Advances in ECG-Based Cardiac Ischemia Monitoring – A Review

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Abstract

Real-time ST-segment monitoring for ischemia detection was introduced for clinical use in the 80s. To overcome the earlier systems' limitation on the number of leads monitored, systems that support continuous 12-lead ECG acquisition were developed. Derived 12-lead ECGs from 5-wire and 6-wire lead sets were also developed when direct 12-lead acquisition was not practical. Several innovative graphical solutions were developed to manage the large amount of date from continuous 12-lead ST monitoring, including ST Map for better visual tracking of ST measurements, STEMI Map for more accurate tracking of STEMI criteria, and ST Topology for more efficient ST trending review. To further improve the accuracy of acute ischemia/infraction detection, two advanced 12-lead based lead derivation methods are being developed. The vessel-specific leads (VSLs) method measures ST elevation from three optimal leads, calculated from the 12-lead ECG, for detecting ST-segment deviation during coronary occlusion. The computed electrocardiographic imaging (CEI) method presents a bulls-eye polar plot of the heart surface potentials based on inverse calculation from the body-surface potential mapping derived from the 12-lead ECG. Early results show that these methods could be a useful clinical decision support tool for improving the accuracy of ECG-based triage of chest-pain patients.

1. Introduction

ST segment monitoring is a clinical decision support tool to assist clinicians in managing and evaluating their patients. The detection of ischemic episodes has always been an important component in identifying and managing patients with acute coronary syndromes [1]. Advances in cardiac patient management, such as early reperfusion with thrombolytic therapy and revascularization with percutaneous coronary intervention (PCI) procedure, have made continuous non-invasive detection of ischemic episodes even more important. The emphasis has shifted from detecting and diagnosing acute coronary syndrome to the continuous monitoring and treatment of evolving and transient ischemic episodes. Monitoring for ST segment deviation has been the most utilized technique for ischemic detection throughout the hospital due to its availability, ease of use, and low cost. It enables the detection and documentation of all ischemic episodes reflected by ST-segment changes whether painful or silent.

Real-time ST-segment monitoring for ischemia detection was introduced for clinical use in the 80s. Fig. 1 shows a block diagram with all the key components of a complete real-time ST-segment monitoring system. This review will focus only on the signal and data management components as shown in the block diagram, including ECG leads formation, real-time ST display, and ST retrospective review. An additional topic named advanced 12-lead based lead derivation will also be discussed.

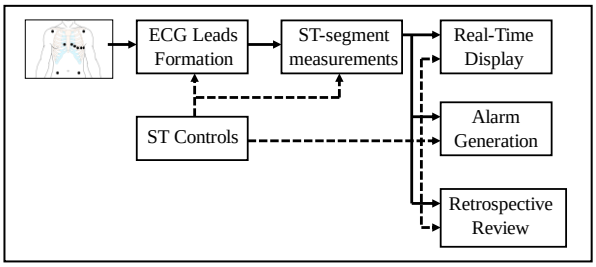

Figure 1. Block diagram of a real-time ST-segment monitoring system.

2. ECG leads formation

One major limitation of the early ST monitoring systems introduced for clinical use was the limited number of ECG leads available for monitoring. Subsequently, for the next 10-15 years, major efforts were focused on the development of systems that can support monitoring of full lead sets whether directly acquired including the Frank XYZ leads and the 12-lead ECG or derived from a subset of leads including using the 5-wire lead set in the EASI configuration [2] and the 6-wire leads with 2 chest leads placement [3]. The results of these development efforts are summarized in Table 1.

By around year 2000, almost all major commercial monitoring systems were able to support full lead set ST-segment monitoring whether directly acquired or derived. These capabilities provided the clinicians the flexibility to tailor the ST-segment monitoring application to their own clinical practice.

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Table 1. Summary of ECG lead systems for in-hospital patient monitoring.

Lead System (Lead Set)	Electrode Placement	Available Leads	Derived Leads
3-wire	M.L.*	I, II, or III	None
4-wire	M.L.	6 limb leads	None
5-wire	M.L.	6 limb leads + 1 chest lead	None
	EASI (On / Off sternum)	EA, AS, & AI	Std. & M.L. 12-lead, 18-lead, & Frank leads
6-wire	M.L. (Multiple sets of dual chest leads**)	6 limb leads + 2 chest leads	Std. & M.L. 12-lead, 18-lead, & Frank leads
8-wire	Frank leads	Frank X, Y, & Z leads	12-lead, & 18-lead
10-wire	Std. / M.L. (10, 5+5, & 6+4)	12-lead	18-lead, & Frank leads

* M.L. = Mason Likar; ** 7 sets: (V1, V3), (V1, V4), (V1, V5), (V2, V4), (V2, V5), (V3, V5), & (V3, V6)

3. Real-time ST display

With the ability to monitor the full lead set, ST measurements for up to 12 leads can now be generated and displayed for real-time monitoring. However, it was quickly noted that it was actually quite difficult for the clinicians to follow these many number of ST values and to detect ST segment changes.

