of SBFR signal using WT is presented and average amplitude and relative amplitude of wavelet coefficient are calculated to form trends and to discriminate between sufficient and insufficient recovery.

METHODS AND MATERIALS

Experimental data was obtained from previous study [17] whereby the SBFR data has been measured using LDF system (PF 5001, Perimed AB, Sweden) with a LDF probe (Probe 407, Perimed AB, Sweden) and analyzed using MATLAB® software (version 8.5.0; The Mathworks®, Inc.) for twenty-one Sprague Dawley rats that were split into three different group. The data was filtered using 4th order low pass Butterworth filter [34] with cut-off frequency of 0.41 Hz to remove noise and the effects of respiration and cardiac activities. The SBFR filtered data were then segmented manually for each cycle to extract the unloading data for all three cycles for the twenty-one samples.

Wavelet Transform was applied to extract wavelet coefficient. Continuous wavelet transform coefficient $\breve{g}\,(s,t)$ of a time domain signal $g(u)$ is calculated as [28–33]:

$$\breve{g}\,(s,t) = \int_{-\infty}^{\infty} \psi_{s,t}\,(u) g(u) du \tag{1}$$

where $\psi_{s,t}$ is the wavelet function and defined as [29 – 32, 37- 41].

$$\psi_{s,t}(u) = \frac{1}{\sqrt{s}} \psi \left(\frac{u-t}{s} \right) \tag{2}$$

where *t* is time factor or translation, *s* is scale factor or dilation. In this study, Morlet wavelet scale 200 has been chosen to provide a good time-frequency localization [28–32, 37, 38, 41]. Morlet wavelet is defined as:

$$\psi_{s,t}(u) = \frac{1}{\sqrt[4]{\pi}} \left(e^{-i\omega_0 u} - e^{\frac{-{\omega_0}^2}{2}} \right) . e^{\frac{-u^2}{2}} \tag{3}$$

where ω_0 was designated as 2π, and central frequency $f_0 = 1$ [32-34] yielding a simple relationship between frequency and scale [32,34-35]

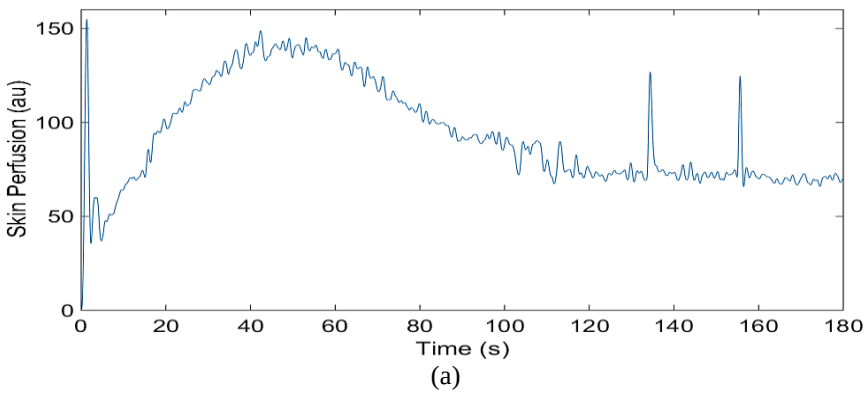
$$f = \frac{1}{s} \tag{4}$$

By averaging the wavelet transform coefficients of each frequency along the time axis, the two-dimensional time and frequency data may be reduced to one-dimensional frequency data [31-32] and is known as Time Average Wavelet Coefficient $A_{WT}(s)$ defined as:

$$A_{WT}(s) = \frac{1}{T} \sum_{t=0}^{T} \breve{g}\,(s,t)\,\Delta t \tag{5}$$

where T is time at the end of one unloading cycle. Note that the length of unloading cycle for each sample group A,B, and C are different.

As for the example, the time-frequency figure of wavelet coefficient for 1st cycle of sample A1 is shown in Figure 2 and the time average wavelet coefficient is shown in Figure 3.



