

Subtraction electrocardiography: Detection of ischemia-induced ST displacement without the need to identify the J point

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Abstract

Background: When triaging a patient with acute chest pain at first medical contact, an electrocardiogram (ECG) is routinely made and inspected for signs of myocardial ischemia. The guidelines recommend comparison of the acute and an earlier-made ECG, when available. No concrete recommendations for this comparison exist, neither is known how to handle J-point identification difficulties. Here we present a J-point independent method for such a comparison.

Methods: After conversion to vectorcardiograms, baseline and acute ischemic ECGs after 3 minutes of balloon occlusion during elective PCI were compared in 81 patients of the STAFF III ECG database. Baseline vectorcardiograms were subtracted from ischemic vectorcardiograms using either the QRS onsets or the J points as synchronization instants, yielding vector magnitude difference signals, ΔH . Output variables for the J-point synchronized differences were ΔH at the actual J point and at 20, 40, 60 and 80 ms thereafter. Output variables for the onset-QRS synchronized differences were the ΔH at 80, 100, 120, 140 and 160 ms after onset QRS. Finally, linear regressions of all combinations of $\Delta H_J + \dots$ versus $\Delta H_{QRS} + \dots$ were made, and the best combination was identified.

Results: The highest correlation, 0.93 ($p < 0.01$), was found between ΔH 40 ms after the J point and 160 ms after the onset of the QRS complex. With a ΔH ischemia threshold of 0.05 mV, 66/81 (J-point synchronized differences) and 68/81 (onset-QRS synchronized differences) subjects were above the ischemia threshold, corresponding to sensitivities of 81% and 84%, respectively.

Conclusion: Our current study opens an alternative way to detect cardiac ischemia without the need for human expertise for determination of the J point by measuring the difference vector magnitude at 160 ms after the onset of the QRS complex.

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Keywords: Electrocardiogram; ST displacement; J-point identification

Introduction

When triaging a patient with acute chest pain at first medical contact, an electrocardiogram (ECG) is routinely made and inspected for signs of myocardial ischemia, to support clinical decision making. Usually, and according to the guidelines [1], the ECG is inspected on signs of ST elevation or depression often measured at the J point or at fixed distance, e.g., 60 ms, thereafter [2,3]. ST deviations in ischemia are classically explained as a consequence of diastolic, phase 4, injury current in combination with systolic injury current [4]. In practice, the interpretation of ST deviations in ischemia is often complicated by pre-existing non-zero ST amplitudes and/or conduction disturbances and by ischemia-induced delayed conduction and/

or early repolarization, sometimes leading to various expressions of a J wave, like notches and slurs, and to an obscured or unidentifiable J point [5–7]. Serial comparison of the acute ECG with a previous ECG of the same patient that was made under conditions that were not suspect for acute ischemia can reveal whether the observed ST deviations and conduction disturbances are new. Serial ECG analysis could also reveal the actual ischemia-induced ST deviation by subtracting the pre-existing from the acute ST amplitude. Vectorcardiographically, this would result in the establishment of the ST difference vector (“injury vector”) that gives the net displacement of the ST segment as a consequence of ischemia [8,9].

The guidelines [1] do not prescribe specific algorithms for serial ECG comparison and what to do when problems arise. For example, ischemia can broaden the QRS complex; in such a case, serial comparison of J-point amplitudes or amplitudes at a fixed distance after the J point would imply that the

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compared acute and pre-existing amplitudes are relatively shifted in the cardiac cycle, making such a comparison somewhat awkward. An even more serious problem arises if it is not possible to identify the J point at all, or if discussion about the position of the J point remains. In the current study, we investigate the possibility of determining an ST difference vector that is J point independent.

