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ORIGINAL SCIENTIFIC PAPER
Acute Coronary Syndromes

Failure of standard contemporary ST-elevation myocardial infarction electrocardiogram criteria to reliably identify acute occlusion of the left anterior descending coronary artery

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Aims

ST-elevation (STE) criteria on the electrocardiogram (ECG) are poorly sensitive for acute coronary occlusion myocardial infarction (ACOMI or OMI). This study evaluates the sensitivity of STE criteria on serial ECGs for total left anterior descending (LAD) coronary artery occlusion. We compared STE criteria with expert interpretation and a validated artificial intelligence (AI) ECG model for diagnosing LAD OMI.

Methods and results

This is a retrospective sub-study of the DOMI-ARIGATO case-control study of OMI (808 patients, 265 with OMI). All cases of total (TIMI-0 flow) LAD occlusion were assessed for STE criteria. An OMI ECG expert blindly interpreted all serial ECGs. An AI model (PMCardio Queen of Hearts) was applied to the first available 12-lead ECG. Among the 53 cases of acute LAD OMI with TIMI-0 flow, 20 (38%) did not meet STE myocardial infarction (STEMI) criteria on any pre-angiography ECG; 16/20 had at least two ECGs before angiography. Both the expert and AI model had 100% sensitivity for diagnosing LAD OMI on the first ECG in these 20 cases. Door-to-balloon time (DBT) was significantly shorter for those meeting STEMI criteria. Infarct size, measured by ejection fraction and peak troponin, did not differ between cases with and without STEMI criteria.

Conclusion

The STEMI criteria missed 38% of acute total LAD occlusions on all serial ECGs. Both expert interpretation and the AI model demonstrated 100% sensitivity on the first ECG for all cases. Despite the lack of STEMI criteria, these cases had similar infarct sizes but were associated with longer DBTs.

Keywords Acute coronary syndromes • STEMI • OMI • LAD occlusion • STEMI criteria • Electrocardiography

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Clinical perspective

- **What is new?** This study demonstrates that standard ST-elevation (STE) criteria on ECGs miss 38% of total LAD occlusions with TIMI-0 flow, while both blinded expert interpretation and an AI model showed 100% sensitivity on the first ECG recorded in these patients.
- **What are the clinical implications?** These findings underscore the need for a paradigm shift from the STEMI model, which relies exclusively on STE, to the OMI-NOMI framework that incorporates additional ECG signs and opens the door for AI integration.
- **Additional insight:** Patients with LAD occlusion not meeting STEMI criteria had similar infarct sizes but longer door-to-balloon times, highlighting the necessity for revised ECG diagnostic methods to reduce treatment delays. An artificial intelligence application designed to diagnose OMI not meeting STEMI criteria had 100% sensitivity.

Research perspective

- **What new question does this study raise?** How can we improve the diagnosis of patients with occlusion myocardial infarction (OMI) who do not present with significant ST-elevation?
- **What question should be addressed next?** Assessment of patient outcome of OMI-based (instead of STEMI-based) diagnostic and management strategies to guide urgent revascularization.
- **Further investigation:** Evaluations should focus on whether incorporating additional diagnostic criteria and AI tools can reduce missed diagnoses and improve clinical outcomes in patients with suspected OMI.

Introduction

Emergency reperfusion is universally recognized as the treatment standard for ST-elevation myocardial infarction (STEMI). This strategy is based on seminal research from over 40 years ago, which established a link between STE on the electrocardiogram (ECG) and acute coronary artery occlusion due to plaque rupture with thrombosis.[1] In this model, the ECG serves as the 'gatekeeper' for identifying patients with acute coronary artery occlusion who require emergent reperfusion. Unfortunately, STE is imperfect for detecting an acute coronary occlusion, resulting in delay in timely reperfusion treatment for many patients. In fact, a recent meta-analysis documented only 43% sensitivity of traditional STEMI ECG quantitative criteria (see *Table 1*) for identifying an acute coronary artery occlusion.[2] Among patients with non-STE myocardial infarction (NSTEMI), 25–34% have thrombolysis in myocardial infarction (TIMI) flow grade 0–1 at next day angiography, and this subgroup has nearly twice the mortality of patients with NSTEMI who demonstrate TIMI flow ≥ 2, despite younger age and fewer comorbidities.[3,4] Koyama *et al.*[5] performed emergent angiography on consecutive patients with suspected MI and persistent symptoms; 57% of STEMI, and 47% of NSTEMI, had TIMI-0 flow. Meyers *et al.*[6] showed that expert OMI ECG diagnosis has double the sensitivity overall for OMI, at nearly equal specificity and better overall accuracy.

In this context, the recent discovery of ECG findings beyond STE that identify acute coronary occlusion myocardial infarction (ACOMI, shortened to OMI) has led to a fundamental change in the acute myocardial infarction (AMI) paradigm from 'STEMI/NSTEMI', which represents one aspect (STE) of one test (the ECG) to 'Occlusion MI vs. Non-Occlusion MI, or 'OMI/NOMI,' a paradigm that describes the underlying pathophysiology.[7] The OMI is defined as persistent acute coronary occlusion without collateral perfusion with imminent and ongoing infarction.[7–21]

In patients with OMI (whether the ECG shows STE or not), there is a high incidence of recanalization (spontaneous reperfusion) aided by antiplatelet and antithrombotic therapy, in the time period between recording the first contact ECG and performing the angiogram.[22] Thus, only 64% of definite true STEMI have TIMI-0 flow at angiography[23] and 16–20% have TIMI-3 flow.[24,25] Nevertheless, the concept of diagnosing patients who have an open artery at angiogram with an 'OMI' remains challenging for many sceptics, and thus, there is a need to assess the sensitivity of STEMI criteria vs. expert interpretation specifically for cases with a culprit with TIMI-0 flow (angiographically confirmed persistent acute occlusion). Furthermore, due to a larger myocardial territory supplied by the LAD, LAD OMI has been shown to result in larger infarcts, with higher mortality, than OMI of other epicardial coronary arteries.[26] Therefore, assessing the sensitivity of STEMI criteria vs. expert annotation for acute total LAD OMI (as defined by culprit TIMI-0 flow) is of significant clinical relevance.