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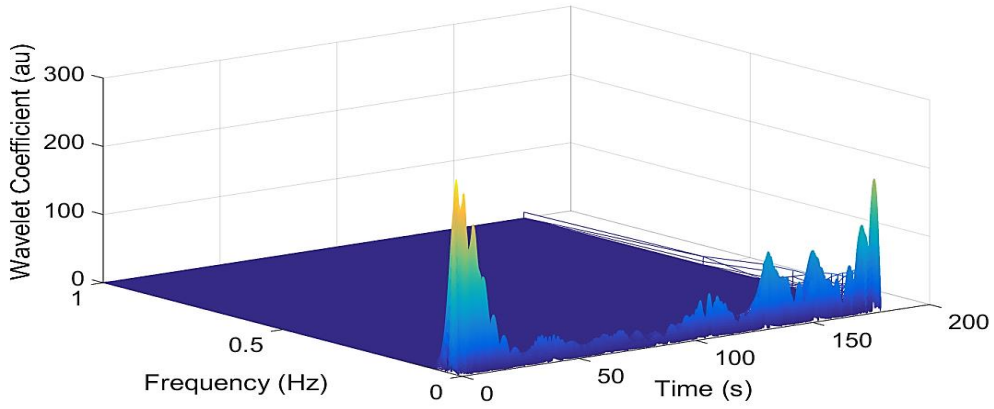

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Figure 2. (a) Time domain of SBFR and (b) Time-frequency plane of Wavelet Transform in 1st cycle for sample A1

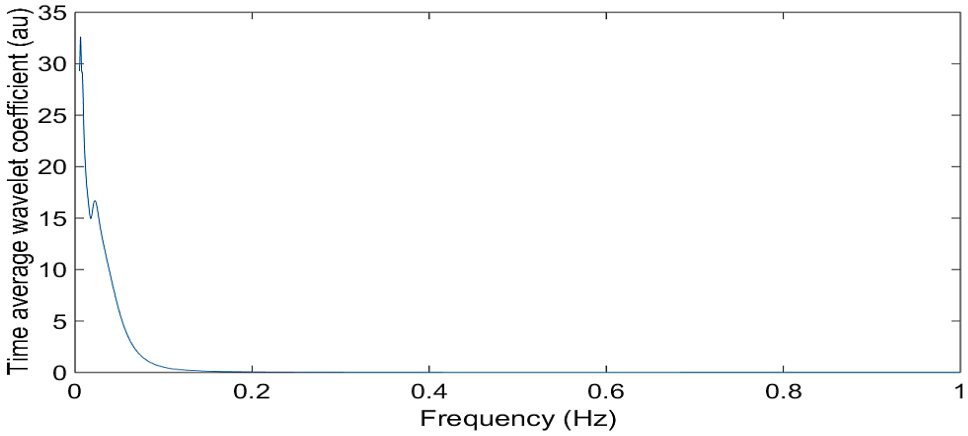


Figure 3. Time average wavelet coefficient in 1st cycle for sample A1

The time average wavelet coefficient can be divided into characteristics five frequency intervals. :0.008 -0.02Hz for metabolic activity, 0.02-0.05Hz for neurogenic activity, 0.05-0.15Hz for myogenic activity,0.15-0.4Hz; for respiratory activity, and 0.4-1.6Hz for cardiac activity [32-34, 37-39]. By averaging the wavelet coefficient of each frequency, the instantaneous activity of metabolic, neurogenic and myogenic can be quantified [31]. The result in Figure 3 showed that the metabolic frequency appeared to be the most dominant frequency during reactive hyperaemia. Hence, only the metabolic frequency range (0.008 -0.02 Hz) is of interest and further investigated.

In this study, cardiac frequency range (0.4-1.6Hz) and respiratory frequency range (0.15-0.4Hz) have been filtered earlier in the preprocessing stage and can be disregarded in order to eliminate the cardiac and respiration effects. The average amplitude within a given frequency band is defined as:

$$A_{ij}(f_{i1}, f_{i2}) = \frac{1}{T_j} \int_0^{T_j} \frac{1}{f_{i1} - f_{i2}} \int_{1/f_{i2}}^{1/f_{i1}} \frac{1}{s^2} |\breve{g}(s,t)| ds\, dt \tag{6}$$

where *i* and *j* represent the characteristic frequency interval and sample group respectively [32,37- 40].