Methods

For this study, we compared baseline ECGs with acute ischemic ECGs during elective percutaneous coronary intervention (PCI). These data belong to the STAFF III database [10,11]. Data processing details can be found in an earlier publication of our group [8]. Briefly, 10-second ECG episodes were selected from the baseline ECG and from the ECG recording made continuously during PCI, the latter after 3 minutes of balloon occlusion. ECGs were analyzed by using the LEADS program [12]. Vectorcardiograms (VCGs) were mathematically synthesized from the standard 12-lead ECGs by matrix multiplication. The vectorcardiographic representation of the averaged beat was output in the form of the 500 Hz sampled X, Y and Z leads. Then, in each patient, the baseline VCG was vectorially subtracted from the ischemic VCG using either the onset of the QRS complex or the J point as synchronization instants. Finally, the vector magnitude signal of the difference between the baseline and the ischemic VCG was computed for both subtraction-synchronization instants. In the following, this difference vector magnitude is denoted as ΔH (the symbol H refers to the heart vector).

Output variables for the J-point synchronized differences were the difference vector magnitudes at the actual J point and at 20, 40, 60 and 80 ms thereafter: ΔH_{J+0} , ΔH_{J+20} , ..., ΔH_{J+80} . Output variables for the onset-QRS synchronized differences were the difference vector magnitudes at 80, 100, 120, 140 and 160 ms after onset QRS: ΔH_{QRS+80} , $\Delta H_{QRS+100}$, ..., $\Delta H_{QRS+160}$. Finally, linear regressions of all combinations of $\Delta H_{J+...}$ versus $\Delta H_{QRS+...}$ were made, and the combination with the highest correlation was identified.

Results

The study group consisted of 81 patients. Patient characteristics are described in Table 1. Fig. 1 gives an example of the signal processing steps in one patient. Panels A and B depict the baseline and ischemic vectorcardiograms (VCGs). Panels C and D show J-point synchronized and onset-QRS synchronized difference vectorcardiograms (baseline VCG subtracted from ischemic VCG); panels E and F depict the corresponding difference vector magnitude signals.

Fig. 2 gives examples of J-point synchronized and onset-QRS synchronized difference vector magnitude signals. Three major patterns of the difference vector magnitude signal were observed. Upper panels A and B depict a pattern that is characterized by a fairly horizontal or slightly up- or down-sloping signal during the ST segment. Middle panels C and D

Table 1
Patient characteristics.

	Number	%
N	81	
Sex (male/female)	52/29	64/36
Mean \pm SD age (years)	60 \pm 12	
Aberrant conduction ^a	4	4.9
Previous infarction ^b	26	32
STEMI occlusion ECG ^c	58	70

^a Number of patients with aberrant conduction in the baseline ECG.

^b Number of patients with a baseline ECG suggestive of previous myocardial infarction.

^c Number of patients in whom the occlusion ECG shows a STEMI pattern [16] (ST elevation of ≥ 0.1 mV in two adjacent limb or precordial leads, except for leads V2 and V3 in which the threshold is 0.2 mV; including "STEMI equivalent": less than or equal to -0.05 mV in V2 and V3).

depict a saddle-shaped pattern. Lower panels E and F show a less-frequently-occurring steeply down-sloping pattern of the difference vector magnitude signal during the ST segment. All three patterns occurred with and without ischemia-induced QRS widening. Ischemia-induced QRS widening (e.g., 18 ms in panels C and D, and 20 ms in panels E and F) gave rise to striking differences over the QRS complex between the J-point and onset-QRS synchronized subtraction signal. The subtraction signal over the ST segment remained, however, relatively unaffected by the subtraction-synchronization instant.

Fig. 3 shows the baseline (panel A) and ischemic (panel B) ECGs of the patient of whom the difference vector magnitude signals are depicted in panels E and F of Fig. 2. Of note, the QRS complex and the T wave, who are clearly separated in the baseline ECG, have merged completely in several leads in the ischemic ECG, and no distinct ST segment can be discerned. This phenomenon occurred in about 10% of the study population; a precise number is difficult to determine because in part of these subjects this phenomenon is present, but less outspoken. In subjects presenting with an unstable difference vector magnitude signal in the ST range, it is evident that the time lag after the synchronization point at which the difference vector magnitude is determined is of much influence on the measurement result.

