Diagnosis of acute coronary occlusion using computed electrocardiographic imaging based on the 12-lead electrocardiogram, in comparison with ST-elevation myocardial infarction criteria.

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Abstract

Introduction: Computed electrocardiographic imaging (CEI) is a method that uses ST-segment deviations from the 12-lead electrocardiogram (ECG) and has been tested on a small number of patients.

Aim: To extend the testing material of the CEI method and deduce a threshold using ECGs recorded pre- and during acute occlusion. The performance of the CEI and ST elevation myocardial infarction (STEMI) criteria will be compared.

Method: Two CEI images were generated from each of 99 patients before and during complete occlusion in the left anterior descending (LAD), right coronary artery (RCA) and left circumflex coronary artery (LCx).

Result: The sensitivity and specificity of STEMI criteria was 61% and 96% respectively for the whole occlusion group. The sensitivities and specificities were 74 %, 97% (LAD); 60%, 94% (RCA); 35%, 100% (LCx) respectively, for STEMI criteria. A threshold of 998 units was deduced from the CEI method.

Conclusion: The CEI method has similar diagnostic performance of an occlusion as STEMI criteria.

Keywords: 12-lead ECG; acute coronary occlusion; computed electrocardiographic imaging; maximum positive heart surface potentials; STEMI- criteria; PCI.
Introduction

Acute coronary occlusion can be diagnosed with electrocardiography (ECG), which is a very useful, widely available and inexpensive diagnostic method. Electrocardiographic changes typically appear several minutes before myocardial ischemia/necrosis can be detected in peripheral blood. The signs on the ECG are ST-segment elevation and/or depression. ST-deviation patterns that are caused by acute myocardial infarction are typically classified as ST-elevation myocardial infarction (STEMI) or non ST-elevation myocardial infarction (NSTEMI). There are specific STEMI criteria where certain magnitudes of ST change have to be met in different ECG leads.

ST depression in leads V1-V3 is often called “STEMI equivalent”, if the depression pattern is considered to possibly reflect occlusion of the left circumflex coronary artery (LCx). This infarction occurs in the posterolateral part of the heart and is viewed as ST-segment depression instead of ST-segment elevation, because ECG leads are missing on the posterolateral part of the thorax.

Patients with acute coronary occlusion should be treated with percutaneous coronary intervention (PCI) or with thrombolytic agents. Early detection with ECG gives improved treatment results and will decrease mortality in those patients. The infarct size would be limited by early therapy and reperfusion.

Measurements of ST-segment levels in the 12-lead ECG have been displayed in the form of maps, and are described and investigated in several studies.

Two studies essentially displayed the 3-dimensional ST-segment vector in two graphic ST displays, one for the frontal plane and one for the transverse plane. The first one presented an “ST compass”, to visualize the ST-segment deviations, and the other one studied the value of adding numeric ST information and/or an “ST map” to the paper print of the conventional 12-lead ECG.

Other studies presented the extent and location of area at risk in patients with acute myocardial infarction, graphically, on a spherical surface (in a geometrical projection). One study presented a geometrical projection containing the ST-segment vector that is transferred to a “bull’s eye image” from the body surface and another study only localized the center of the ischemic area.
Another study\(^{10}\) derived polar plots representation to localize myocardium at risk and to determine the infarct size. These plots were compared to the distribution of ST-segment deviations from the 12-lead ECG, magnetic resonance imaging and to myocardial single photon emission computed tomography (SPECT) images.

An automated/statistical method was also developed in one study\(^{11}\) that displayed, from an ECG, the localization of the ischemic part of the myocardium.

An alternative method of calculating and displaying heart-surface potentials was developed and labeled “computed electrocardiographic imaging”, (CEI), as shown in figure 1\(^{12,13}\). The CEI method is based on heart surface potentials maps, estimated from a 12-lead ECG\(^{12-14}\). The ST deviations from the ECG are represented as a bull’s eye image (CEI image). The CEI method was tested by qualitatively comparing the heart-surface potential maps from the 12-lead ECG with myocardial SPECT images that estimate acute ischemia in small groups of patients undergoing PCI for treatment of stable coronary artery disease\(^{12}\). The test results showed good agreement between areas of decreased isotope uptake in myocardial SPECT images and the presence of ST elevation on the heart surface as displayed on the CEI image. Therefore, the CEI method may facilitate diagnosis of acute coronary occlusion in comparison to assessing the conventionally displayed 12-lead ECG\(^{12,13}\).

**Aim**

The aim of this study is to extend the testing material of the CEI method to a larger cohort of patients, before and during complete balloon occlusion. In addition, the performance of the CEI method will be compared to the performance of ST-elevation myocardial infarction (STEMI) criteria. A threshold on the maximum positive heart surface potentials will also be deduced.
Methods

Study population

STAFF III
Electrocardiographic recordings are available from 99 patients undergoing elective PCI \(^{15}\). The patient data were collected in West Virginia (USA) at Charleston Area Medical Centre during 1995-1996, in a study named STAFF III. There were 63 males and 36 females included in the study, with an age of \(\geq 60\) years.

