Appendices:Runtime Verification of Implantable Medical Devices Using Multiple Physiological Signals

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Appendix1: ECG-PPG correlation

In the proposed monitoring approach for pacemaker, input events to be fed into the runtime monitor are extracted from the person's PPG and ECG. Generally, the PPG signal lag ECG by pulse arrival time i.e. the time delay from the R-peak of the electrocardiogram (ECG) to a peak of photoplethysmogram (PPG) in periphery of the body [4]. Since, PPG provides an insight into cardiovascular assesment, we need to study the correlation between ECG and PPG. A brief idea on PPG is already presented. Here, we discuss the correlation of PPG to ECG and mapping pacemaker timers to PPG intervals.

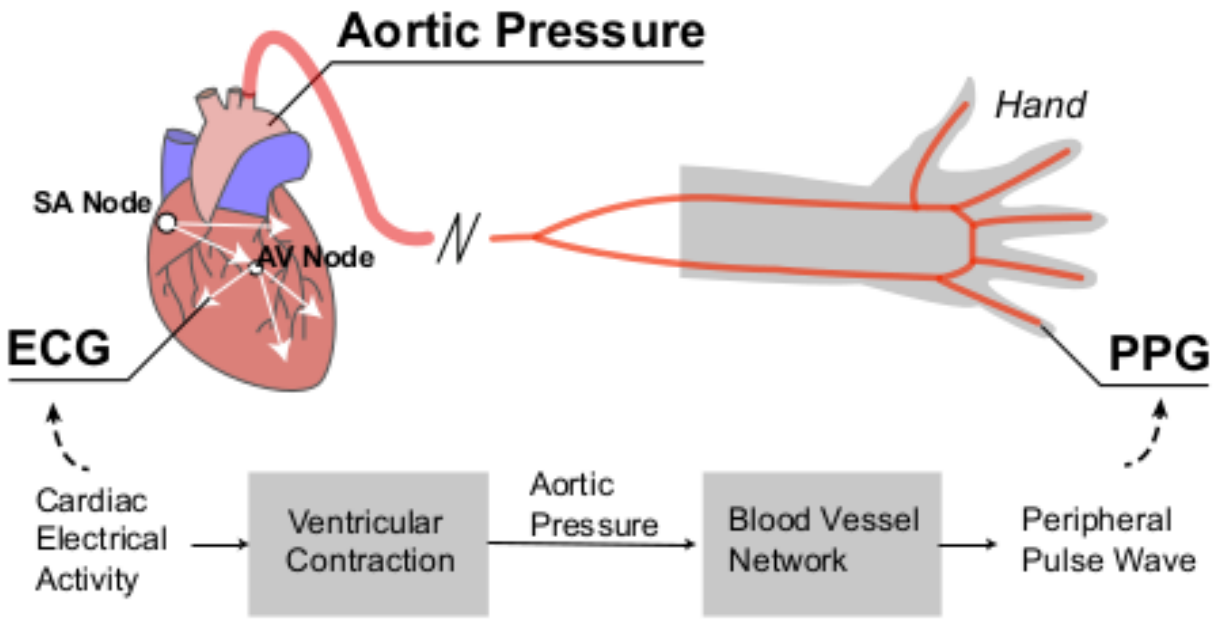

Figure 1: PPG and ECG [1] Sir,Plz suggest about the diagram

Like ECG, PPG also represent a complete cardiac cycle. A cardiac cycle is broadly consists of two phases: systole and diastole. The anacrotic phase of PPG represents systole and the dicrotic phase reflects diastole phase of a cardiac cycle. The *peak-peak interval* represents a complete cardiac cycle. The systolic peak of PPG reflects ventricular contraction of heart. The dicrotic notch represents the closure of the valve, after which the repolarization of the ventricle begins. The ventricular relaxation starts at the dicrotic notch which continues till

subsequent onset. The time between systolic peak and diastolic peak, (ΔT), is the time taken for the pressure wave to propagate from the heart to periphery and back. A typical ECG and PPG signal representing atrial and ventricular events during a cardiac cycle is shown in Fig. 2.