3.1. ST Map

To improve the ability to monitor ST-segment changes, a graphic ST Map was developed to display the 12-lead ST values in a side-by-side frontal plan and transverse plane as shown in Fig. 2.

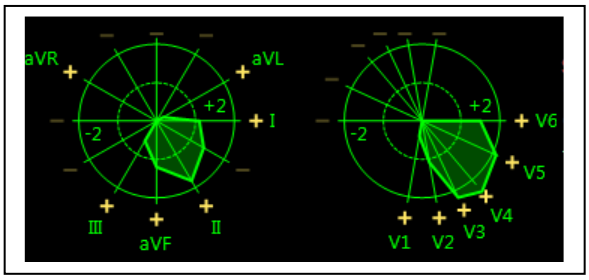

Figure 2. ST Map for graphic display of ST measurements.

The 2 concentric circles represent ST values of 1 and 2 mm (with 0 at the centre). The scales can be changed depending on the range of ST measurements. Each lead is plotted through the centre according to the spatial direction of the lead. With the positive side indicated by a "+" sign next to the lead label. For each ST value, a point is marked on the corresponding lead axis. The ST Map is completed by connecting the ST points to form a polygon. The size and orientation of the polygons indicate the magnitude and direction of the ST measurements respectively.

For real-time monitoring, the 12 numeric ST values can now be replaced with the ST Map as shown in Fig. 3. With this graphic presentation, clinicians can now monitor the ST measurements more easily by just looking at the graphic ST polygons.

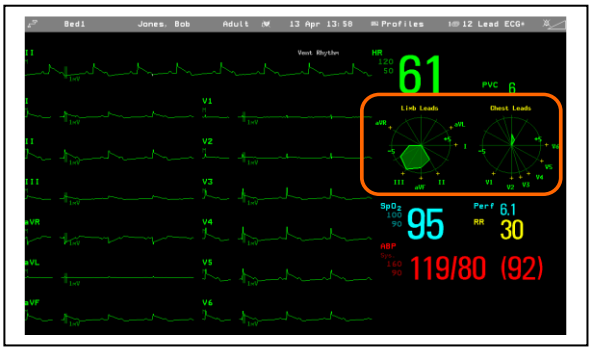

Figure 3. ST Map for real-time ST measurements display.

To further improve the ability to detect ST-segment changes, a baseline ST polygon can be established for comparison. ST trending can also be accomplished by showing multiple polygons at pre-specified time interval. These capabilities are shown in Fig. 4.

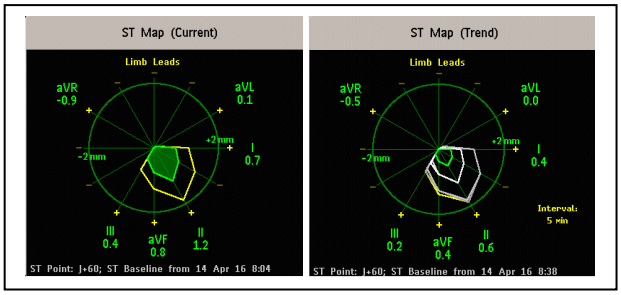

Figure 4. Tracking of ST changes: Current vs. baseline ST (Left), ST trending (Right).

3.2. STEMI Map

Another important condition to detect in ST monitoring is the ST elevation MI (STEMI). The STEMI criteria require two contiguous leads to exceed the limits. The STEMI criteria can be graphically presented as the shaded areas on the ST Map as shown in Fig. 5. A STEMI condition is detected if a polygon overlaps with the shaded STEMI area and there are at least two contiguous leads

exceeding the lead-specific STEMI limits. To indicate this condition the overlapping area of the ST polygon and the STEMI area is coloured in red. For the male example (Left), it is not STEMI because only one lead exceeded the limit. For the female example (Right), this is a STEMI because there are two contiguous leads exceeded the limits.