Considering the above issues and recognizing the continued importance of the ECG in AMI management, an artificial intelligence (AI)–powered ECG analysis, compared with STEMI criteria, has doubled the sensitivity for OMI at equal specificity and may improve precision in ECG interpretation in suspected STEMI, leading to improved outcomes.[27] Therefore, we also sought to evaluate the performance of an AI algorithm for identifying acute OMI due to total LAD occlusion among patients who did not meet current STEMI ECG criteria.

Table 1 ST-elevation myocardial infarction criteria from the 4th universal definition of myocardial infarction[29,54]

Electrocardiographic manifestations suggestive of acute myocardial ischaemia (in the absence of left ventricular hypertrophy and bundle branch block)
New ST-elevation at the J-point in two contiguous leads with the cut-point ≥ 1 mm in all leads other than leads V2–V3 where the following cut-points apply: ≥2 mm in men ≥40 years; ≥2.5 mm in men < 40 years; or ≥1.5 mm in women regardless of age

Methods

Study design and setting

This is a sub-study of a retrospective case-control study called the Diagnosis of Occlusion MI And Reperfusion by Interpretation of the electrocardioGram in Acute Thrombotic Occlusion (DOMI ARIGATO) database (clinicaltrials.gov number NCT03863327), a collaboration between two medical centres aimed at examining the sensitivity and specificity of blinded expert interpretation of the ECG for OMI. Stony Brook University Hospital (SBUH) is a suburban academic hospital functioning as a regional cardiac catheterization referral centre. The emergency department (ED) at Hennepin County Medical Center (HCMC) is situated in an urban academic setting. Both institutions experience more than 100 000 ED visits annually. Ethical approval was obtained from the Institutional Review Boards at both sites. This study did not receive any funding from external sources. For full details, see Meyers *et al.*[6] and *Figure 1*.

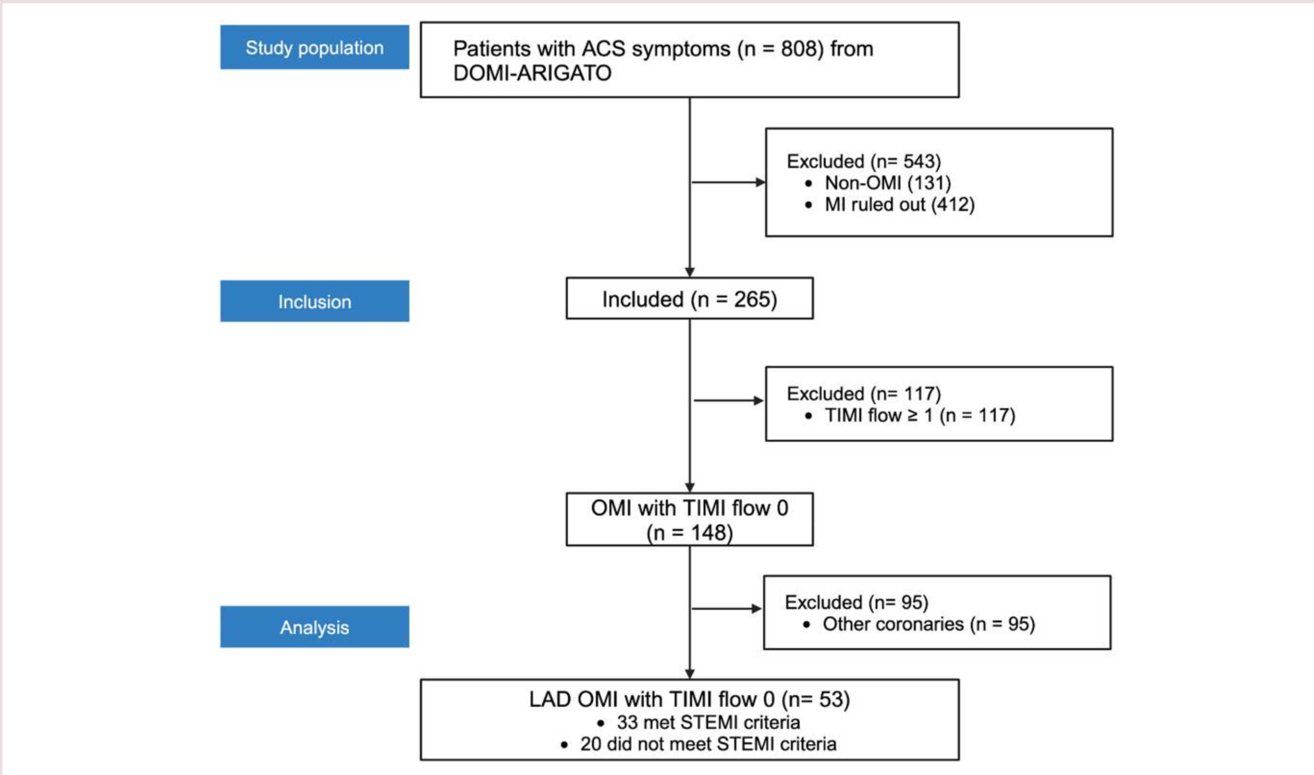

Figure 1 Flowchart showing inclusion and exclusion criteria used to arrive at the primary analysis cohort.

