Title of the work: Automated Hilbert Envelope Based **Respiration Rate Measurement** from PPG Signal for Wearable Vital Signs Monitoring Devices

Summary of the work: Respiratory rate (RR) is one of the most vital signs to predict symptoms of serious illnesses and also used as a vital indicator or significant physiological parameter for early disease warning (early detection of patient deterioration) and to monitor person's physical and emotional stress. In this work, we propose an automated Hilbert envelope based respiration rate estimation method using the photoplethysmogram (PPG) signal. The proposed Hilbert transform RR (HT-RR) method is tested by using the signals taken from BIDMC and CapnoBase databases. On the benchmark performance metrics, the proposed method had a mean absolute error (MAE) in terms of median (25th-75th percentile) of 3.7(1.8-5.5) breaths per minute (brpm) and 2.6 (0.8-5.5) brpm for 30 and 60 second PPG signals respectively. The method had the processing time of 4.81 ± 0.80 milliseconds to compute RR value from 30 seconds duration PPG signal. From the evaluation results, it can be observed that the proposed method outperforms the recent RR estimation methods.

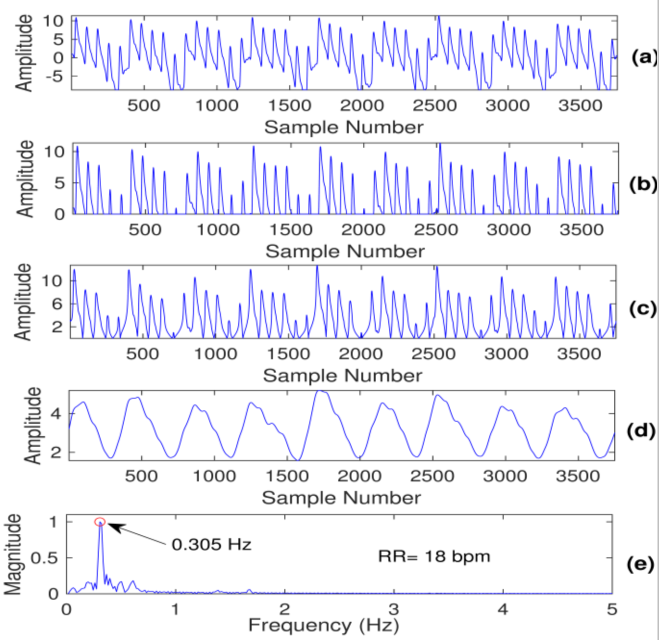

Figure 1: Illustrates the outputs of the proposed Hilbert envelope based respiration rate measurement method (a) Original PPG taken from CapnoBase database, (b) Output of the positive clipping operation, (c) Hilbert envelope, (d) Smoothed Hilbert envelope, and (e) Fourier magnitude spectrum of smoothed Hilbert envelope.

TABLE I: Pseudocode-Hilbert Envelope based RR Estimation

procedure [RR]=Hilbert-RR(x, Fs)
Input: $x[n]$:= PPG signal; $n = 1, 2, \ldots.., L$
Fs= Sampling frequency
Output: RR= Respiration rate
Step0: Acquire the PPG signal $x[n]$.
Step1: Subtract mean from the signal
$x = x - mean(x)$
Step2: Extract positive portion of PPG signal
$$x_p[n] = \begin{cases} x[n] & x[n] > 0 \\ 0 & x[n] < 0 \end{cases}$$
Step3: Compute Hilbert Transform
$h1 = hilbert(x_p)$;
Step4: Compute the envelope of the positive portion of PPG signal
$h = abs(h1)$
Step5: Apply smoothing on envelope portion
$a = 1$
$b = rectwin(Fs)/Fs$
$y = filfilt(b, a, h)$
Step6: Compute FFT, $Y[k] = \text{fft}(y[n], \text{NFFT})$,
$\text{NFFT} = 2^{\text{nextpow2}(L)}$
Step7: Compute magnitude spectrum, $|Y[K]| = \text{abs}(Y[K])$
Step8: Find the local spectral maximum ($k_{\max}$) between 0.1 Hz to 1 Hz
Step9: Compute the RR $= \frac{k_{\max} * F_s}{N} \times 60$(in bpm)
endprocedure

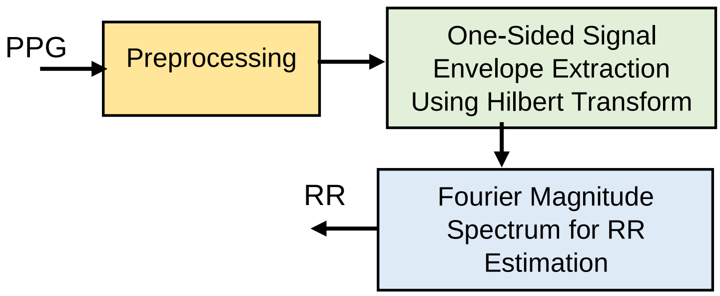

TABLE II: Performance Comparison (Mean Absolute Error (MAE) (Median (25th-75th Percentile)

RR Estimation Method	30 seconds Segment		60 seconds Segment	
	BIDMC	**CapnoBase**	**BIDMC**	**CapnoBase**
Our Method	3.7 (1.8-5.5)	1.2(0.6-2.8)	2.6 (0.8-5.5)	0.6(0.4-1.9)
Nilsson* [12]	5.4 (3.4-9.2)	10.5(4.9-12.7)	4.6(2.5-8.5)	10.2 (4.8-12.4)
Fleming* [13]	5.2 (2.6-7.7)	1.4(0.5-3.8)	5.5 (2.7-8.1)	1.1 (0.4-3.5)
Karlen* [14]	5.8 (1.9-9.7)	1.2 (0.5-3.4)	5.7 (1.5-9.7)	0.8 (0.3-2.7)
Shelley* [15]	3.5 (1.5-9.4)	4.5(0.8-10.5)	2.3(0.9-7.9)	2.2 (0.2-8.3)
Pimentel [18]	4 (1.8-5.5)	1.5(0.3-3.3)	2.7 (1.5-5.3)	1.9 (0.3-3.4)