Fig. 4 depicts the difference vector magnitudes averaged for the study group as a function of the time lag after the subtraction-synchronization point. J-point synchronized subtraction data are displayed at the J point and at 20, 40, 60 and 80 ms thereafter. Onset-QRS synchronized subtraction data are displayed at onset QRS plus 80, 100, 120, 140 and 160 ms. The J-point synchronized subtraction-data curve flattened at 40 ms after the J point. The onset-QRS synchronized subtraction-data curve flattened at 140 ms after the onset of the QRS complex. The average amplitudes in the terminal parts of both curves were almost identical. E.g., at a time lag of 40 ms after the J point, the mean \pm SD difference vector magnitude was 0.14 ± 0.12 mV, and at a time lag of 140 ms after the onset of the QRS complex the mean \pm SD difference vector magnitude was 0.15 ± 0.15 mV.

The highest correlation between $\Delta H_{J+...}$ and $\Delta H_{QRS+...}$, 0.93 ($p < 0.01$), was found between the measurements 40 ms

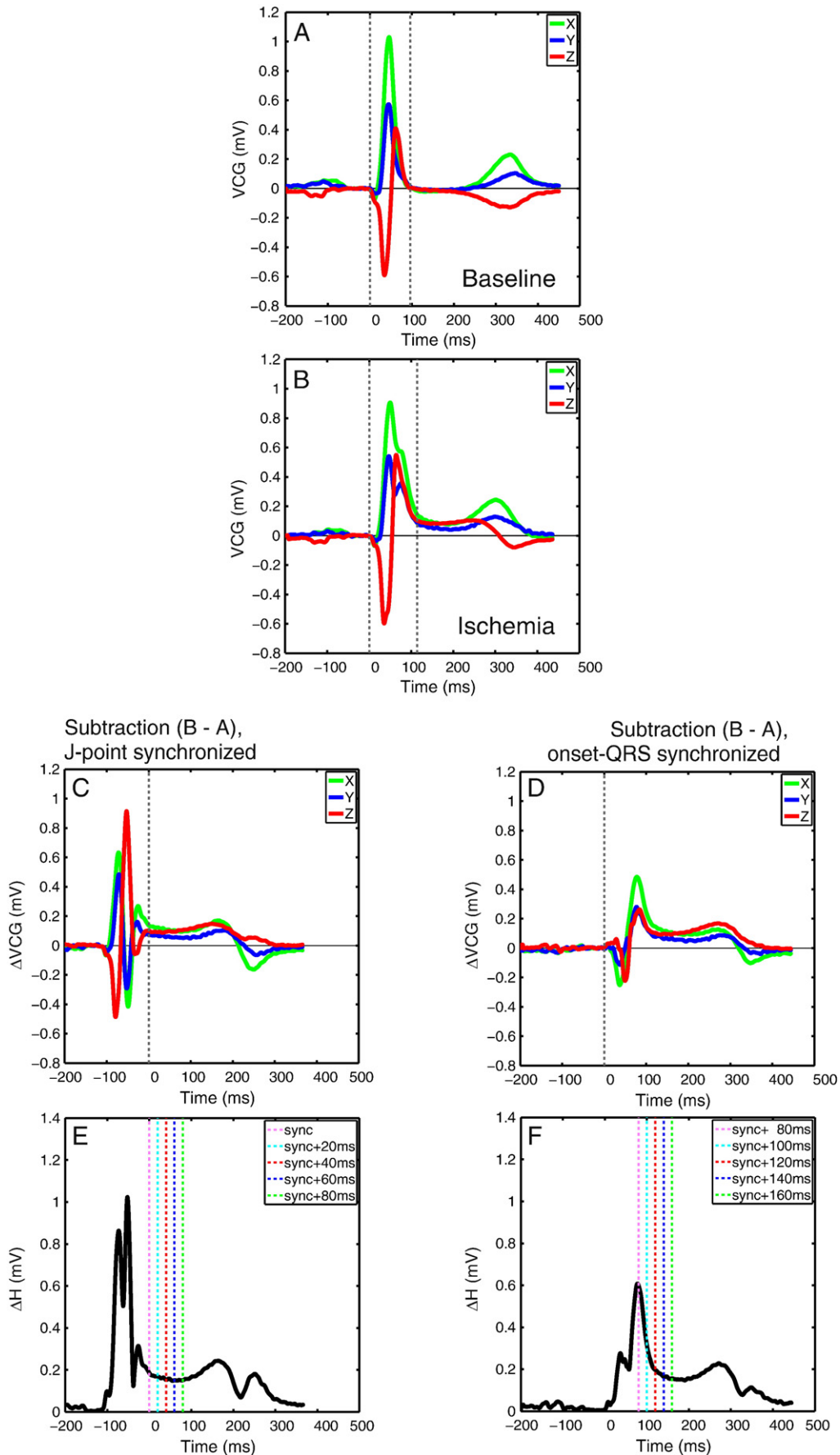


Fig. 1. Example of J-point synchronized and onset-QRS synchronized subtraction of a baseline VCG from an ischemic VCG in a patient (subject #11 in the STAFF III database). Panels A and B: baseline and ischemic VCG. Panels C and E: J-point synchronized subtraction. Panels D and F: onset-QRS synchronized subtraction. Panels C and D: lead-dependent baseline-ischemia amplitude-difference (ΔVCG) signal. Panels E and F: baseline-ischemia difference-vector-magnitude (ΔH) signal.

