Monitoring Cardiovascular System using Timed Automata-based Runtime Monitors

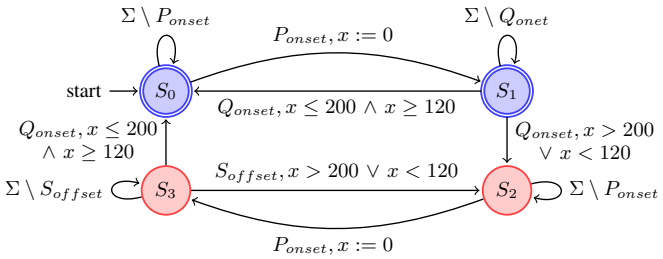

Fig. 1: Policy φ_{ECG1} specified as TA.

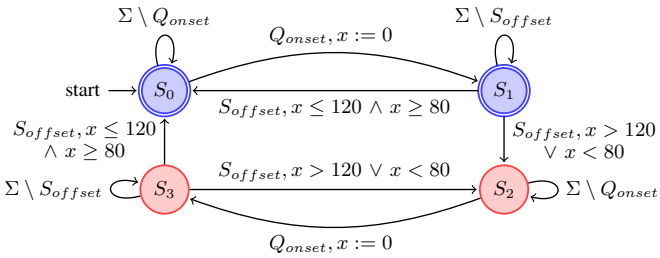

Fig. 2: Policy φ_{ECG2} specified as TA.

APPENDIX A
CAPTURING HEART ABNORMALITIES AS TIMED AUTOMATA

In this previous section, will discuss the cardiac problems caused by temporal feature deviations and the timed policies considered to monitor and classify ECG. A typical ECG signal has various temporal aspects, including PR, QT, RR, and P-wave intervals, as well as conventional ranges. Any variations from these normal electrical patterns can suggest a variety of heart conditions.

The table I presents different ECG waves and intervals, their usual ranges, and abnormalities in the heart when these properties deviate from their safe ranges.

A. Capturing cardiac complications due to extended PR interval as TA

Regular PR intervals average between 0.12 and 0.20 seconds. A prolonged PR interval showing delayed transmission of the SA node impulse to the ventricles is diagnostic of first-degree AV block. Firstdegree heart block is a clinically insignificant finding on its own; however, heart diseases such as acute rheumatic carditis, an overdose of digoxin, or an electrolyte imbalance may arise because of it. A Harvard study found that people with PR intervals longer than 200 ms had an increased risk of atrial fibrillation, pacemaker insertion, and premature death by roughly a factor of 1.5. Wolff-ParkinsonWhite and Lown-Ganong-Levine syndromes are two conditions in which a short PR interval is seen because the heart is able to bypass the AV node delay. The TA in Fig. 1 captures the extended PR interval. The RV monitor raises the alarm whenever the standard PR interval is violated, indicating the possibility of cardiac abnormalities due to the prolonged PR interval.

B. Capturing wide QRS complex as TA

In general, the QRS-complex ranges between 0.08 and 0.10 seconds. When the time span is between 0.10 and 0.12 seconds, we classify it as intermediate or prolonged QRS-complex. This may indicate a left anterior or posterior fascicular block, or an incomplete right or left bundle branch block. When the QRS-complex lasts longer than 0.12 seconds, medical attention is warranted. An extended QRS duration is a symptom of a variety of heart rhythm disorders, such as right bundle branch block, left bundle branch block, non-specific intraventricular conduction delay, and ventricular arrhythmias such as ventricular tachycardia. Right-sided heart problems are often indicated by a phenomenon known as right bundle branch block (RBBB). However, the left bundle branch block (LBBB) is always associated with heart disease, most frequently in the left ventricle. The prolonged QRS duration is captured by the TA in Fig. 2. Every time the expected duration is exceeded, the RV monitor triggers warning of the potential for cardiac problems caused by the prolonged QRS interval.

C. Capturing prolonged QT interval as TA

The QTc interval should be between 0.35 and 0.48 seconds. It is prolonged in people with certain electrolyte disorders, and it is also prolonged by some drugs. Ventricular tachycardia can be caused by a prolonged QT interval (more than 480 ms). Long QT Interval Syndromes occur when the QT is larger than 480 ms (LQTS). This condition has significant clinical implications because it typically suggests a higher risk of malignant ventricular arrhythmia, syncope, and sudden death. Short QT syndrome occurs when QT is less than 0.35 s and can result in hypercalcemia and malignant arrhythmia. The elongated QT interval is depicted by the TA in Fig. 3. When the typical QT interval is exceeded, the RV monitor triggers a warning because this may be a sign of cardiac problems.

D. Capturing wide P-wave as TA

In addition, when the P-wave duration is longer than normal, it usually indicates that one or both atria are enlarged (hypertrophied). P waves can broaden or amplify as a result of atrial enlargements. The shape of the P waves can be altered by ectopic atrial beats. An absence of P waves is a characteristic of many abnormal heart rhythms, such as atrial fibrillation

TABLE I: ECG features and heart abnormalities

ECG waves and intervals	Normal Range	Abnormal duration	Heart Abnormality	References
PR interval	0.12-0.20s	$\leq$ 0.12 s	Pre-excitation syndromes	[1]
		$\geq$ 0.2 s	First-degree AV block	[1]
QRS complex	0.08-0.12 s	0.1 - 0.12 s	Incomplete bundle branch block	[1]
		$\geq$ 0.12 s	Complete bundle branch block	[1]
QT interval	350-480 ms	$\geq$ 480 ms	Abnormal ventricular repolarization	[1]
		$\leq$ 390 ms	Abnormal ventricular depolarization or repolarization	[1]
RR interval	0.6-1.2 s	variable	Irregular heart rhythm	[1]
P-wave	$\leq$ 0.12 s	$\geq$ 0.12 s	atrial enlargement	[1]

