REVIEW ARTICLE

Electrocardiographic Body Surface Mapping: Potential Tool for the Detection of Transient Myocardial Ischemia in the 21st Century?

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Coronary artery disease (CAD) is one of the leading causes of cardiovascular mortality and morbidity worldwide. CAD presents as a wide spectrum of clinical disease from stable angina to ST segment elevation myocardial infarction. The 12-lead electrocardiogram (ECG) has been the main tool for the diagnosis of these events for almost a century but is limited in its diagnostic ability. For patients with suspected angina, the exercise tolerance test is often used to provoke and detect stress-induced ischemia but does not provide a definitive answer in a substantial proportion of patients. Body surface mapping (BSM) is a technique that samples multiple points around the thorax to provide a more comprehensive electrocardiographic data set than the conventional 12-lead ECG. Moreover, recent preliminary data demonstrate that BSM can detect and display transient regional myocardial ischemia in an intuitive fashion, employing subtraction color mapping, making it potentially valuable for diagnosing CAD causing transient regional ischemia. Research is ongoing to determine the full extent of its utility.

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coronary artery disease; body surface mapping; Delta map

Coronary artery disease (CAD) is a leading global cause of morbidity and mortality.^{1,2} CAD can lead to a broad spectrum of clinical presentations including: (1) stable angina and (2) the acute coronary syndromes (ACS) comprising unstable angina, non-ST segment elevation myocardial infarction (NSTEMI), and ST segment elevation myocardial infarction (STEMI).

Fundamental to the assessment and appropriate treatment of patients with CAD is the ability to detect myocardial ischemia. The universally employed screening tool for this purpose is the 12-lead electrocardiogram (ECG),³ despite its age and recognized limitations.^{4–6} Thus, for stable patients, the majority will undergo exercise tolerance testing (ETT) in order to assess the likelihood of them having CAD-induced ischemia. This technique also

has well-documented shortcomings that limit its clinical utility.^{7,8} Similarly, most NSTEMI patients are routinely assessed by the serial 12-lead ECGs. The consequences of failing to detect transient regional myocardial ischemia (TRMI) in these patient groups are obvious, particularly given the increasing range of pharmacological and interventional techniques that are now available.

Alternative noninvasive tests to assess for TRMI include stress echo, myoview, and MRI scanning, which all provide greater sensitivity and specificity as well as positive and negative predictive value, than the ETT. They are, however, limited by their higher cost and restricted availability. An easily accessible, rapid, sensitive, easily analyzed test that improves upon the diagnostic accuracy of the conventional 12-lead ECG in the detection of

Disclosures: MR and NC are currently conducting noncommercial research on the PRIME ECG system.

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TRMI could have widespread applicability in the screening of patients with stable chest pain and NSTEMI.

ELECTROCARDIOGRAPHIC BODY SURFACE MAPPING

Body surface mapping (BSM) is a noninvasive, real-time technique that samples electrical activity over a more extensive thoracic surface than that seen with the 12-lead ECG with up to 120 electrodes being placed on the anterior and posterior thorax.

HISTORICAL PERSPECTIVE

Taccardi sampled electrical activity at up to 400 points along the thorax and on the basis of this work, the distribution of heart potentials across the thorax was described in 1963.⁹ Subsequently, the maxima and minima of cardiac electrical activity detected on the thoracic surface¹⁰ were first described.

The developmental process for BSM has culminated in single-use disposable units employing a thin adhesive film that holds radio-transparent electrodes to the chest wall. The ability of BSM to accurately detect cardiac electrical activity has been determined^{11,12} and limits of normality established.¹³ The acquisition of data have been validated for reliability^{14–17} and superiority when compared with the 12-lead ECG.^{18,19} Automated analysis^{20–22} has also allowed real-time applicability for conventional BSM techniques in which results are displayed as a set of color-coded "maps."

Conventional maps are constructed following analysis of four segments of the ECG complex as follows:

1. The QRS isointegral map that represents ventricular depolarization
2. STT isointegral map that is representative of ventricular repolarization
3. The ST₀ (J point) isopotential map that measures any changes in voltage at the beginning of the ST segment
4. ST₆₀/ST₈₀ isopotential map that analyses changes in voltage 60/80 ms past the isoelectric J point.