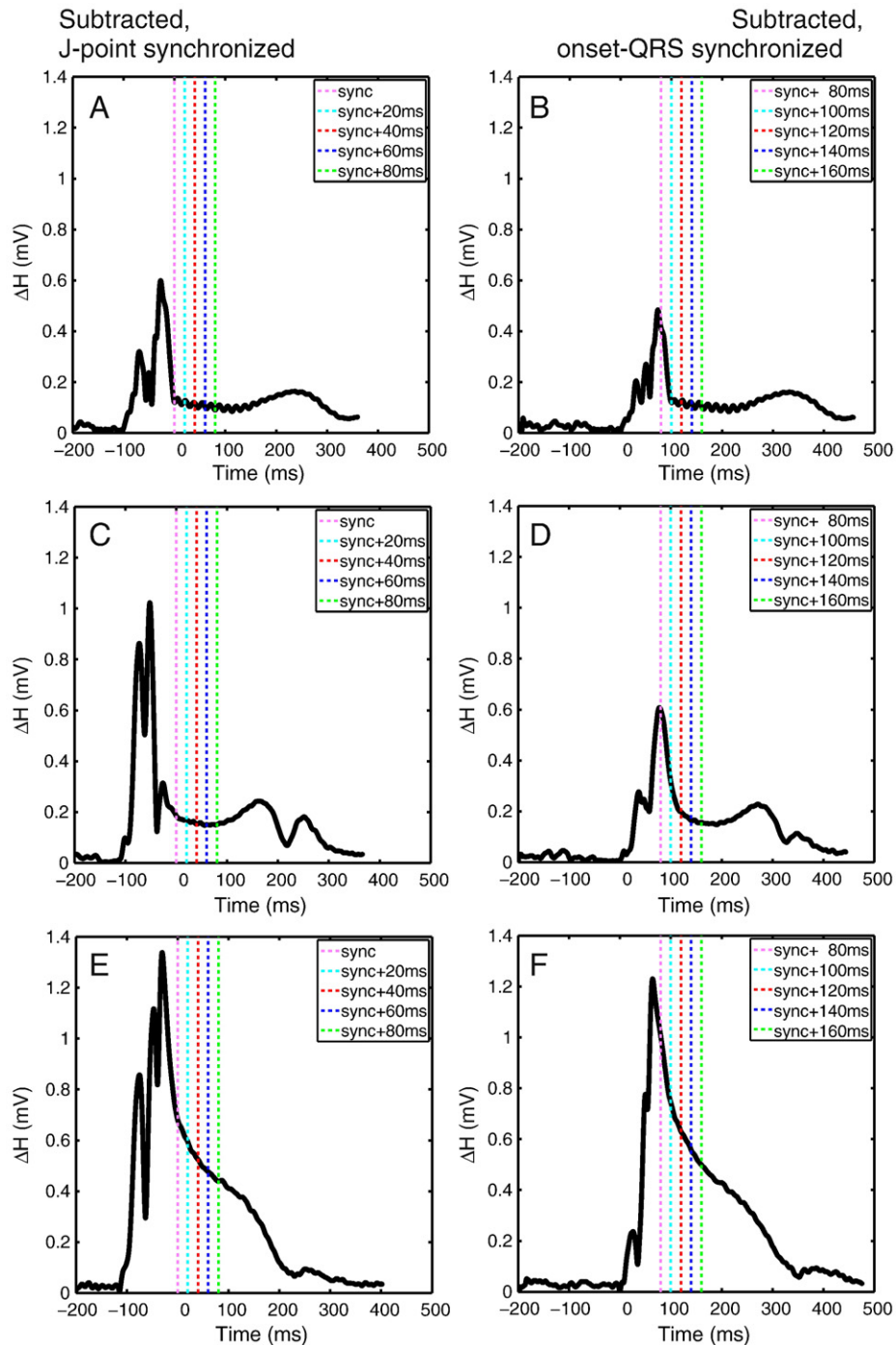


Fig. 2. Three typical difference vector magnitude (ΔH) patterns in the ST segment as met in the study population. Panels A and B (subject #84 in the STAFF III database): fairly horizontal or slightly up- or down-sloping. Panels C and D (subject #11 in the STAFF III database): saddle shaped. Panels E and F (subject #44 in the STAFF III database): steeply down-sloping. All three patterns can occur with or without ischemia-induced QRS widening. It is a general observation that ischemia-induced QRS widening (e.g., 18 ms between panels C and D, and 20 ms between panels E and F) gives rise to striking differences between the J-point and onset-QRS synchronized subtraction signal over the QRS complex. The subtraction signal over the ST segment remains, however, relatively unaffected by the subtraction-synchronization instant.

after the J point, ΔH_{J+40} , and 160 ms after the onset of the QRS complex, $\Delta H_{QRS+160}$. Fig. 5 shows the corresponding scatterplot. In previous publications [8,9] we have suggested a difference-vector-magnitude ischemia threshold of 0.05 mV. In the current study, with the measurements made at a time lag of 40 ms after the J point and at a time lag of 160 ms after the onset of the QRS complex, 66/81 and 68/81 subjects were

above the ischemia threshold, corresponding to sensitivities of 81% and 84%, respectively.

Discussion

We vectorially subtracted baseline ECGs from acute ischemic ECGs (see Fig. 1) in 81 patients who underwent