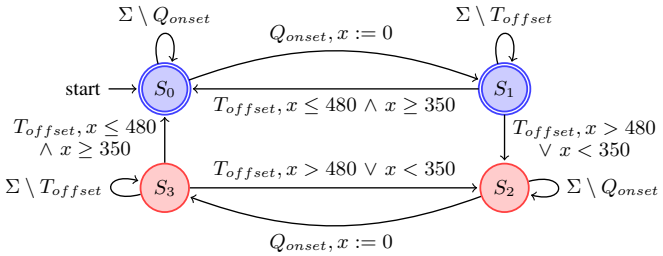

Fig. 3: Policy φ_{ECG3} specified as TA.

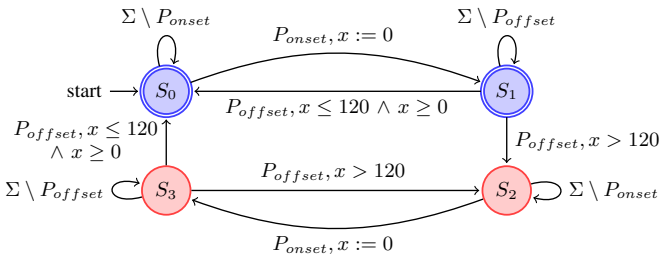

Fig. 4: Policy φ_{ECG5} specified as TA.

and junctional arrhythmias. Short RP can occur when the P waves are obscured by the end of the QRS complex, as can happen in atrioventricular reentrant tachycardia. The wide P-wave interval is depicted by the TA in the Fig. 5. When the specified duration is exceeded, the RV monitor will sound the alarm to alert the user to the fact that there is a potential for cardiac irregularities as a result of the longer P-wave interval.

E. Capturing variation in heartbeat as TA

Variations in the RR interval have been extensively researched in the context of irregular cardiac rhythm. The fluctuations in the time intervals between individual heartbeats (R-peaks) are measured by heart rate variability (HRV). The HRV can provide insights into autonomic neural function as well as sympathetic-parasympathetic autonomic balance and cardiovascular health ([13]). The extended RR interval is captured by the TA in Fig. 4. Every time the normal RR interval is violated, the RV monitor sounds the alarm, potentially alerting the patient to the likelihood of cardiac problems caused by the prolonged RR interval.

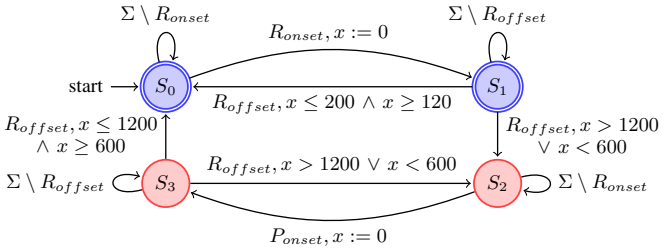

Fig. 5: Policy φ_{ECG4} specified as TA.

APPENDIX B
EXECUTION TIME

To implement signal processing algorithms to compute ECG events python module are used to analyzes ECG signals from the PTB-XL dataset [2] and it outputs an array of ECG events P_{onset}, P_{offset}, QRS_{onset}, QRS_{offset} and T_{end} along with their time.

Performance analysis

The studies are carried out using a 64-bit version of Ubuntu 18.04 and an Intel Core i5-7200 processor clocked at 3.6 GHz with 16 GB of installed RAM.

TABLE II: Execution time of the RV monitor

Policy	No. of ECG cycles	ECG processing Time (ms)	ECG RV monitor Time (ms)	Total Time (ms)
P_{ECG1}	1	207.80	15.175	222.255
P_{ECG1}&P_{ECG2}	1	207.80	52.175	259.255
$P_{ECG1} \cdots P_{ECG3}$	1	207.80	321	528.80
$P_{ECG1} \cdots P_{ECG4}$	1	207.80	321	528.80
$P_{ECG1} \cdots P_{ECG5}$	1	207.80	321	528.80

Execution time: Additionally, we investigated how long the runtime monitor took to process a cycle of an ECG. [1] The average execution times for the RV monitor and the ECG processing module across several runs are shown in Table II (approximately 1000 runs). For an ECG cycle, it takes the ECG processing module about 207.80 ms to find desired ECG events. The execution time for the combined policy is around 321 ms for an ECG cycle trace. We can see from the Table II that the ECG processing module and RV monitor module

[1]Since the policies are independent, the RV monitors for each policy may be executed in parallel. In this experiment, we have explored the sequential execution of the RV monitors for each policy. In this case, dividing the total time indicated above by the number of monitors would give the overall execution time.

take roughly 528.80 ms to complete one ECG cycle. Since an ECG cycle lasts roughly 1000-1200 ms, the RV framework is incredibly quick to report any ECG irregularities and identify any heart issues.

REFERENCES

[1] J. R. Hampton and J. Hampton, *The ECG made easy e-book*. Elsevier Health Sciences, 2019.

[2] P. Wagner, N. Strodthoff, R.-D. Bousseljot, D. Kreiseler, F. I. Lunze, W. Samek, and T. Schaeffter, "Ptb-xl, a large publicly available electrocardiography dataset," *Scientific data*, vol. 7, no. 1, pp. 1–15, 2020.