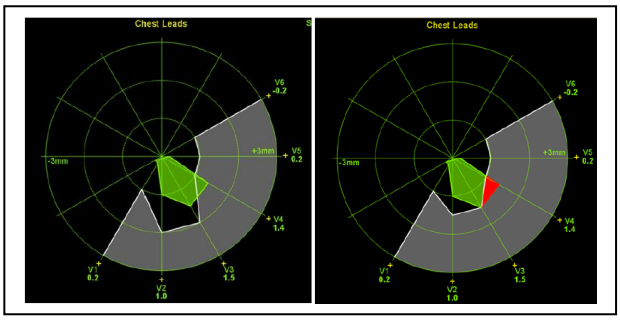

Figure 5. STEMI Maps: Male (Left), Female (Right).

4. Retrospective review – ST Topology

For retrospective ST review, traditional trend plots require a lot of space to display the full range of ST values. To reduce the space requirement, a compact trend display called ST Topology was developed as shown in Fig. 6. The ST values are color-coded using red for maximum elevation and blue for maximum depression. The y-axis is used for lead labels with the 6 limb leads in the Cabrera order on top of the 6 chest leads. Due to its compact size, the ST Topology can be used for retrospective review together with the associated ST waveforms while allowing for uninterrupted continuous real-time monitoring by showing the real-time ECGs on the same display.

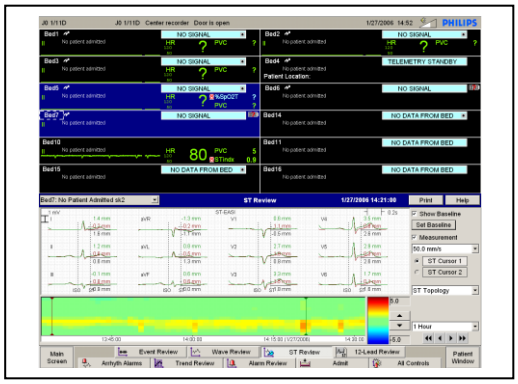

Figure 6. Retrospective ST review with ST Topology.

5. Advanced leads derivation

For the advanced 12-lead based leads derivation review, two topics are covered: The vessel specific leads (VSLs) method [4] and the computed electrocardiographic imaging (CEI) method [5].

5.1. Vessel-specific leads (VSLs)

The development of the VSLs was motivated from the ST body surface potential mapping (BSPM) data recorded at peak balloon inflation for LAD, RCA, and LCx during PCI procedure as shown in Fig. 7. These averaged recordings showed that the maximum ST elevation and depression points are usually not captured directly by the standard placement of the 12-lead ECG. Thus, by capturing the potentials at these maximum ST locations through lead derivation, perhaps these additional derived leads can be used together with the 12-lead ECG for improved Acute MI detection.

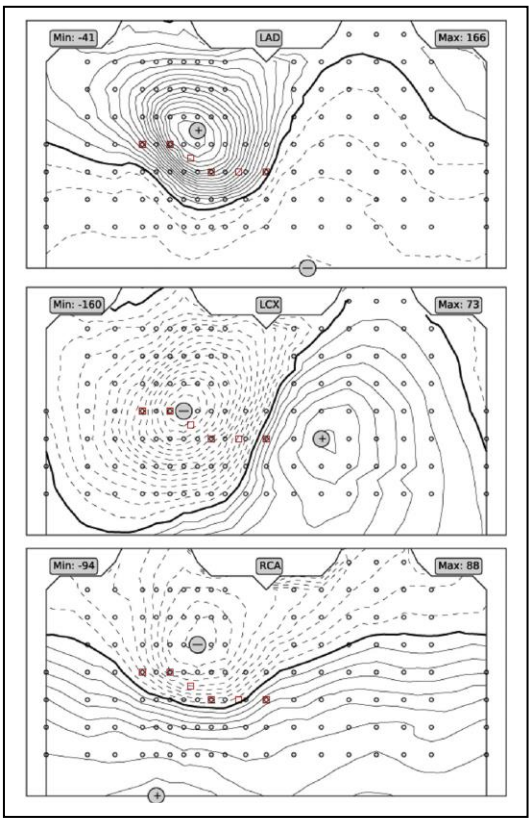

Figure 7. Averaged ST BSPM recorded at peak balloon inflation during elective PCI procedure for each of the three main coronary arteries: LAD (top), LCx (middle), and RCA (bottom).