Selection of participants

This retrospective cohort study included patients presenting to two EDs with symptoms indicative of possible ACS. This study was a sub-study of the DOMI-ARIGATO database, for which detailed selection of participants has been described previously. In brief, both sites performed searches of the cath lab activation databases, as well as ED to hospital admissions for possible ACS. Patients without ECGs in the electronic medical record or without sufficient retrospective information available to determine the primary outcome (the presence or absence of our OMI definition) were excluded. The definition of OMI for DOMI-ARIGATO was (i) TIMI-0/1/2 flow or (ii) TIMI-3 flow with peak 4th generation troponin T of at least 1.0 ng/mL or peak 4th generation troponin I of at least 10 ng/mL. For this analysis, the final study group in this analysis consisted of patients with an LAD culprit and TIMI-0 flow.

Measurements

Chart review and data collection methods have been described in detail.[6] Demographic data, clinical status, laboratory results, serial ECGs, and angiographic findings were collected using the web-based Research and Electronic Data Capture (REDCap) site hosted by SBUH.[28] All available transfer, pre-hospital, and study site ECGs were included. The first and subsequent serial ECGs of all patients of the original study (cases and controls) were measured and assessed for STEMI criteria and for OMI/Not-OMI by one of the authors (S.W.S.). The ECG interpretation was blinded to all patient information, except age and sex, which are necessary for determining the presence of STEMI criteria. Serial ECGs were interpreted (and STE measured) sequentially for each patient, with the interpreter unable to change prior interpretations, and blinded to the baseline ECG until after interpreting the first ECG of the series and then re-interpreted that first ECG with access to the baseline ECG. The STEMI criteria were defined according to the fourth universal definition of MI and thus measured in millimetres using the QRS onset (PQ junction) and the J-point (see *Table 1*).[29] If any ECG prior to angiogram met STEMI criteria, the patient was considered to be STEMI(+) OMI; if not, then STEMI(−) OMI. Finally, all initial ECGs were interpreted by the PMcardio OMI AI ECG model (Queen of Hearts, Powerful Medical, Slovakia).

In addition to diagnostic STE (suspected true positive STEMI criteria), when the subjective interpretation was OMI, ECG findings[20] which influenced that interpretation were recorded for each lead: subtle STE not meeting criteria, hyperacute T-waves (including the 'de Winter pattern'),[12] reciprocal STD and/or negative hyperacute T-waves, STD maximal in V1–V4 indicative of lateral (formerly 'posterior') OMI,[30] suspected acute pathologic Q waves (meaning Q waves associated with subtle STE which cannot be attributed to old MI), terminal QRS distortion (absence of S-wave preceding any subtle STE, where an S-wave would be expected),[31] any STE in inferior leads with any STD or T-wave inversion in lead aVL,[32] and positive modified Sgarbossa criteria (MSC) for a patient with left bundle branch block (LBBB) or ventricular paced rhythm (VPR).[33–35] Sensitivity was defined as the rate of true positives among those with the outcome (OMI, better defined in next paragraphs). Specificity, defined as the true negative rate among those without the outcome, could not be calculated because our data excluded those without LAD OMI.

Inter-rater agreement

In the original study, inter-rater agreement was assessed between HPM and SWS for all cases interpreted by both, with 97.2% agreement for the determination of STEMI criteria (kappa = 0.893) and 94.0% agreement for the diagnosis of OMI (kappa = 0.849). For this sub-analysis, all cases of LAD OMI with TIMI-0 flow were separately and blindly adjudicated for formal STEMI criteria by an independent cardiologist (W.H.F.) without knowledge of study goals or patient selection process.

Outcomes

In this present analysis, OMI was determined solely by angiographic findings as reported in the catheterization report. If the report stated a culprit artery with total occlusion, 100% occlusion, or TIMI-0 flow, it was coded as TIMI-0 flow. If no TIMI flow was reported in the catheterization report, an angiographer reviewed all the cineangiograms to report a TIMI flow. We report

Table 2 Eight hundred eight patients with symptoms of acute coronary syndrome, 265 OMI of any artery and 131 NOMI (by broad definition of OMI[a]), and 412 ruled out for any kind of MI

Culprit TIMI flow	*n*	Meets STE criteria on at least one pre-angiography ECG	Expert diagnoses OMI on at least one pre-angiography ECG (sensitivity)
0	148	73 (49%)	141 (95%)
1	23	8 (35%)	20 (90%)
2	48	14 (29%)	32 (67%)
3	44	12 (27%)	31 (70%)

[a]'Broad definition of OMI' is (i) TIMI-0/1/2 flow or (ii) TIMI-3 flow with peak troponin T of at least 1.0 ng/mL or peak troponin I of at least 10 ng/mL. Two patients died before angiography, so the total is 263 with recorded TIMI flow.

Table 3 Of the 808 patients in *Table 2*, those with LAD occlusion by various definitions

Artery	TIMI flow	*n*	Meets STE criteria on at least 1 pre-angiography ECG (sensitivity %)	Expert diagnoses OMI on at least one pre-angiography ECG (sensitivity%)	AI model diagnoses OMI on at least one ECG pre-angiogram (sensitivity %)
LAD	Using OMI definition from original study)[a]	90	44 (49%)	81 (90%)	[b]
	0	53	33 (62%)[c]	53 (100%)[c]	53 (100%)[c]
	1	8	5 (63%)	8 (100%)	8 (100%)
	2	14	2 (14%)	8 (57%)	[b]
	3	15	4 (27%)	12 (80%)	[b]

LAD, left anterior descending coronary artery.
[a]OMI outcome definition of the original study is (i) TIMI-0/1/2 flow or (ii) TIMI-3 flow with peak troponin T of at least 1.0 ng/mL or peak troponin I of at least 10 ng/mL.
[b]Because the topic here is LAD occlusion with TIMI-0 flow, we applied the AI model only to cases of (i) LAD occlusion with TIMI-0 flow and (ii) with TIMI-1 flow.
[c]$P < 0.0001$ by χ^2 comparing sensitivity of STEMI criteria with expert and AI model.

numbers of ECGs recorded, door-to-balloon times (DBTs), peak troponins, and ejection fractions (EFs) for those with vs. without STEMI criteria.