There has been some evaluation of the role of BSM in mapping atrial activity²³ but the majority of work had been focused on ventricular activity.

BSM and Acute Myocardial Infarction (AMI)

BSM has been shown to be useful in confirming the diagnosis of myocardial infarction (reported sensitivity 94.2% and specificity of 98.8%²⁴) and elucidating regions of myocardial infarct that have previously been difficult to detect with the 12-lead ECG.^{25,26} These include cases of myocardial infarction in the context of left bundle branch block,²⁷ silent myocardial infarction in pediatric Kawasaki's Disease,²⁸ and right ventricular infarction.²⁹

It has also been demonstrated that BSM can increase the sensitivity and specificity of diagnosing AMI in patients presenting with ST depression only³⁰ and in those with no 12-lead ECG changes.³¹ BSM has also been used to assess the adequacy of reperfusion after thrombolysis and percutaneous coronary intervention (PCI)³² with BSM reperfusion findings correlating more closely with the thrombolysis in myocardial infarction (TIMI) score than that seen with the results from the 12-lead ECG.

BSM and ETT

In 1982, Yanowitz et al. demonstrated that the areas of maximal ST change during exercise testing were in areas not sampled by the conventional ECG in a third of their research subjects,³³ a finding that was subsequently independently confirmed.³⁴ Montague used ST-T isointegral maps to estimate the ischemic burden in a group of patients with CAD and this study was able to correlate, in addition, the extent of ischemia by BSM with quantitative assessment on angiography.³⁵ Using a subtraction method where the ST-T isointegral map for control subjects was used as a baseline "normal," Montague subtracted the ST maps of the controls from those from patients with ischemic heart disease and found that even with low-level exercise there was significant enough change on the BSM map to suggest myocardial ischemia.³⁶

Hänninen showed that both the ST-T isointegral map and the T-wave amplitude decrease could be used to detect exercise-induced myocardial ischemia,³⁷ especially in patients with advanced CAD. In other experiments, they also identified

Figure 1. The body surface mapping vest with a total of 80 electrodes. (This figure is reproduced in color in the online version.)

the gradient of the ST segment (ST slope) as a sensitive and specific marker for exercise-induced ischemia.³⁸

The PRIME ECG BSM System

The PRIME ECG system is one of the commonly used commercially available BSM apparatus. PRIME acquires data from the use of a two-paneled, 80-electrode "vest." Both anterior and posterior panels are composed of a series of strips of electrodes that are applied in relation to prespecified anatomical landmarks (Fig. 1).

Once the vest is in place, it is connected to a dedicated portable computer system that acquires at least 10 seconds worth of ECG data simultaneously from all 80 electrodes. The 80 electrodes (Fig. 2A) reflect voltage magnitude and also quantify the temporal and spatial extent of that change.

A full description of the process of data analysis is beyond the scope of this review and has been described in considerable detail previously.³⁹ Briefly, as a first step in the analysis, the ECG trace from one reference electrode is used to set "beat markers" that represent the instant of zero potential for all the ECG complexes generated during data acquisition (Fig. 2B). One beat marker is set at the beginning of the QRS complex, another at the isoelectric (J) point and one more at the end

of the T wave (U wave if present) to delimit the initiation and completion of ventricular depolarization and the period of ventricular repolarization, respectively. The QRS and ST segments between these markers are then translated into a series of result maps that represent electrical activity at different points in the cardiac cycle. Depending on whether there is net positive or negative deflection from the isoelectric point, a color change on the resulting map is present. On each map, confluent regions of the same color represent areas of equal potential. Absence of deviation from the isoelectric point is denoted by the color green. A positive deflection (ST elevation) is represented by the color red whereas blue indicates a negative deflection (e.g., ST segment depression). The intensity of color is directly proportional to the degree of change in a positive or negative direction. It is conventional to display the results as either three-dimensional "torso maps" (Fig. 3), where electrical activity is displayed in color codes on a simulated torso, or alternatively, "flat maps" (Fig. 4) may be used where the torso is digitally "unhinged" from the right axilla and posterior electrical activity is displayed to the right of the anterior electrical findings.

As is seen with other BSM systems, PRIME also composes four color-coded maps based on interrogation of the QRS and ST segments of the ECG.