As shown in Fig. 7, the three bi-polar VSLs are formed with the positive pole at the max ST elevation point and the negative pole at the maximum ST depression point.

In a 12-lead ECG presentation as shown in Fig. 8, the three VSLs can be plotted in the area usually used for plotting the three rhythm strips. The fact that the LAD VSL shows a significant ST elevation is an indication this is likely a case of LAD occlusion and this can be confirmed by looking at the 3x4 12-lead ECG at the top.

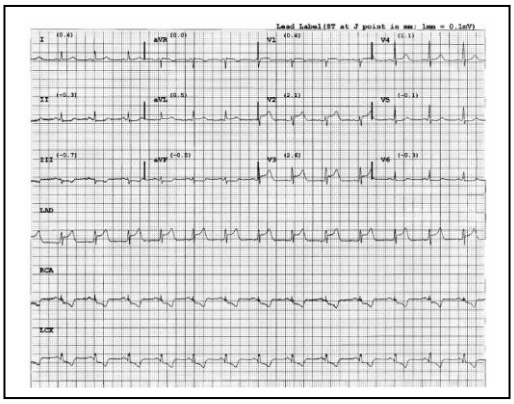

Figure 8. 12-lead ECG with three VSLs.

The three VSLs can also be plotted as three additional leads at the bottom of an expanded ST Topology plot as shown in Fig. 9. For this example, the RCA VSL shows the maximum ST elevation in red indicating that these three isolated ST episodes were likely to be RCA occlusions.

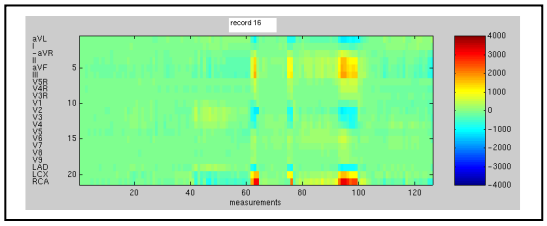

Figure 9. An example of the expanded ST Topology plot with the three VSLs added at the bottom.

5.2. CEI method

Unlike the electrocardiographic imaging (ECGI) method [6] where large number of mapping leads and patient-specific imaging data are required for the inverse solution to produce a diagnostic mapping of the epicardial potential, the question is whether for real-time monitoring it is feasible to just use the 12-lead ECG to derive the BSPM and obtain the epicardial potential by performing a universal inverse solution. Fig. 10 shows the CEI results for three examples of vessel occlusions: from left to right LAD, LCx, and RCA. The top row shows the BSPM derived from the 12-lead ECG, the middle row shows the results of the bull's eye plots of the epicardial potentials mapping (ESPM) obtained from the inverse solution on the derived BSPM. For comparison, the bottom row showed the actual single photon emission computed tomography SPECT images for these three cases. As shown here, the black under-perfused area in the SPECT images matched fairly well with the red elevation area in the bull's eye polar plots computed from the CEI method. This could be significant since CEI only need the 12-lead ECG as input and thus can be produced in real-time just like the ST-segment measurements.

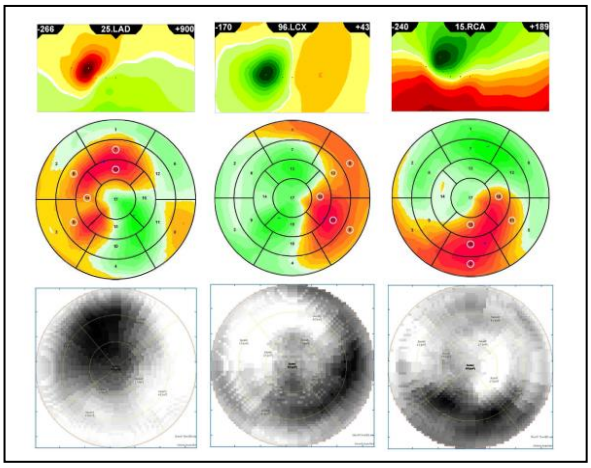

Figure 10. Examples of CEI results for coronary occlusion of LAD (Left), LCx (Center), and RCA (Right).

6. Conclusions

Several advances in signal and data management for ST-segment monitoring, including the full lead sets acquisition whether directly or derived, ST Map and STEMI Map for real-time ST display, and ST Topology for retrospective have been reviewed. In addition, also reviewed are two advanced lead derivation methods, VSLs and CEI, for improved acute ischemia detection. The clinical values of these new methods for real-time monitoring application remain to be validated.

References

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