Analysis

Descriptive statistics were calculated for cases and controls. Inter-observer agreement was calculated using κ values for categorical variables. Outcomes were compared between groups using Mann–Whitney *U* or Kruskal–Wallis tests for continuous measurements and Pearson's χ^2 or Fisher's exact test for categorical measures. Where appropriate, median ± interquartile range (IQR) and mean ± standard deviation were reported. All tests were two-sided, and statistical significance was accepted at the 0.05 level, with Bonferroni corrections applied when applicable.

Results

Among the 808 patient study cohort, 148 (18.3%) patients had an acute completely occluded culprit coronary artery (TIMI-0 flow); the LAD was the infarct related artery in 53 of 148 (36%) patients (see *Figure 1*). Twenty of the 53 (38%) did not meet ECG criteria for STEMI. The site of LAD occlusion was proximal ($n = 8$) and mid ($n = 12$); 19/20 patients underwent revascularization and 1 died before intervention. *Tables 2* and *3* show context of these LAD occlusion patients among the entire original cohort of 808 patients, specifically showing the results for each level of culprit artery TIMI flow.

Table 4 shows details of each of the 20 LAD occlusion (TIMI-0) patients who never met STEMI criteria on any serial ECG, including the peak troponin, location of LAD occlusion, EF, DBTs, number of ECGs, and time from first to last ECG. *Table 5* compares those with vs. without STEMI criteria.

The AI model and the expert both correctly identified all 53 patients with an LAD occlusion on the first recorded ECG, including the 20 patients who did not meet ECG criteria for STEMI. Each of the 20 ECGs is shown in the Supplementary material. The frequency of each OMI ECG characteristic was as follows: STE < 1 mm, 85%; hyperacute T-waves, 85%; at least one pathologic Q-wave, 70%; and reciprocal ST-segment changes, 50% (*Table 6*).

Among the 20 patients not meeting STEMI ECG criteria, the number of ECGs recorded prior to angiography ranged from 1 to 6, and 16 of 20 patients had at least 2 ECGs before angiogram. Among these 16, the median time from the first to last ECG was 44 min (IQR: 13–147 min), range 17–2640 min. None of the serial ECGs met STEMI criteria. The median DBT for the 20 patients without STEMI criteria was 97 min (IQR 60–248 min) vs. 40 min (IQR 26–61 min) for those with STEMI criteria ($P < 0.001$). The DBT was > 90 min in 11/20 (55%) of those without STEMI criteria vs. 7/33 (21%) ($P = 0.012$) for those with STEMI criteria (*Tables 4* and *5*).

Outcomes

There was no significant difference in peak troponins between STEMI(+) LAD OMI vs. STEMI(−) LAD OMI and no difference in post-revascularization EF. Peak troponin levels (4th generation troponin I at

Table 4 Characteristics of all 20 patients with TIMI-0 flow in the left anterior descending coronary artery whose serial ECGs never meet STEMI criteria: (i) peak contemporary (not high sensitivity) troponin measured, or maximum, as indicated by *; (ii) location of LAD occlusion; (iii) ejection fraction post-angiogram; (iv) cardiologist ECG interpretation as STEMI or not; and (v) door-to-balloon times

Case	HCMC peak troponin I (ng/mL)	SBUH peak troponin T (ng/mL)	Location of LAD occlusion (m, mid; p, proximal)	Ejection fraction (%) on echocardiogram performed after angiogram	Door-to-balloon time in minutes	Number of ECGs	Time from first to last ECG in minutes	Final Dx: STEMI vs. NSTEMI vs. unknown
1		3.19	Mid	35	83	2	37	S
2		1.87	Mid	61	124	5	44	U
3	60.9		Mid	25	69	5	43	U
4	5.6		Mid	40	1032	3	945	N
5	71.6		Mid	52	56	3	49	S
6	14.4*		Proximal	25	105	3	59	N
7	19.0		Mid	43	175	3	50	N
8		1.33	Mid	56	2212	6	1070	N
9		8.53	Proximal	10	108	3	38	S
10		0.53	Proximal	50	81	1	N/A	S
11		0.89*	Mid	30	35 883	4	2634	N
12		94.8	Proximal	(died before echo)	63	1	N/A	N
13		4.34	Mid	55	405	2	121	N
14		15.8	Mid	43	43	1	N/A	S
15		8.82	Mid	37	50	2	36	S
16		4.82	Proximal	45	19	2	17	S
17		2.23	Proximal	45	579	6	532	N
18		7.29	Proximal	35	71	1	N/A	S
19		35.7	Mid	35	451	2	225	S
20		7.7	Proximal	45	97	1	N/A	S
Median (IQR)	19.1 (10–66)	4.8 (1.9–8.8)		43 (35–50)	97 (60–428)	2.5 (1.5–3.5)	43.5 (8.5–173)	

For all 20, sensitivity of the expert and of AI model were 100% on the first ECG. *Not measured to peak; highest troponin measured is displayed.
IQR, interquartile range; S, STEMI; N, NSTEMI; U, discharge diagnosis unknown; mLAD, mid LAD; pLAD, proximal LAD.

Table 5 LAD TIMI-0 OMI, comparing those with vs. without STEMI criteria

STE criteria (on any serial pre-cath ECG)	#	DBT, median (IQR)	DBT < 90 min	Ejection fraction (%), median (IQR)	Peak troponin I (ng/mL) (HCMC), median (IQR)	Peak troponin T (ng/mL) (SBUH), median (IQR)
No	20	97 (60–428)	9/20 (45%)	43 (35–48)	19.1 (14–61)	4.8 (1.9–8.8)
Yes	33	40 (22–61)	26/33 (79%)	40 (35–49)	12.4 (4.5–56)	7.1 (2.9–11.2)
P value		<0.001	0.012	0.94	0.53	0.52

DBT, door-to-balloon time; HCMC, Hennepin County Medical Center; SBUH, Stony Brook University Hospital; IQR, interquartile range.