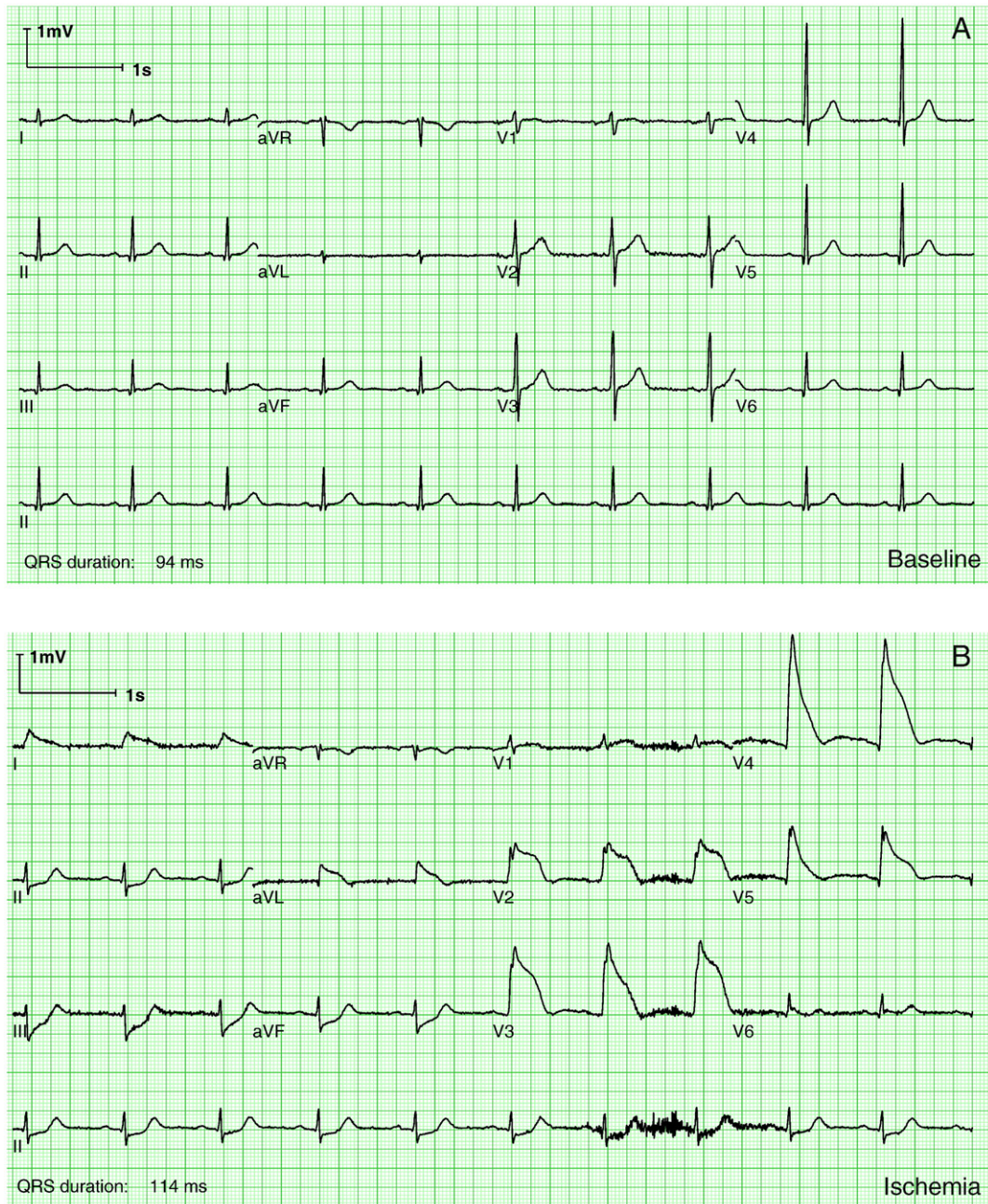


Fig. 3. Baseline and ischemic ECG in subject #44 in the STAFF III database. The J-point and onset-QRS synchronized subtraction signals of this patient are shown in panels E and F of Fig. 2. In this patient, the QRS complex and the T wave, who are distinctly separated in the baseline ECG, have merged completely in several leads in the ischemic ECG, and no distinct ST segment can be discerned. This type of ischemic ECG change and the associated difference-signal pattern as seen in panels E and F of Fig. 2 occurred in about 10% of the study group.

elective PCI, and studied the behavior of the difference vector magnitude signals. Subtractions were done in two ways: synchronized on the J points or synchronized on the onsets of the QRS complexes in the baseline and ischemic ECGs.