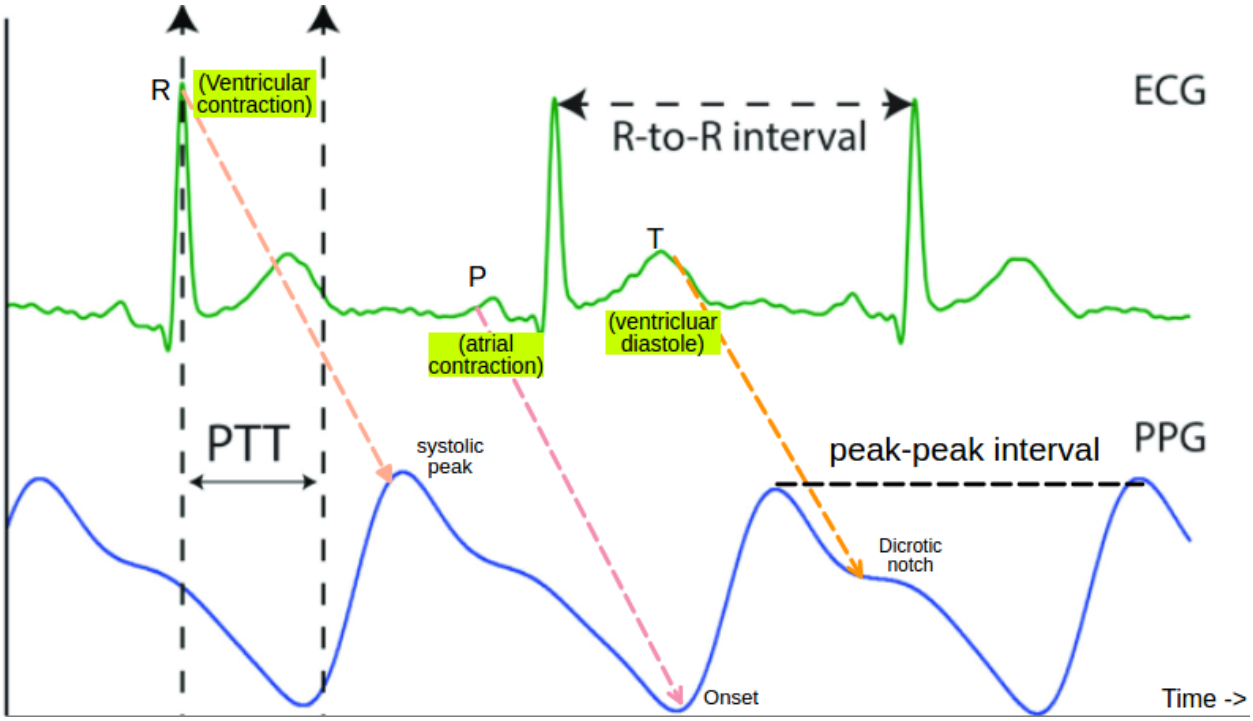

Figure 2: Simultaneous record of ECG, PPG showing cardiac activities.

There are multiple works for establishing the relationship between ECG and PPG [7, 2, 3]. In [7], the author has correlated the systole and diastole interval of an ECG signal with a PPG signal using neural networks model. It is established that the systolic peak of a PPG signal corresponds to the R-wave of an ECG signal as both reflect ventricular contraction [2]. The R-R interval in the ECG is highly correlated to the Peak-Peak interval of PPG signal as both represent a completed heart cycle [2]. The peak-peak interval has been used to detect the heart in PPG signals [3]. The dicrotic notch of the PPG is similar to the T-wave of the ECG as both corresponds to ventricular repolarization, the closure of the aortic valve and subsequent retrograde blood flow [8].

Inorder to monitor the security policies of a pacemaker, we further establish detailed corrleation between ECG-PPG events and time intervals within a cardiac cycle. We studied the simultaneous recordings of ECG-PPG available in the BIDMC database under physionet [5]. The database contains 53 recordings, each of 8 minutes duration. The signals were pre-processed for removal of noise and artifacts. The events of interest are extracted from the signal using both manual annotations and automated method using signal processing algorithms. Since, the dataset contains simultaneous recording of ECG-PPG of a person, we correlated the R-wave of ECG signal to systolic peak of PPG signal for each cardiac cycle to detect other correlated events. Further, from the physiological analysis and observation of both ECG-PPG, the following mappings are concluded.

- The P-wave of ECG corresponds to onset of PPG signal.
- The R-wave corresponds to systolic peak of PPG.
- The P-R interval of ECG is correlated to systole time period of PPG.
- Both, the R-T interval of ECG and the systolic peak-dicrotic notch interval of PPG signal represents systole period of the cardiac cycle.
- The T-R interval of the ECG signal and the dicrotic notch-systolic peak interval of the PPG signal represents the diastole period of the cardiac cycle.