HCMC, 4th generation troponin T at SBUH) are listed in *Table 4*. Among SBUH patients, for those with a DBT of <90 min, the median peak troponin T was 7.29 ng/mL; for those with DBT > 90 min, the median peak troponin T was 4.34 ng/mL ($P = 0.52$ by Mann–Whitney U test). Among the 20 patients with LAD occlusion not meeting STEMI criteria, 11 (55%) had EF < 50% and 1 (5%) died during index hospitalization. The median EF after angiogram for those which did ($n = 33$) vs. did not ($n = 20$) meet STEMI criteria was 40% (IQR 35–49) vs. 43% (35–48) ($P = 0.94$). Recovery EF was not available. Among the patients whose ECGs did not meet STEMI criteria on any ECG, the interventional cardiologist gave a final diagnosis of 'STEMI' in 10/20 patients and 'NSTEMI' in 8/20 patients. This final diagnosis was significantly correlated with DBT; a proven NSTEMI patient with DBT less than 120 min was likely to receive a final diagnosis of 'STEMI' (9/12 patients, 75%), while a patient with a DBT greater than 120 min was likely to receive a final diagnosis of NSTEMI (7/8 patients, 88%) (see *Table 7*).

Inter-rater agreement

Finally, another (cardiologist) interpreter assessed all 53 TIMI-0 LAD OMI: of the 20 OMI that were assessed as not having met STEMI criteria, the independent blinded cardiologist agreed with the absence of STEMI criteria in 19 cases (95%), and the last case was a woman judged to have exactly enough STE to meet criteria (1.0 mm STE in V1 and 1.5 mm in V2). We resolved the disagreement between the two interpreters using computer automated measurement of the ST segments, which found insufficient STE for formal STE criteria. Of the 33 that met STEMI criteria, the independent blinded cardiologist agreed on all 33.

Discussion

To our knowledge, this is the first study to document the sensitivity of contemporary STEMI criteria for identifying an acute LAD occlusion (TIMI-0 flow). The main findings in this study include the following: (i) guideline-defined STEMI ECG criteria are absent in 38% of patients with AMI with total LAD occlusion; (ii) patients with acute LAD occlusion not meeting STEMI criteria had significantly longer DBTs than those meeting STEMI criteria; (iii) significant left ventricular dysfunction was present and statistically similar in LAD occlusion patients regardless of STEMI criteria; (iv) all patients with an acute LAD occlusion were correctly identified by both an expert and an AI model on the first ECG, offering an opportunity to provide timely treatment of AMI with an occluded culprit artery to a substantially greater number of patients; and (v) the majority of these subtle LAD OMI with TIMI-0 flow did not undergo timely reperfusion, likely because they did not have STE that meets 'criteria'. While many clinicians feel that 'missed STEMI' is mostly a problem for the circumflex distribution,[36] our findings contradict this notion by highlighting the proportion of anterior acute coronary occlusions missed in the highest risk artery.

The 2022 American College of Cardiology (ACC) chest pain guidelines[12,30,37,38] and the recent 2024 Society for Cardiovascular Angiography & Interventions (SCAI) Expert Consensus Statement on Managing Patients with STEMI[39] recognized the limited sensitivity of traditional electrocardiographic STE criteria to identify patients with acute coronary artery occlusion. To improve diagnostic sensitivity, additional criteria beyond STE were proposed including the following: (i) presence of hyperacute T-waves (including the subset known as de Winter T-waves); (ii) presence of findings consistent with acute posterior myocardial infarction; and (iii) presence of left bundle branch block or paced rhythm meeting the Smith-modified Sgarbossa criteria. Importantly, this ACC document does not address subtle STE (e.g. less than STEMI millimetre criteria), and no criteria for hyperacute T-waves and acute posterior myocardial infarction are offered. Therefore, many physicians and first responders are either unfamiliar with these new recommendations or find them too complicated to be useful in making the decision to activate the cardiac catheterization laboratory.

It is noteworthy that hyperacute T-waves were observed in 85% of cases not meeting STEMI criteria, though defining them precisely can be quite challenging. We know that they are not defined by amplitude alone.[12] Although we believe that a major component is the 'bulk' of the T-wave, as measured by a large area under the curve in proportion to QRS amplitude, and excessive symmetry,[12] this has not yet been quantitatively proven. Smith *et al.*[40] have shown that, in anterior OMI, T-waves do not have greater amplitude than is seen in normal variant STE (early repolarization), but they do have a far higher T-wave to R-wave amplitude ratio because the R-waves in anterior OMI are smaller. The AI algorithm does recognize hyperacute T-waves, as demonstrated in the explainability maps, but the exact mechanism behind this remains unclear (see *Figure 2*).

Acute coronary artery occlusion is a dynamic process[1,22]; consequently, recording serial ECGs has been recommended to improve the detection of acute coronary artery occlusion when the initial ECG does not manifest traditional STEMI criteria.[41–43] Although current guidelines recommend serial ECGs in suspected AMI, the diagnostic performance of this approach has never been documented.[44] It is widely believed that hyperacute T-waves are a transitional state preceding ST-elevation[45–48] Thus, it is tempting to postulate that early cases of OMI will eventually evolve to STEMI; yet, our data contradict that notion. In our study, 17/20 patients with acute complete LAD occlusion had hyperacute T-waves on their initial ECG; of these, 16 (94%) had subsequent ECG(s) recorded and none ever evolved to STEMI criteria.

