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

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December 16, 2020

## Appendix1: ECG-PPG correlation

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

The proposed ECG-PPG correlation is validated by off-line analysis and testing on our monitoring framework. Our monitoring framework runs two parallel monitors, ECG and PPG monitor. 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 **?** is shown in Fig. 3. 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. 3, 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

Table 1: Summary of correlated ECG, PPG and cardiac 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 |

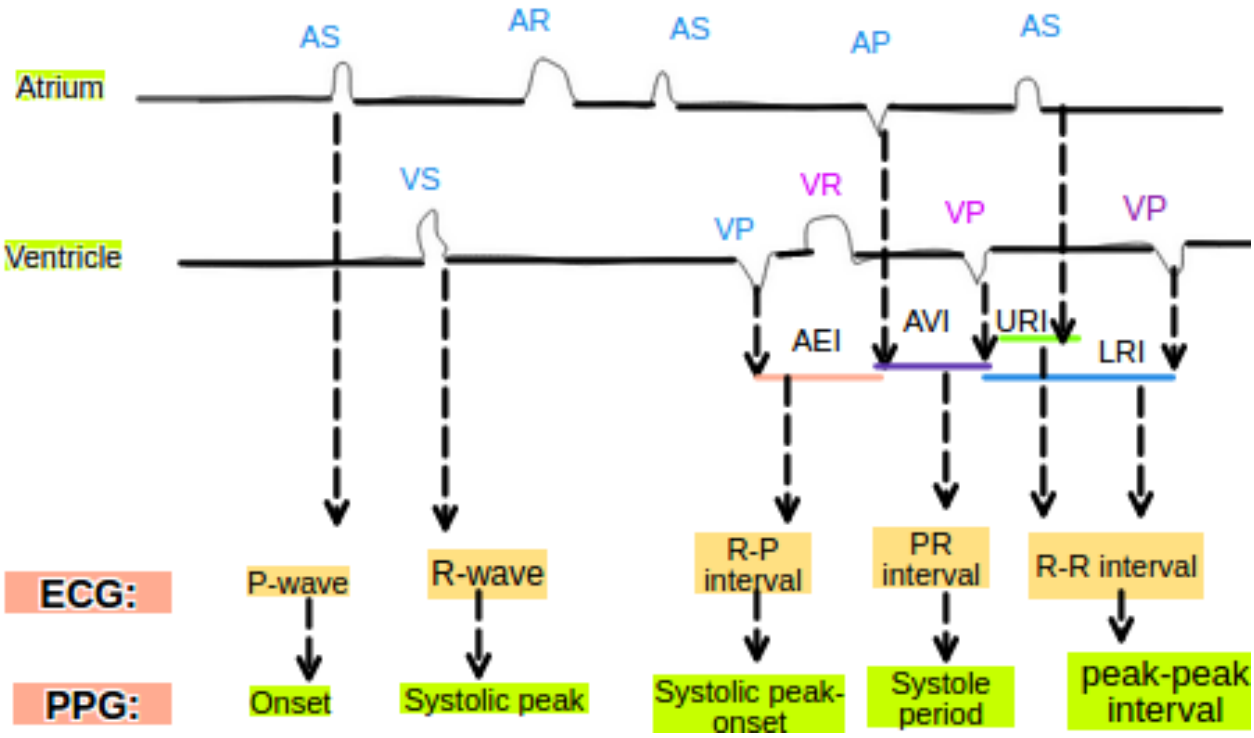


Figure 1: Mapping ECG, PPG to cardiac events and intervals.

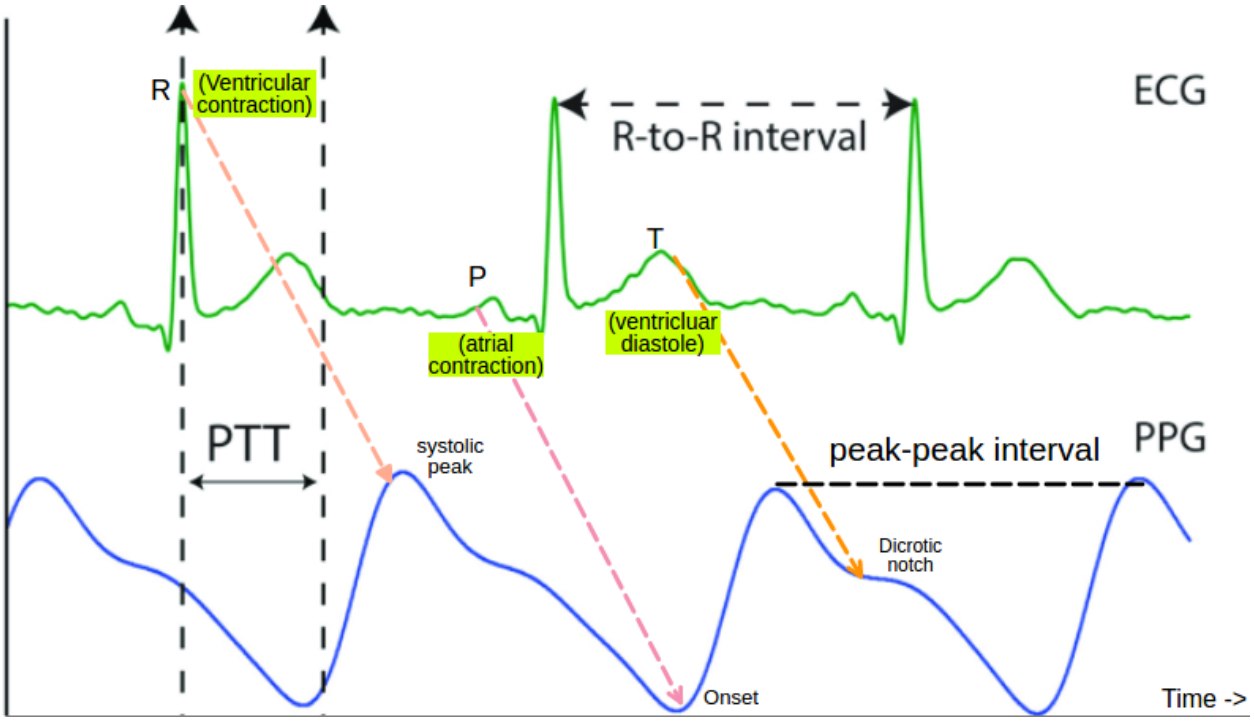


Figure 2: Simultaneous record of ECG, PPG showing cardiac activities.

period of PPG, but the objective is to validate that the respective intervals satisfy safety constraint (in this case 210 ms). Similar approach was adpoted for mapping other correlated intervals.

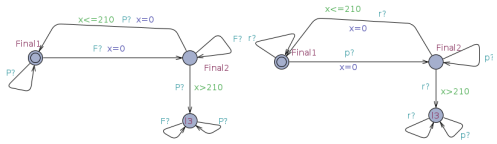


Figure 3: Automata for $P_2$ w.r.t PPG (left) and ECG (right).

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

Let us consider property $P2$ as the property to be verified ($\varphi$). The TA defining property $P2$ w.r.t PPG and ECG (in UPPAAL format) is illustrated in Fig. 3. 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 |