The relative amplitude [32, 37-39] represents the ratio of average amplitude within specific characteristic frequency interval and average amplitude for all frequencies (A_{total}). Note that (A_{total}) is different for each cycle and sample since it contains all frequency interval (metabolic, neurogenic, myogenic, cardiac and respiratory). The relative amplitude of each frequency band is defined as:

$$a_{ij}(f_{i1}, f_{i2}) = \frac{A_{ij}(f_{i1}, f_{i2})}{A_{total}} \tag{7}$$

In the previous study [31], it has been established through indirect evidence that the 0.008-0.02 Hz frequency be associated with the endothelial nitric oxide which related to metabolic activities and has garnered much attention due to its potential impact on the early detection of pressure ulcer [31]. Stewart et al. examined whether the nitric oxide synthesis inhibitor, nitro-L-arginine (NLA), produces selective decreases in power or amplitude of the 0.008–0.02 Hz frequency

before and after pressure induced [42]. In this study, the average amplitude and relative amplitude in the metabolic frequency is computed.

RESULTS AND DISCUSSION

The results of average amplitude and relative amplitude in metabolic frequency are shown in Figure 4 and 5 and their trends are summarized in Table 6 and 7 respectively.

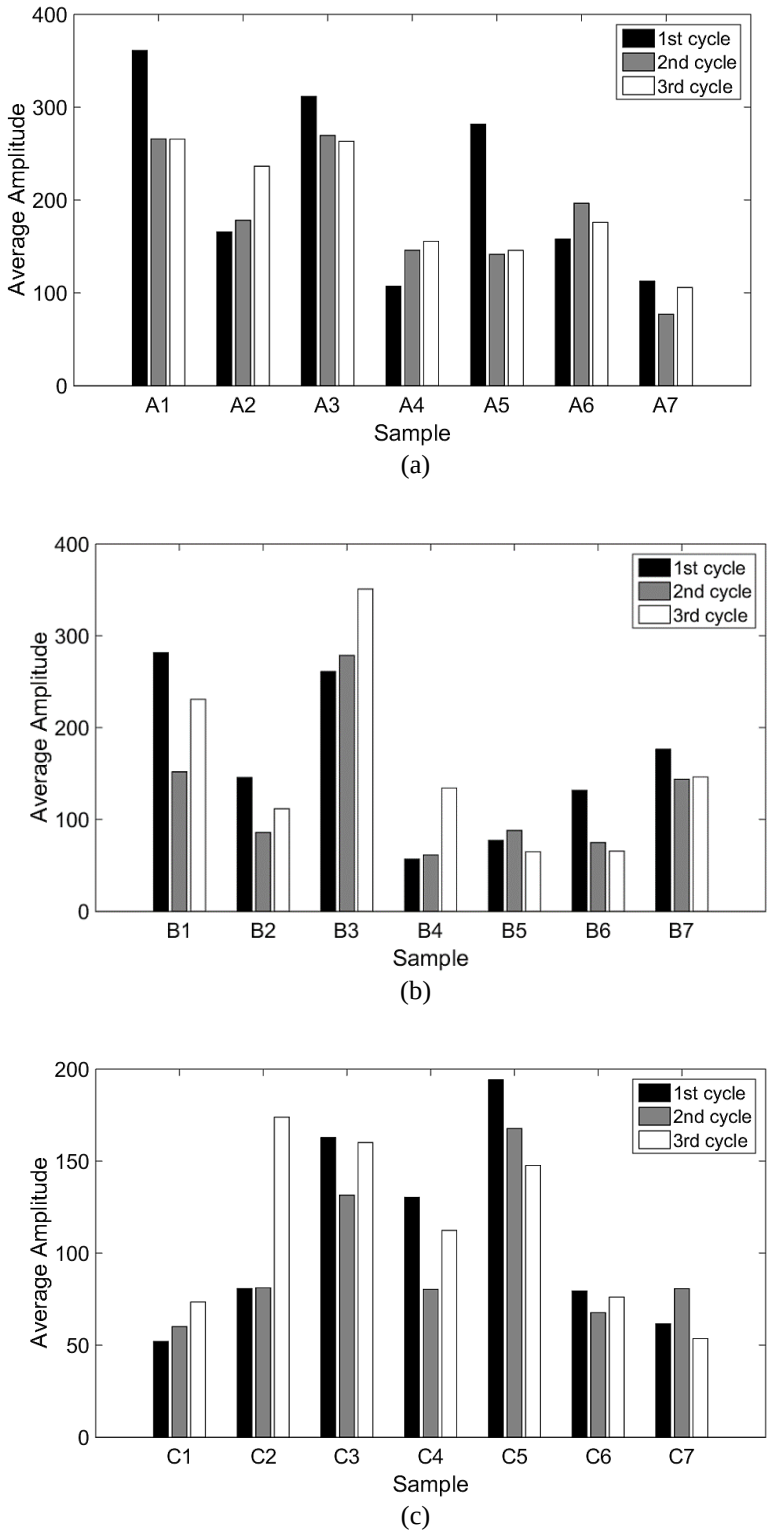
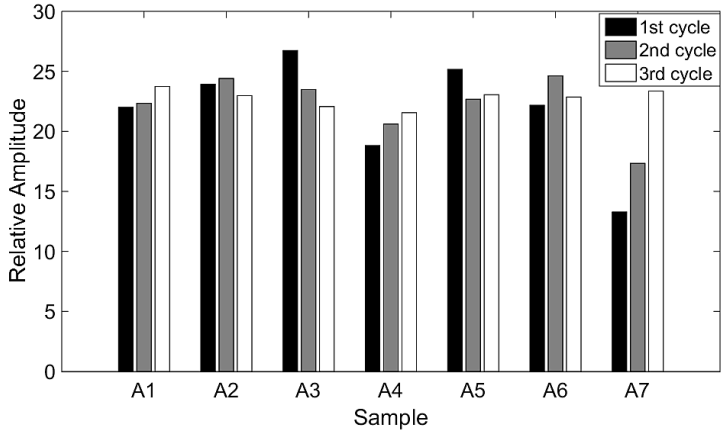