The majority of patients with electrocardiographically subtle LAD occlusion and TIMI-0 flow did not undergo timely reperfusion, likely because they did not meet contemporary STEMI criteria for acute revascularization. Utilization of the AI model would have resulted in a 100%

Table 6 Frequency of OMI findings in 20 cases of LAD OMI with TIMI-0 flow which did not meet STEMI criteria

Hyperacute T-waves[12]	17 (85%)
Pathologic Q-waves (meaning Q waves associated with subtle STE which were not attributed to old MI)	14 (70%)
Terminal QRS distortion (terminal QRS does not extend down to the baseline, with absence of both a J-wave and an S-wave)[31]	4 (20%)
Reciprocal STD and/or T-wave inversion	10 (50%)
Subtle STE not meeting criteria	17 (85%)
STD maximal in V2–V4 indicative of posterior OMI[30]	0 (0%)
Any STE in inferior leads with any STD/T-wave inversion in aVL[32]	4 (20%)
Positive modified Sgarbossa criteria in LBBB or VPR[33–35]	0

Table 7 DBT by final diagnosis for 20 LAD OMI that did not meet STEMI criteria

Final diagnosis	Median (IQR[a])	*P* value
STEMI ($n = 10$)	76 (50–97)	0.038
NSTEMI ($n = 8$)	492 (140–1622)	

No final diagnosis available for two cases.
[a]IQR, interquartile range.

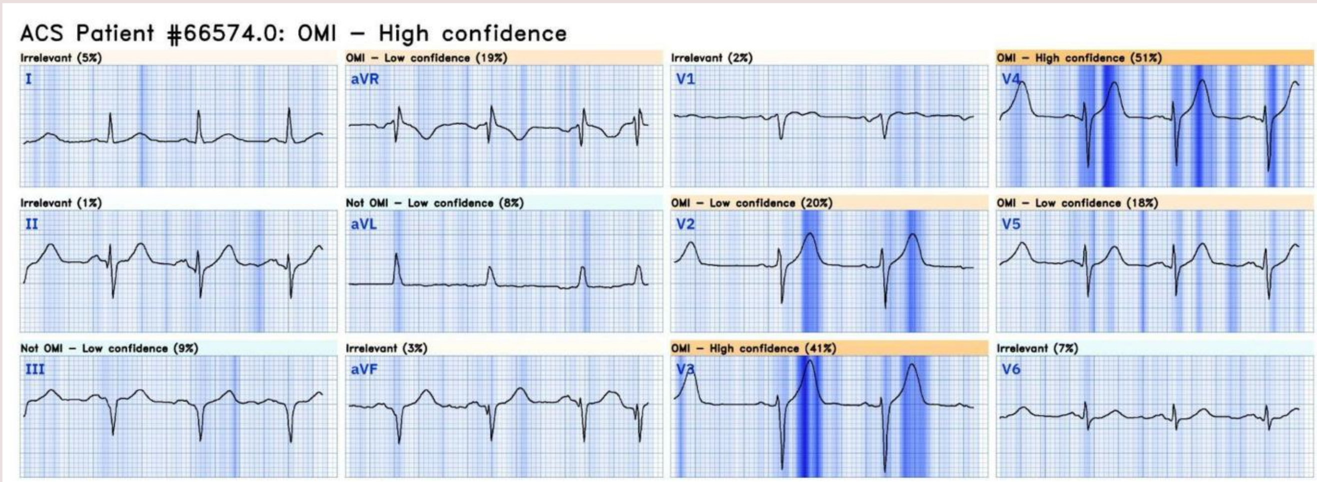

Figure 2 This is the electrocardiogram from Case 1 (case details in Supplementary material section). Hyperacute T-waves are shown in leads V2–V4 and highlighted by saliency mapping with vertical darker shading.

sensitivity and the possibility of significantly shorter DBT and potentially improved outcomes for these patients.

McLaren *et al.*[13] found that, when there is OMI with large infarct but without STE, the final discharge diagnosis is not changed from NSTEMI to STEMI, but when there is STE but no OMI, the diagnosis is changed away from STEMI. We found that among OMI, when there is absence of diagnostic STE, the discharge diagnosis of STEMI vs. NSTEMI correlated with DBT rather than with actual STEMI criteria; those with long DBT were much more likely to get a discharge diagnosis of NSTEMI and those with a short DBT got a diagnosis of STEMI. This raises the possibility that STEMI vs. NSTEMI diagnoses may sometimes be retrospectively influenced by quality measure considerations.

Although we showed that AI was more sensitive than STEMI criteria, analysing specificity was not possible in this study. However, in the validation study, at fixed specificity, the AI model recorded double the sensitivity (67% vs. 33%) of STEMI millimetre criteria for OMI as defined by TIMI-0/1 flow or TIMI-2/3 flow with culprit and intervention.[27] Other studies have assessed the performance of STEMI criteria by different definitions to diagnose LAD OMI. Smith *et al.*[40] studied 355 consecutive LAD OMI, comparing the 143 (40%) which had 'subtle' STE to normal variant STE; 'subtle STE' was defined by absence of diagnostic STE, upward concavity in all of V2-V6, absence of terminal QRS distortion, absence of pathologic Q-waves, and absence of any ST depression except in aVR. Using logistic regression on these 143 cases, compared with a control group of 171 cases with normal variant STE, a formula was derived and then validated, which differentiates normal variant STE from LAD OMI STE with high accuracy. The formula uses R-wave amplitude in lead V4 and the corrected QT interval, in addition to STE at 60 ms after the J-point in lead V3. Driver et al. improved the formula by adding the total QRS amplitude in lead V2 to the model. Bozbeyoglu *et al.*[49] confirmed these findings in an external validation of the model. Together, these studies showed that using features other than STE, both sensitivity and specificity for LAD OMI could be improved. In another study by Smith,[50] 43% of LAD OMI had subtle STE and 20% had both subtle STE and upward concavity in all of leads V2-V6. Martí *et al.*[51] took all consecutive patients with suspicion of ACS and any amount of STE for angiography and found that 20 of 156 with (13%) acute LAD (TIMI-0/1 flow) had ≤1 mm of STE, but they did not report on STEMI criteria; given that STEMI criteria require 1.5–2.5 mm in V2 and V3, depending on age and sex, the proportion that failed to meet STEMI criteria is doubtless more than 13%. Subtle STE was not associated with better outcome than LAD occlusion with 'diagnostic' STE by both univariate and multivariate analysis. Unfortunately, neither Khan *et al.*[4] nor Hung *et al.*[3] reported the infarct artery that was occluded in their meta-analysis of NSTEMI-OMI.