Table 1: Summary of correlated ECG, PPG and cardiac events and timers.

Cardiac Events & Timers	**ECG Events & Timers**	**PPG Events & Timers**
AS or AP	P -wave	Onset
VS or VP	R-wave	Systolic peak
AVI	PR interval	Onset-systolic peak interval
AEI	RP interval	Systolic peak-onset interval
LRI	RR interval (maximum)	Systolic peak - systolic peak interval (maximum)
URI	RR interval (minimum)	Systolic peak - systolic peak interval (minimum)
Systole period	RT interval	Systolic peak - dicrotic notch interval
Diastole period	TR interval	Dicrotic notch - systolic peak interval

- The R-P interval of the ECG is correlated with the time interval of systolic peak to subsequent onset.

The summary of cardiac events and timers and the correlated ECG-PPG events and intervals is presented in table 1. Fig. 3 presents a graphical view of above correlations.

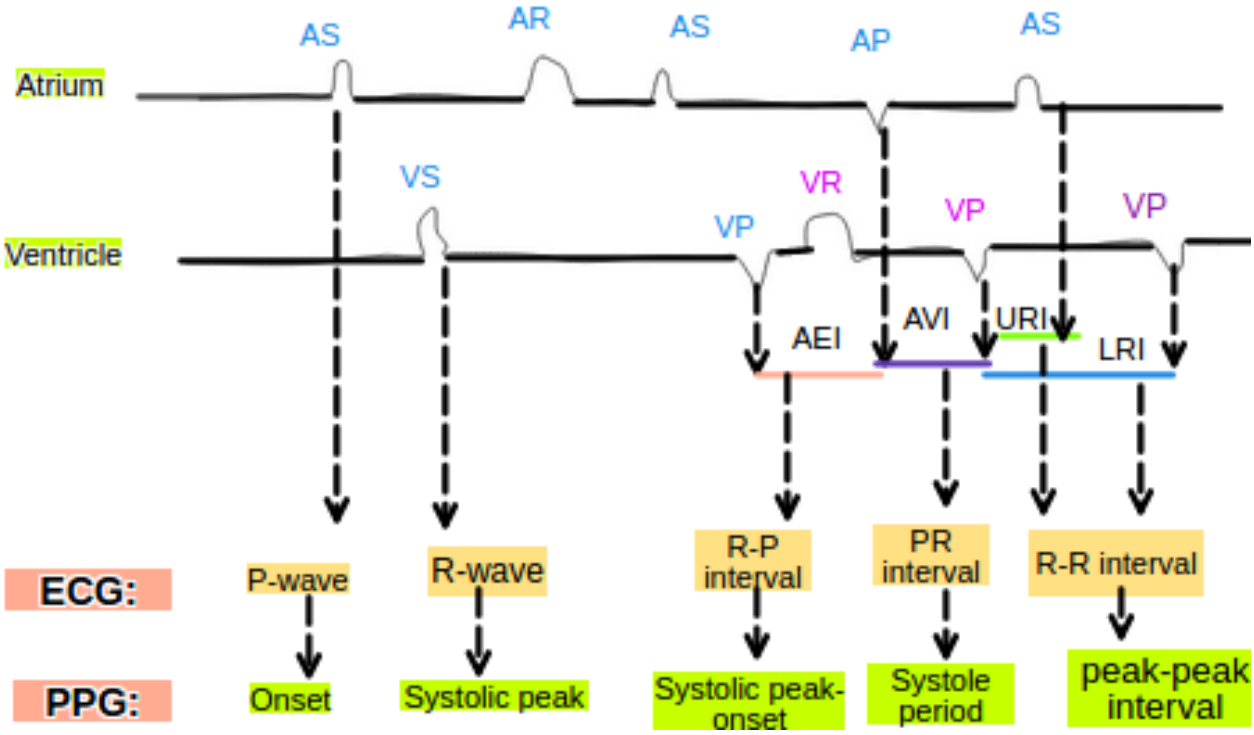

Figure 3: Mapping ECG, PPG to cardiac events and intervals.