Figure 4. Results of average amplitude trends in metabolic frequency of filtered SBFR signal. (a) short (b) moderate (c) prolonged

Table 6. Average Amplitude trends in metabolic frequency in three groups

Average Amplitude Trends	Recovery Time		
	Group A	Group B	Group C
Increasing	2	2	2
Decreasing	2	1	1
Inconsistent	3(43%)	4(57%)	4(57%)



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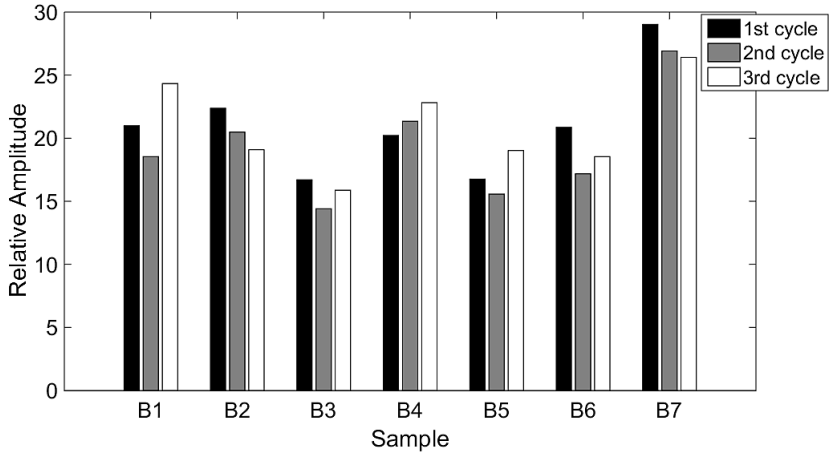