These patients had chronic ischemic heart disease and a stenosis in at least one of the major coronary arteries. They underwent elective PCI with non-perfusion balloon catheter inflated during five minutes, causing an occlusion in one of the major coronary arteries.

ECG recordings from the 99 patients were made before (preocclusion, baseline), during (at peak inflation) and after complete balloon occlusion. Each patient had two ECGs included in this study, one at preocclusion and the other one at occlusion. Totally, 198 ECGs from 99 patients are used in this study.

Out of the 99 patients, 35 were occluded in the left anterior descending coronary artery (LAD), 47 in the right coronary artery (RCA) and 17 in the left circumflex (LCx) coronary artery.

The detailed location of the intracoronary balloon is known for the material and is the gold standard for this study.

The local investigational review board approved the study and informed permission was obtained from each patient before enrolment.

Computed electrocardiographic imaging, CEI
All the ECG recordings (from the STAFF III patients) were available in Dalhousie University, Halifax, Canada where the ECGs were processed. In-house software was used to locate the J-point in each lead, i.e. the point where QRS ends and the ST-segment begins. Amplitude measurements at the J-point were then used to generate 198 CEI images with the maximum positive heart surface potential as an indicator for the presence of an occlusion. ST elevation is shown as dark red area on the CEI image (figure 1).

The CEI method has been described previously \(^{12,13}\). This method is based on ST-segment deviations from the 12-lead ECG that is transformed to body surface potential maps (BSPM). From the BSPM, epicardial heart surface potentials are estimated by an inverse solution.
Finally, the heart surface potentials are projected to a 17-segment bull’s eye plot\textsuperscript{16}, also named CEI image. The segments represent different parts of the heart and the colors indicate the range of epicardial potentials from elevation (red) to depression (green). Areas with the highest positive values indicate the location of the possibly ischemic region of the heart. The magnitudes are also of importance. LAD, RCA and LCx are the different coronary arteries in the myocardium to be considered.

\begin{figure}[h]
\centering
\includegraphics[width=0.6\textwidth]{cei_image.png}
\caption{CEI image, which is a flattened image of the myocardium, in a patient with RCA occlusion and its maximum and minimum heart surface potential indicated above the image. The colors indicate the range of potentials from ST elevation/occlusion (red) to depression (green). The white circles indicate areas of the myocardium with the largest sum of positive potentials. The central (middle) part of the CEI image represents the apical part of the myocardium and the outermost segments of the CEI image illustrate the basal part. The septal, inferior, lateral and anterior part, as well as the segments of the myocardium, are shown in the image.}
\end{figure}
**Quantitative assessment**

The CEI images with the maximum positive heart surface potential were derived from the 12-lead ECG at preocclusion and complete balloon from the STAFF III population. Maximum positive heart surface potentials from the CEI at preocclusion are used for determining the specificity of the CEI method. Maximum positive heart surface potentials from the CEI after five minutes of complete balloon occlusion from the same patients are used for determining the sensitivity of CEI in detecting an occlusion, and also for detecting the occluded coronary artery. These sensitivities and specificities of the CEI are compared to those using STEMI criteria.

The STEMI criteria are as follows:\(^2\):

- The amplitude at the J point in both V2 and V3 as contiguous pair is \(\geq 200 \mu V\) in men and \(\geq 150 \mu V\) in women
- The amplitude at the J point in both V1 and V2 as contiguous pair is in lead V1 \(\geq 100 \mu V\) in both genders, and in lead V2 \(\geq 200 \mu V\) in men and \(\geq 150 \mu V\) in women
- The amplitude at the J point in both V3 and V4 as contiguous pair is in lead V3 \(\geq 200 \mu V\) in men and \(\geq 150 \mu V\) in women, and in lead V4 \(\geq 100 \mu V\) in both genders
- The amplitude at the J point in any of the contiguous lead pairs (V4, V5), (V5, V6), (aVL, I), (I, –aVR), (–aVR, II), (II, aVF), (aVF, III) were \(\geq 100 \mu V\) in both genders
- The lead –aVR denotes the inverted lead aVR.