The above proposed correlation is validated by off-line analysis and testing on our monitoring framework. The monitoring framework runs two parallel monitors, ECG and PPG monitor synthesised from timed properties of respective signals. The events and intervals of ECG-PPG, to be correlated, modelled as timed automata, are arguments to the respective monitors. An example of timed-automata modelling of events and intervals using UPPAAL tool [6] is shown in Fig. 4. The input to the parallel monitors are traces of both the signals. We fed the correlated (as per off-line analysis) events of both the signal and the standard time interval to our monitors to validate the correlation. When the correlation is validated, the output would be true in both the monitors; false otherwise. Let us consider a scenario of establishing the correlation of P-R inteval of ECG to onset-systolic peak interval (systole period) of PPG. As mentioned, we extract the events P-wave, R-wave in ECG and onset, dicrotic-notch in PPG, using both manual annotations and automated method detailed in Section **??**. We consider

each cycle of ECG-PPG in a loop of the recordings. For example, consider a trace of P, R events of ECG along with time of occurrence: [(p, 728), (r, 888)] where p and r stands for P-wave and R-wave respectively. The PPG trace corresponding to ECG cycle are: [(F, 1416), (P, 1568)] where F and P stands for onset and systolic peak respectively. It may be observed that the events in PPG are delayed which is due to lag (pulse arrival time) between ECG and PPG (almost constant for a person). We fed both the traces to our monitoring frameworks in parallel i.e ECG traces are input to ECG monitor (resp. PPG). We maintained a guard of 210 ms in both monitoring clocks as shown in Fig. 4, as standard PR interval of ECG is 210 ms (average), which needs to be correlated to systole period of PPG. This is repeated in a loop throughout the recording. The monitor raises complaint whenever there is a violation. The fact that, both the monitors agree in more than 90% cases, establish the proposed correlation. In some cases, the violation occurs because of the distortions in signal acquisition (noisy signal and motion artifacts). However, we would like to address such signal quality issues in future work. Also, there may be minimal difference between PR interval of ECG and systole period of PPG, but the objective is to validate that the repective intervals satisfy safety constraint (in this case 210 ms). Similar approach was adpoted for mapping other correlated intervals.

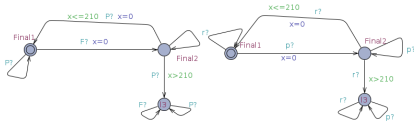

Figure 4: Automata for P_2 w.r.t PPG (left) and ECG (right).

Appendix2: Input-output behavior of the monitor & Performance analysis

Let us consider property $P2$ as the property to be verified (φ). The TA defining property $P2$ w.r.t PPG and ECG (in UPPAAL format) is illustrated in Fig. 4. We correlate the PR interval of ECG and onset to systolic peak interval of PPG. The average interval to be checked is set to 210 milliseconds, and x is the clock. Since the time intervals differ from patient to patient, the average duration is considered for the verification purpose. The ECG (resp. PPG) monitor is invoked with its respective property to verify, and an input event sequence (input sequence to be checked against the property).

Consider an example ECG input event sequence: [(p, 728), (r, 888), (p, 1400), (r, 1480)]. Since the PPG lag ECG by pulse arrival time, the PPG sequence corresponding to the above ECG trace is: [(F, 1416), (P, 1568), (F, 2080), (P, 2240)]. Here F stands for onset, P stands for systolic peak. Each event is associated with a delay, indicating the time elapsed after the previous event or the system initialization. Both the ECG and PPG monitors executed simultaneously with their respective input traces from the processing modules.

The PPG monitor receives the first action F at $t = 1416$. Since, the property is not violated the monitor will output verdict . At $t = 1568$, the second event P comes, the monitor will again emit verdict since P event has come before FP interval and the property is not violated. The monitor emits for third action F at $t = 2080$. The fourth action P comes at $t = 2240$, here also the property is satisfied. So, the monitor will output verdict , indicating property is satisfied by the current observed trace. Similarly, for the ECG input sequence, the ECG monitor will yield the same verdict at each step considering the PR interval. Thus, the output of merge, which combines the verdicts of both the monitors (using conjunction) to give final verdict will be at every step.

Table 2: Performance Evaluation

Property	No. of PPG cycles	PPG processing Time (ms)	PPG RV monitor Time (ms)	Total PPG Time (ms)	No. of ECG cycles	ECG processing Time (ms)	ECG RV monitor Time (ms)	Total ECG Time (ms)	Maximum Time (ms)
P_1	2	75.265	30.426	105.691	2	207.80	30.175	237.975	237.975
P_2	2	75.265	32.137	107.402	2	207.80	35.739	243.539	243.539
P_3	2	75.265	32.481	107.746	2	207.80	31.800	239.6	239.6
P_4	2	75.265	37.307	112.572	2	207.80	36.739	244.539	244.539
P_5	2	75.265	28.655	103.92	2	207.80	27.248	235.048	235.048

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