According to current insight, ischemia-induced differences in the J-point amplitudes are primarily caused by the baseline displacement due to the ischemia-induced phase-4 injury current that flows from partly depolarized ischemic tissue to the fully polarized surrounding healthy tissue. Additionally, other ischemia-related effects contribute to the J-point amplitude difference. Ischemia alters the entire action potential morphology of the involved myocytes, hence, there

are also injury currents flowing at the J-point instant (see Figs. 12-31 and 12-32 in Braunwald's Heart Disease [4]). Possible pre-existing or ischemia-induced delayed conduction and/or early repolarization hamper detection of the J point and affect its amplitude [5–7]. It is unlikely that the above-mentioned contributions to the J-point displacement can be unraveled; this is an intrinsic difficulty for the interpretation of ischemic ECGs.

A basic question is how to measure the ST displacement: at the J point or at a fixed time lag thereafter. Subtraction of the baseline ECG from the ischemic ECG is a logical first step, because that corrects for possible pre-existent non-zero

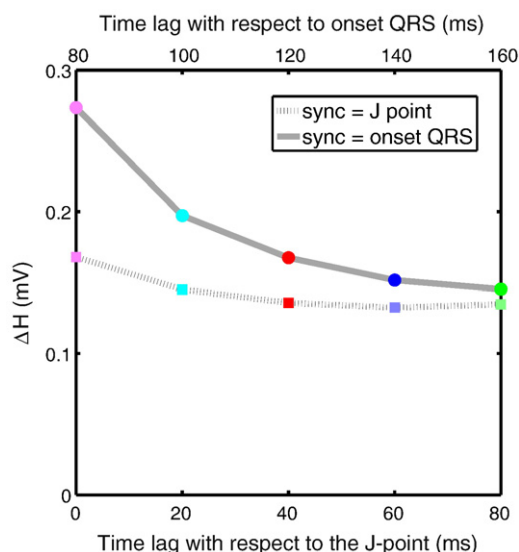


Fig. 4. Average difference vector magnitudes (ΔH) in the study group as a function of the time lag with respect to the subtraction-synchronization points. The marker colors correspond to those used for the dashed lines in Fig. 2 and in panels E and F of Fig. 1 that denote the time lag with respect to the subtraction-synchronization points.

amplitudes. Where to measure exactly, has ever been a point of discussion. The guidelines [1] suggest that measurements be made at the very J point, but several authors have suggested a fixed time interval thereafter, *e.g.*, after a time lag of 40 or 60 ms [2,3]. We were curious to see how critical the measurement instant is for the ST displacement. This appeared not to be very relevant, as is evident from the average J-point synchronized difference vector magnitude displayed in Fig. 4. The insensitivity of the ST displacement for the exact measurement instant is caused by the limited dynamics of the difference vector magnitude signal in the ST segment (see Fig. 2 panels A and C), except for a minority of cases (see, *e.g.*, Fig. 2 panel E). The phase-4 injury-current induced baseline shift likely generates a constant difference vector magnitude signal throughout, while the dynamics in the difference vector magnitude signal are caused by injury currents that occur during the action potential itself. See Figs. 2 and 4.

Strikingly, there was little difference between the ST displacement when assessed either by J-point synchronized or by onset-QRS synchronized subtraction. In our study population, measurements made at a time lag of 40 ms after the J point (ΔH_{J+40}) and at a time lag of 140 ms after the onset of the QRS complex ($\Delta H_{QRS+140}$) were almost similar: the slope of the regression line, 0.98, equals almost 1, the intercept of the regression line, 0.01, equals almost 0, and the correlation, 0.93, is very high (see Fig. 5). While the synchronization instant for subtraction (the J point or the onset of the QRS complex) can give rise to differences in the QRS and/or T range (compare panels C and D and panels E and F in Fig. 2), the differences in the ST range remain limited.