Limitations

This is a retrospective study based on data from two centres, with all of the inherent limitations. The number of patients analysed is relatively small, but we believe the findings are an accurate representation of the opportunity to improve the diagnosis of acute coronary artery occlusion. We examined a high risk group with a high incidence of OMI and STEMI. Next, the study did not enrol consecutive patients with acute chest pain, potentially biasing the results. Expert OMI interpretation was not performed by both expert interpreters for all 20 TIMI-0 LAD OMI; thus, we cannot comment on possible inter-rater variability. Lastly, we did not have long-term clinical outcomes or recovery EF available; however, peak troponin correlates closely with EF recovery.[52] In addition, peak troponin is highly correlated with mortality in patients with NSTEMI.[53]

Conclusion

Contemporary STE criteria for the diagnosis of acute left anterior descending coronary occlusion missed 38% of those with complete artery occlusion (TIMI-0 flow). In no case did serial ECGs develop STE criteria. These cases of OMI with subtle findings were associated with long DBTs and large infarct size as measured by peak troponin and EF, which did not differ from those with diagnostic STE. An AI platform algorithm for the ECG diagnosis of acute coronary artery occlusion had 100% sensitivity, equivalent to that of an expert, on the first ECG for all 20 of these electrocardiographically subtle acute LAD Occlusions.

Supplementary material

Supplementary material is available at *European Heart Journal: Acute Cardiovascular Care* online.

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Conflict of interest: H.P.M. is a consultant of Powerful Medical. R.H. is the Chief Medical Officer of Powerful Medical. H.P.M., R.H., and S.W.S. all own stock in Powerful Medical.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