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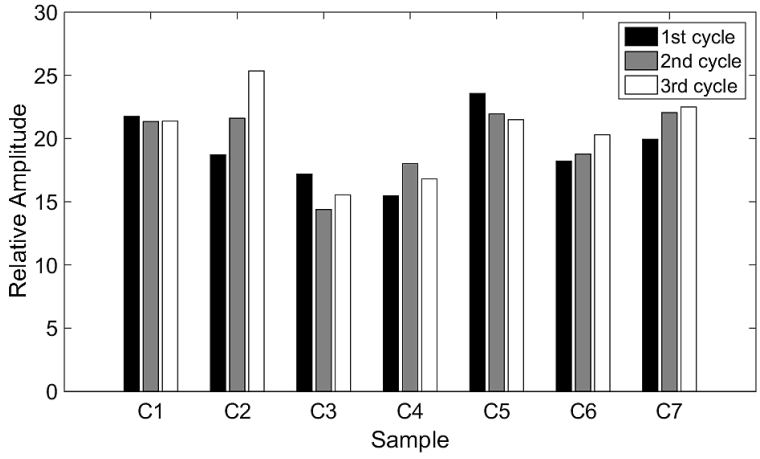

(c)

Figure 5. Results of relative amplitude trends in metabolic frequency of filtered SBFR signal. (a) short (b) moderate (c) prolonged

Table 7. Relative Amplitude trends in metabolic frequency in three groups

Relative Amplitude Trends	Recovery Time		
	Group A	Group B	Group C
Increasing	3	1	3(43%)
Decreasing	1	2	2
Inconsistent	3(43%)	4(57%)	2

The results form Figure 4 and Table 6 indicate that 3 out of 7 samples (43%) exhibit the inconsistent trend in short recovery time group (from 1st to 3rd cycle) and 4 out of 7 samples (57%) from samples exhibit the inconsistent trend in prolonged recovery time group. Meanwhile 4 out of 7 samples (57%) in moderate recovery time show the inconsistent trend. It can be observed that the number of samples representing inconsistent trends is dominant in each group suggesting that average amplitude is not suitable enough in distinguishing between sufficient and insufficient recovery time. It was hypothesized that short recovery time probably distinguish insufficient recovery time and probably exhibit higher percentage in increasing trend. Furthermore, these percentages are similar to the results of area under the curve for SBFR time domain signal in Table 3. In comparison to the studies in [2, 40], where average amplitude is used to discriminate between control and pathological, it appears that this feature may not be suitable for trend studies.

The results form Figure 5 and Table 5 show 3 out of 7 samples (43%) from samples exhibit the increasing that inconsistent trend in short recovery time group (from 1st to 3rd cycle) and 3 out of 7 samples (43%) from samples exhibit the increasing trend in prolonged recovery time group. Furthermore, out of 7 samples (57%) in moderate recovery time show the inconsistent trend. The result shows that relative amplitude is unable to discriminate between insufficient (group A) and sufficient recovery time (group C) due to the inconsistent percentages in each group and each trend. The percentage is also different in comparison with average amplitude due to the influence of the values of total average amplitude. Higher relative amplitude is associated with certain samples at certain cycle due to the average amplitude of neurogenic and myogenic component. The reason of higher amplitudes of neurogenic and myogenic is unknown. Since the component of amplitudes of neurogenic and myogenic may be affecting the relative amplitude trends, it should be further investigated.

In previous study, it has been shown that the number of samples with increasing trend of peak RH decrease when the recovery time increase and the number of samples with inconsistent trend of peak RH increase as the recovery time increase. Thus results agree with the hypothesis that peak RH as a feature has the potential to determine if the sample obtain either sufficient or insufficient recovery time. However, the result in this study does not support the same hypothesis with average amplitude and relative amplitude being the features because the number of samples with inconsistent trend in group A (short recovery time) and the number of samples increasing trend in group C (prolonged recovery time) are relatively small. The results indicate that average amplitude and relative amplitude trends in metabolic frequency component using wavelet transform are not suitable in discriminating between sufficient and insufficient recovery time that may be due to the small sample size and limited loading and unloading cycles. It is suggested to increase the sample size and number of loading-unloading cycle.

In this study, only average amplitude and relative amplitude in metabolic frequency have investigated while the other characteristic frequencies (neurogenic and myogenic) have not been investigated yet. Other characteristic frequencies may influence the blood flow changes due to induced pressure and should be investigated too for further work.

CONCLUSIONS

In this study, the use of average amplitude and relative amplitude of metabolic component features based on wavelet coefficient is investigated. Morlet wavelet function scale 200 is used to analyze three groups of animal model subjected to different unloading time. The results show that percentages of trends associated with group do not meet the requirement for successful discrimination between sufficient and insufficient recovery time.

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