The J point is classically defined as the time instant at which an ECG tracing changes slope abruptly at the end of the S wave [13]. In a 12-lead ECG, theoretically, 12 different lead-dependent J points could be identified; the global J point

is the latest of the lead-dependent J points [14,15]. Determination of the J point can be problematic, especially in ischemic ECGs. In our view, accurate establishment of the J point requires a superimposed magnified display of all ECG leads, a form of ECG rendering that is not routinely available in the clinic. Irrespective the available ECG display modality, the ECG analyst is faced with a difficult task. Small amounts of noise can already mask a J point. Moreover, delayed conduction as well as early repolarization, manifesting as notches, slurs or J waves [5–7], are further complicating this task. These phenomena have reopened the discussion about where exactly in the ECG ST elevation should be measured [7]. Our study suggests that a solution can be found in a measurement at a fixed distance, 160 ms, after the onset of the QRS complex. This yields a sensitivity of 84% at an ischemia threshold of 0.05 mV for the difference vector magnitude in our study group. This means that still 16% of the cases are missed, but it is a considerable improvement with respect to the 70% sensitivity yielded by the STEMI criteria (Table 1).

Experienced electrocardiographers often visually recognize ischemia by inspecting the entire QRST morphology, instead of, or in addition to, focussing on the J amplitudes only. Obviously, this strategy is not only chosen because of the difficulty of identifying the J point and performing precise J-point amplitude measurements in a conventional ECG tracing, but also because the ischemia-induced action potential changes cause ECG changes throughout the entire QRST wave shape. The findings in our study correspond to this practice. An important advantage of a J-point independent method for ischemia detection by subtraction electrocardiography would be that it can be implemented in automated ECG analysis algorithms. This would make the diagnosis more objective and widely available, also in circumstances where there is a lack of experienced electrocardiographers.

Much is still to be investigated, among others, first-medical-contact ECGs should be studied. When myocardial ischemia is present, the occlusion will not always be complete and will generally have existed for a longer period than 3 minutes, in contrast to our current study group. Also, to

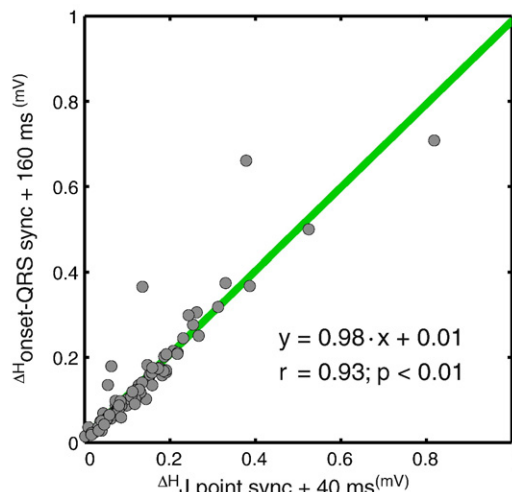


Fig. 5. Scatterplot and linear regression results of the difference vector magnitudes (ΔH) measured in the study group at 40 ms after the J point (X axis) and at 160 ms after the onset of the QRS complex (Y axis).

determine specificity, ECGs made in patients with chest pain due to other causes, should be investigated. Finally, it is relevant to include in such validation studies the performance of experienced electrocardiographers. Sometimes, experts can extract more information from the ECG by global visual inspection rather than by following strict decision rules. An example of this phenomenon has been described in a recent study, where culprit artery assessment in acute ischemic ECGs was correct in 43/53 cases by global visual inspection, and only 38/53 cases by a computer algorithm in which the expert decisions had been formalized. However, an alternative computer algorithm based on a physiological model outperformed the experts (47/53 correct) [17].

Admittedly, subtraction electrocardiography requires a baseline ECG; that is not standard available. However, we believe that with increasing pervasion of digital technology and databases, this will become less an obstacle in the near future.

In conclusion, our current study opens an alternative way to detect cardiac ischemia without the need for human expertise for determination of the J point, by measuring the difference vector magnitude at 160 ms after the onset of the QRS complex.

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