**Statistical analysis**

Receiver operating characteristic curves (ROC curves) are plotted to visualize the specificities (preocclusion) and sensitivities (occlusion) when using each patient’s maximum positive heart surface potential, with the statistical program SPSS version 20.0. Further, ROC curves are plotted for maximum positive heart surface potentials for each occlusion site (LAD, RCA, LCx) (sensitivity) against maximum positive ST-heart surface potentials at preocclusion (specificity), for the same patients. For comparison between the performance of the CEI and STEMI criteria, a point indicating the specificity and sensitivity of published STEMI criteria\(^2\) is included for each of the above described ROC.
Results

Three typical CEI images, one at preocclusion and two at occlusion (LAD and LCx respectively) are presented in figure 2. The preocclusion image (2A) shows a non-distinct pattern, while the occlusion images show distinct, focal patterns. Figure 2B exhibits a region of positivity (dark red colour) in the anteroseptal region (2B), while figure 2C exhibits a region of positivity in the inferolateral region. These patterns are consistent with ST-segment deviation due to regional ischemia induced by the balloon occlusions.

The ROC curve for the whole STAFF III population is shown in figure 3A and the point representing the sensitivity (61%) and specificity (96%) of STEMI criteria is positioned on the ROC curve.

The ROC curve for the patients with LAD occlusion (sensitivity) and preocclusion (specificity), presented in figure 3B, the point indicates the sensitivity (74%) and specificity (97%) for STEMI criteria is positioned below the curve.

For the patients with RCA occlusion, the ROC curve in figure 3C represents the sensitivity and specificity 60% and 94% respectively for STEMI criteria that is positioned above but very close to the ROC curve.

The ROC curve for patients with LCx occlusion, the position of the point in figure 3D indicates the sensitivity (35%) and specificity (100%) for STEMI criteria and is on the y axis.

A  B  C

MIN -858  MAX 603  MIN -392  MAX 424  MIN -719  MAX 789

**Figure 2.** CEI image in a patient at A) preocclusion, B) LAD occlusion, C) LCx occlusion, and the maximum and minimum heart surface potential above each image.
Figure 3. ROC curve illustrating the sensitivity and specificity when using each patients’ maximum positive heart surface potentials from the CEI at preocclusion and occlusion. Using STEMI criteria as a positive indicator of occlusion is shown as a point on the ROC curves of the
A) whole STAFF III population, B) LAD population, C) RCA population, D) LCx population.
In order for the CEI method to result in the specificity obtained for the STEMI criteria in this material (96%), a threshold of 998 units has to be applied. This threshold yields the same sensitivity (61%) for both methods as presented in table 1.

The sensitivities and specificities for each of the occlusion sites LAD, RCA and LCx, as presented in table 1 are similar, where a higher sensitivity and specificity are observed in patients occluded in the LAD coronary artery, when diagnosed with the CEI method. The sensitivity, in patients with an occlusion in the RCA, of the CEI method is lower than for the STEMI criteria, but the specificity is similar in the two methods. The specificity of patients occluded in the LCx coronary artery is higher with STEMI criteria, in comparison to the CEI method and the sensitivity is higher in the CEI method.

In the occlusion group (table 2), both the CEI method and STEMI criteria agreed on the presence of occlusion in 53 patients and in six patients there was a disagreement, where STEMI criteria were correct in the detection of the occlusion. Eight patients were detected as non-occlusion with STEMI criteria, which is incorrect, and detected as occlusion with the CEI method, that is, according to the gold standard, the correct diagnosis. The presence of occlusion was not detected with both methods in 32 patients.

In the preocclusion group (table 3), both STEMI criteria and the CEI method failed in the detection of non-occlusion in one patient, which was classified as occlusion. In three patients there were a disagreement in the absence of occlusion. Three patients were detected as non-occlusion with STEMI criteria, which is correct, but the CEI method detected these patients as occlusion. In 92 patients, both methods agreed in the absence of occlusion.

Table 1. Summary of the performance of STEMI criteria versus the CEI method.

<table>
<thead>
<tr>
<th></th>
<th>CEI method</th>
<th>STEMI criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sensitivity</td>
<td>Specificity</td>
</tr>
<tr>
<td>All cases (n = 198)</td>
<td>61%</td>
<td>96%</td>
</tr>
<tr>
<td>LAD (n = 70)</td>
<td>83%</td>
<td>100%</td>
</tr>
<tr>
<td>RCA (n = 94)</td>
<td>49%</td>
<td>94%</td>
</tr>
<tr>
<td>LCx (n = 34)</td>
<td>47%</td>
<td>94%</td>
</tr>
</tbody>
</table>
Table 2. Summary of the sensitivity of STEMI criteria versus CEI method on occlusion ECGs.

<table>
<thead>
<tr>
<th>CEI method</th>
<th>STEMI criteria</th>
<th>Occlusion</th>
<th>Non-Occlusion</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Occlusion</td>
<td>53</td>
<td>8</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>Non-Occlusion</td>
<td>6</td>
<td>32</td>
<td>38</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>59</td>
<td>40</td>
<td>99</td>
</tr>
</tbody>
</table>

Table 3. Summary of the specificity of STEMI criteria versus CEI method on preocclusion ECGs.