Figure 2. (A) A multi-electrode map displaying electrical activity in 61 anterior chest leads and 16 posterior chest leads. Limb leads not displayed. (B) Placement of beat markers for body surface mapping analysis where (A) is the QRS onset, (B) is the QRS offset, positioned at the J point, and (C) is the T-wave offset, positioned at the end of the T wave or U wave if present. (This figure is reproduced in color in the online version.)

Although rich with valuable electrocardiographic data, the analysis of these maps is labor intensive and requires a high level of specialist training. The concept of subtraction maps has been proposed as a potential solution for this—minimizing the complexity of data interpretation by showing only di-

agnostic information. Furthermore, the ability to detect changes in electrocardiac parameters would make BSM a potentially invaluable tool in tracking transient myocardial ischemia.⁴⁰

Early work using canine and human models demonstrated that myocardial ischemia could be

Figure 3. Torso map demonstrating a normal QRS isointegral map. (This figure is reproduced in color in the on-line version.)

detected with the use of complex vectorcardiogram subtraction maps.⁴¹ Dunning and colleagues⁴² utilized the QRS "difference" maps to demonstrate myocardial ischemia during coronary angioplasty in regions supplied by the left anterior descending (LAD), left circumflex (LCx), and right coronary (RCA) arteries. Interestingly, although it was possible to detect ischemic change in the LAD and RCA maps preangioplasty, it was only after application of the subtraction map that changes in the LCx territory became apparent.

This translation of subtraction maps into clinical practice is hampered by the complex interpretation of the derived data and its displays. To address this, our group has described a novel BSM technique called Delta subtraction mapping⁴³ to detect TRMI. In patients undergoing single-vessel PCI, changes in ST60 values for each electrode from time points before treatment and at 60 seconds after a balloon was inflated in a coronary artery were measured and then the difference in these values at different time points were calculated. These changes from baseline were then displayed on a color map according to (1) the extent of ST60 shift and (2) its direction. By displaying the baseline map as a universal green, only ST changes are then displayed as color, hence creating an intuitive color image of TRMI. This technique has been used to detect transient myocardial ischemia induced both at angioplasty⁴³ and during stress nuclear perfusion imaging.⁴⁴ The potential for this Delta map color display

for screening patients with stable chest pain (by stress or rest protocols) or NSTEMI/UA ACS (with and without pain) is exciting because it has the potential to provide intuitive, real-time information about TMRI. These clinical studies are currently underway.

Limitations of BSM

Despite the potential benefits to be had from the use of BSM, it has some limitations. While there is uniform agreement among BSM investigators about the benefit of additional electrodes to evaluate cardiac electrical activity, there is as yet no consensus about the optimal number and placement of electrodes. The number of electrodes used varies from 63 to 219 in the most commonly used vests. The method by which results are displayed on torso or flat maps also varies,⁴⁵ such factors making it difficult to conduct comparable cross-centre research. To ameliorate the problem of multicenter variability, the European Commission has sponsored the noninvasive evaluation of the myocardium (NEMY) project that aims to standardize BSM.⁴⁵ As a result of this work, it has been determined that at least 64 electrodes are needed for satisfactory myocardial evaluation.⁴⁶

Although extensive research has been done to optimize the positioning of the electrodes for BSM, Hoekema and colleagues demonstrated that even among normal subjects there is some interindividual variability in the maps derived depending on the heart's position within the thorax.⁴⁷ There is no suggestion that this translates into an inaccurate study per se but makes comparison of maps between different patients somewhat limited. This is not an issue peculiar to BSM and has been noted with the 12-lead ECG as well.⁴⁸

The time taken to place the BSM electrodes has previously been cited as a reason to preclude its clinical use. This is particularly relevant in the field of acute MI.⁴⁹ Although the application of electrodes takes slightly longer than with the 12-lead ECG, this is marginal in the case of contemporary vests, in which the application time has been reported to be around 5 minutes.⁴⁵ Our group has had a similar experience.

Finally, a practical limitation of the BSM vest is the difficulty maintaining the adhesive strips during exercise testing when contact is sometimes lost with the skin.

Figure 4. Flat map indicating corresponding areas of myocardium. (This figure is reproduced in color in the online version.)