<table>
<thead>
<tr>
<th>CEI method</th>
<th>STEMI criteria</th>
<th>Occlusion</th>
<th>Non-Occlusion</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Occlusion</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Non-Occlusion</td>
<td>3</td>
<td>92</td>
<td>95</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>4</td>
<td>95</td>
<td>99</td>
</tr>
</tbody>
</table>
Discussion

The aim of this study was to extend the testing material of the CEI method to a larger cohort of patients, before and during complete balloon occlusion. In addition, the performance of the CEI method was compared to the performance of STEMI criteria. A threshold on the maximum positive heart surface potentials was also deduced. Previous studies have made qualitative assessment of the CEI image\(^{12, 13, 15-17}\), where the studies compared the CEI image with myocardial SPECT images using small numbers of patients. Thus, no studies have made a quantitative assessment of the CEI method and no thresholds have previously been deduced. However, the present study is the first one to do this.

The point on the ROC curve illustrating the sensitivity and specificity when using the maximum positive heart surface potentials of the whole STAFF III population is positioned on the curve, indicating that the CEI method and STEMI criteria have similar diagnostic performance. The point is positioned below the curve on the LAD ROC curve, indicating that the CEI method has a better diagnostic performance than STEMI criteria, in diagnosing an occlusion. On the RCA ROC curve, the point is located above, but very close to the curve. Thus, STEMI criteria have a better diagnostic performance than the CEI method for this patient category. For the LCx ROC curve, the specificity was estimated at 100%. If another point on the ROC curve is chosen, where the sensitivity is 80% and the specificity is 95%, the performance of the CEI will be much improved compared to STEMI criteria, in the diagnosis of an occlusion. The number of patients in each occlusion site is not equal and small and that might affects the results. The group with the smallest number of patients was the LCx (17 patients) and might have resulted in a specificity of 100%.

The overall sensitivities and specificities (of the whole population, as well as LAD, RCA and LCx), from the CEI method and STEMI criteria are similar, but the sensitivity of the CEI in the RCA patients is much lower than for STEMI criteria. In 53 patients, both the CEI method and STEMI criteria agreed on the presence of occlusion. Both methods agreed on the absence of the occlusion in 92 patients.

A threshold of 998 units was deduced in the present study, and a further validation is therefore needed, to investigate whether this threshold is clinically applicable. Using another
patient population with the deduced threshold or with another threshold, the sensitivity and specificity of the CEI might improve.

On the ROC curve for the whole STAFF III population, a further extra point could be included, indicating the sensitivity and specificity when using CEI or STEMI criteria, to investigate whether the diagnostic performance of the ECG improves.

Two studies \(^6\)\(^7\) displayed a 3-dimensional ST-segment vector in two graphic ST displays in the frontal- and transverse plane. The first one \(^6\) presented an ST compass and the other one \(^7\) studied the usefulness of adding ST measurements to the conventional 12-lead ECG. Other studies \(^8\)\(^11\) described a geometric projection of the ST-segment vector onto a heart-shaped object. Another study \(^9\) derived an ST vector from the 12-lead ECG onto a left ventricular model to facilitate the localization of ischemia. A further study \(^10\) created polar plots representation to localize myocardium at risk. All the described methods as well as the CEI method \(^12\)\(^13\) can be easily integrated into cardiac monitors interpretive ECG carts and can be used in emergency care units and ambulances. Since the CEI method is based on the inverse solution that uses an estimated body surface map whose accuracy has been validated, it is expected that it will produce a better representation of "true" epicardial potentials than the projection methods that are described in \(^6\)\(^-\)\(^11\).

The STAFF III study is very unique because of the prolonged PCI treatment (approximately five minutes) that reflects the clinical situation of an acute coronary artery occlusion \(^18\).

The pattern of the CEI image can also be used in the diagnosis of acute coronary occlusion, taking into account different colors indicating the range of epicardial ST potentials from elevation (red) to depression (green). In further studies, the assessment of patterns should be combined with quantitative data of the maximum positive heart surface potentials.

**Limitations**

Percutaneous coronary intervention treatment was used to cause an occlusion in the STAFF III population coronary arteries and the CEI image that is derived from the 12-lead ECG still does not reflect the situation in patients’ real life. It might be more interesting to include patients with acute coronary occlusion when presenting at an emergency room.
There are several versions of STEMI criteria and only the conventional criteria have been used in this study. It is possible when choosing other (or further) STEMI criteria, the sensitivity and specificity of the present study will improve.

**Conclusion**

The maximum positive ST heart surface potential from the CEI image has similar diagnostic performance of a coronary artery occlusion as STEMI criteria. However, further studies are needed to investigate whether the CEI image can improve the diagnosis of coronary occlusion when using its maximum positive heart surface potential value in combination with the pattern of the CEI image.

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References