BSM—Delta Subtraction Maps for TRMI and Future Directions

The conventional 12-lead ECG has been relatively unchanged for 80 years. It remains the pivotal component of investigation of patients with chest pain to detect TMRI. Both the 12-lead ECG and the ETT have served as creditable methods for demonstrating ST segment shift. Their well-documented limitations, however, mean that their application to many patients, particularly in the context of the ETT, is flawed. In earlier work on the detection of myocardial ischemia, Maynard and colleagues showed correlation between acute coronary occlusion during PCI and regional ST segment changes on BSM maps.²⁷ Interestingly, the areas of maximal electrical activity were found to lie outside those regions covered by the 12-lead ECG. In additional studies with balloon inflation during

PCI, the extent of myocardial ischemia exhibited on BSM was significantly greater than that shown on 12-lead ECG⁵⁰ (53.8% vs 17.9%, $P < 0.001$). This group has additionally studied the relationship between specific single coronary artery intervention and the ability of Delta map BSM to detect TRMI^{43,44} with very promising results. We have now devised and partially validated a novel, intuitive, accessible method to display TMRI using the Delta map. Additional investigation into the ability of this novel imaging tool is required. Thus far, we have described the ability to detect regional ischemia in the context of coronary artery occlusion at PCI⁴³ (Fig. 5). We have also published a case in which the Delta map identified LAD territory ischemia in a patient whose stress nuclear perfusion scan produced a similar result⁴⁴ (Fig. 6).

Additional data are now required to compare the ability of the Delta map to detect TRMI with

Figure 5. Delta map demonstrating regional ischemia with coronary artery occlusion at PCI. Reconstruction of electrocardiac data at baseline, then after 1-minute balloon inflation (peak), and again after 3 minutes recovery (late) during an angioplasty to the right coronary artery (RCA) in the first PRIME ECG study. Reproduced with permission from Carley et al.⁴³ (This figure is reproduced in color in the online version.)

stress nuclear myocardial perfusion imaging and stress MRI. In addition, the potential role of BSM Delta map analysis in the rapid diagnosis of TRMI in patients presenting with NSTEMI ACS will be assessed.

CONCLUSION

There is a need for more sensitive and specific screening tests and methods of diagnosing CAD. The limitations of existing technologies have been explored. BSM, using Delta subtraction mapping, may be a feasible and intuitive alternative tool. The multiple electrodes used sample electrical activity of the cardiac muscle, almost in its entirety. The

method of application of the vest requires minimal prerequisite training and is user friendly. Analytic software has been recently tailored to make it more easily accessible to frontline staff. Furthermore, myocardial infarction/ischemia detected by BSM has been shown to consistently correlate with angiographic findings. Work is ongoing in the field of using BSM to detect transient myocardial ischemia, making it more applicable to the legions of patients who present daily to the Emergency Departments and general practitioner (GP) surgeries with chest pain of uncertain etiology. Preliminary studies have been promising.

In their 2007 review of the 12-lead ECG, the American Heart Association Electrocardiography

Figure 6. PRIME ECG subtraction map demonstrating the presence of reversible regional myocardial ischemia. Left panel shows baseline color map in patient being investigated by dobutamine stress myoview scan for angina. The baseline color has been removed by resetting the color display. Right panel: at peak stress, only change at baseline ST60 of any of the 80 leads is displayed as color. A large blue area is seen in the anterolateral chest indicating ST segment depression in this territory. Bottom panel: The myoview was reported (completely independently and blinded from this result) “reversible ischemia in the anterior and septal territory.” The subsequent coronary angiogram demonstrated a significant stenosis in the proximal LAD. The patient had previously undergone PCI to the circumflex artery where the stent remained widely patent. Reproduced with permission from Hatrick et al.⁴⁴ (This figure is reproduced in color in the online version.)

and Arrhythmias Committee, Council on Clinical Cardiology; the American College of Cardiology Foundation; and the Heart Rhythm Society⁵¹ acknowledged the contribution of additional leads

in the diagnosis of acute infarction but cited the complexity of BSM as an impediment to replacing the 12-lead ECG. Given the advancement in making the acquisition and analysis of these maps less

unwieldy, it might soon be time to reevaluate the role of BSM in the assessment of the patient with CAD. The way forward might be best paved with electrodes.

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