References

1. DeWood MA, Stifter WF, Simpson CS. Coronary arteriographic findings soon after non-Q-wave myocardial infarction. *N Engl J Med* 1986;**315**:417–423.
2. de Alencar Neto JN, Scheffer MK, Correia BP, Franchini KG, Felicioni SP, De Marchi MFN. Systematic review and meta-analysis of diagnostic test accuracy of ST-segment elevation for acute coronary occlusion. *Int. J. Cardiol. [Internet]* 2024;**402**:131889.
3. Hung C-S, Chen Y-H, Huang C-C, Lin M-S, Yeh C-F, Li H-Y, *et al.* Prevalence and outcome of patients with non-ST segment elevation myocardial infarction with occluded "culprit" artery—a systemic review and meta-analysis. *Crit. Care [Internet]* 2018;**22**:34.
4. Khan AR, Golwala H, Tripathi A, Abdulhak AAB, Bavishi C, Riaz H, *et al.* Impact of total occlusion of culprit artery in acute non-ST elevation myocardial infarction: a systematic review and meta-analysis. *Eur. Heart J. [Internet]* 2017;**38**:3082–3089.
5. Koyama Y, Hansen PS, Hanratty CG, Nelson GIC, Ramussen HH. Prevalence of coronary occlusion and outcome of an immediate invasive strategy in suspected acute myocardial infarction with and without ST-segment elevation. *Am J Cardiol* 2002;**90**:579–584.
6. Meyers HP, Bracey A, Lee D, Lichtenheld A, Li WJ, Singer DD, *et al.* Accuracy of OMI ECG findings versus STEMI criteria for diagnosis of acute coronary occlusion myocardial infarction. *IJC Heart & Vasculature [Internet]* 2021;**33**:100767.
7. McLaren J, de Alencar JN, Aslanger EK, Pendell Meyers H, Smith SW. From ST-segment elevation MI to occlusion MI: the new paradigm shift in acute myocardial infarction. *JACC Adv* 2024;**3**:101314.
8. Aslanger EK, Meyers PH, Smith SW. STEMI: a transitional fossil in MI classification? *J. Electrocardiol. [Internet]* 2021;**65**:163–169.
9. Smith SW, Meyers HP. ST elevation is a poor surrogate for acute coronary occlusion. Let's replace STEMI with occlusion MI (OMI)!!. *Int. J. Cardiol. [Internet]* 2024;**407**:131980.
10. Meyers HP, Smith SW. OMI Literature Timeline [Internet]. Dr. Smith's ECG Blog. [cited 2024 Feb 21]; Available from: https://hqmeded-ecg.blogspot.com/p/omi-literature-timeline.html (21 February 2024).
11. Herman R, Smith SW, Meyers HP, Bertolone DT, Leone A, Bermpeis K, *et al.* Poor prognosis of total culprit artery occlusion in patients presenting with NSTEMI. *Eur. Heart J. [Internet]* 2023;**44**:ehad655–ha1536.
12. Smith SW, Meyers HP. Hyperacute T-waves can be a useful sign of occlusion myocardial infarction if appropriately defined. *Ann. Emerg. Med. [Internet]* 2023;**82**:203–206.
13. McLaren JTT, El-Baba M, Sivashanmugathas V, Meyers HP, Smith SW, Chartier LB. Missing occlusions: quality gaps for ED patients with occlusion MI. *Am. J. Emerg. Med. [Internet]* 2023;**73**:47–54.
14. Meyers HP, Bracey A, Lee D, Lichtenheld A, Li WJ, Singer DD, *et al.* Comparison of the ST-elevation myocardial infarction (STEMI) vs. NSTEMI and occlusion MI (OMI) vs. NOMI paradigms of acute MI. *J. Emerg. Med. [Internet]* 2021;**60**:273–284.
15. Aslanger EK, Meyers PH, Smith SW. Time for A new paradigm shift in myocardial infarction. *The Anatolian Journal of [Internet]* 2021;**25**:156–162.
16. Aslanger EK, Yıldırımtürk Ö, Şimşek B, Bozbeyoğlu E, Şimşek MA, Karabay CY, *et al.* DIagnostic accuracy oF electrocardiogram for acute coronary OCClUsion resuLTing in myocardial infarction (DIFOCCULT study). *Int J Cardiol Heart Vasc [Internet]* 2020;**30**:100603.
17. Alencar JND, Feres F, Marchi M. Beyond STEMI-NSTEMI paradigm: Dante Pazzanese's proposal for occlusion myocardial infarction diagnosis. *Arq. Bras [Internet]* 2024;**121**:e20230733.
18. Abusharekh M, Kampf J, Dykun I, Souri K, Backmann V, Al-Rashid F, *et al.* Acute coronary occlusion with vs. without ST-elevation: impact on procedural outcomes and long-term all-cause mortality. *Eur Heart J Qual Care Clin Outcomes [Internet]* 2024;**10**:402–410.
19. Sankardas MA, Ramakumar V, Farooqui FA. Of occlusions, inclusions, and exclusions: time to reclassify infarctions? *Circulation [Internet]* 2021;**144**:333–335.
20. Miranda DF, Lobo AS, Walsh B, Sandoval Y, Smith SW. New insights into the use of the 12-lead electrocardiogram for diagnosing acute myocardial infarction in the emergency department. *Can. J. Cardiol. [Internet]* 2018;**34**:132–145.
21. Aslanger EK, Meyers HP, Smith SW. Recognizing electrocardiographically subtle occlusion myocardial infarction and differentiating it from mimics: ten steps to or away from cath lab. *Turk Kardiyol Dern Ars* 2021;**49**:488–500.
22. Verheugt FW, Liem A, Zijlstra F, Marsh RC, Veen G, Bronzwaer JG. High dose bolus heparin as initial therapy before primary angioplasty for acute myocardial infarction: results of the heparin in early patency (HEAP) pilot study. *J. Am. Coll. Cardiol. [Internet]* 1998;**31**:289–293.
23. Karwowski J, Gierlotka M, Gąsior M, Poloński L, Ciszewski J, Bęćkowski M, *et al.* Relationship between infarct artery location, acute total coronary occlusion, and mortality in STEMI and NSTEMI patients. *Pol Arch Intern Med [Internet]* 2017;**127**:401–411.
24. Stone GW, Cox D, Garcia E, Brodie BR, Morice M-C, Griffin J, *et al.* Normal flow (TIMI-3) before mechanical reperfusion therapy is an independent determinant of survival in acute myocardial infarction: analysis from the primary angioplasty in myocardial infarction trials. *Circulation [Internet]* 2001;**104**:636–641.
25. Cox DA, Stone GW, Grines CL, Stuckey T, Zimetbaum PJ, Tcheng JE, *et al.* Comparative early and late outcomes after primary percutaneous coronary intervention in ST-segment elevation and non–ST-segment elevation acute myocardial infarction (from the CADILLAC trial). *Am. J. Cardiol. [Internet]* 2006;**98**:331–337.
26. de Waha S, Patel MR, Thiele H, Udelson JE, Granger CB, Ben-Yehuda O, *et al.* Relationship between infarct artery, myocardial injury, and outcomes after primary percutaneous coronary intervention in ST-segment-elevation myocardial infarction. *J. Am. Heart Assoc. [Internet]* 2024;**13**:e034748.
27. Herman R, Meyers HP, Smith SW, Bertolone DT, Leone A, Bermpeis K, *et al.* International evaluation of an artificial intelligence–powered electrocardiogram model detecting acute coronary occlusion myocardial infarction. *Eur Heart J Digit Health [Internet]* 2023;**5**:123–133.
28. Harris PA, Taylor R, Thielke R, Payne J, Gonzalez N, Conde JG. Research electronic data capture (REDCap)–a metadata-driven methodology and workflow process for providing translational research informatics support. *J. Biomed. Inform. [Internet]* 2009;**42**:377–381.
29. Thygesen K, Alpert JS, Jaffe AS, Chaitman BR, Bax JJ, Morrow DA, *et al.* Executive group on behalf of the Joint European Society of Cardiology (ESC)/American College of Cardiology (ACC)/American Heart Association (AHA)/World Heart Federation (WHF) task force for the universal definition of myocardial infarction. Fourth universal definition of myocardial infarction (2018). *J. Am. Coll. Cardiol. [Internet]* 2018;**72**:2231–2264.
30. Meyers HP, Bracey A, Lee D, Lichtenheld A, Li WJ, Singer DD, *et al.* Ischemic ST-segment depression maximal in V1–V4 (Versus V5–V6) of any amplitude is specific for occlusion myocardial infarction (versus nonocclusive ischemia). *J Am Heart Assoc* 2021;**10**:e022866.
31. Lee DH, Walsh B, Smith SW. Terminal QRS distortion is present in anterior myocardial infarction but absent in early repolarization. *Am. J. Emerg. Med. [Internet]* 2016;**34**:2182–2185.
32. Bischof JE, Worrall C, Thompson P, Marti D, Smith SW. ST depression in lead aVL differentiates inferior ST-elevation myocardial infarction from pericarditis. *Am. J. Emerg. Med. [Internet]* 2016;**34**:149–154.
33. Dodd KW, Zvosec DL, Hart MA, Glass G 3rd, Bannister LE, Body RM, *et al.* Electrocardiographic diagnosis of acute coronary occlusion myocardial infarction in ventricular paced rhythm using the modified Sgarbossa criteria. *Ann. Emerg. Med. [Internet]* 2021;**78**:517–529.
34. Smith SW, Dodd KW, Henry TD, Dvorak DM, Pearce LA. Diagnosis of ST elevation myocardial infarction in the presence of left bundle branch block using the ST elevation to S-wave ratio in a modified Sgarbossa rule. *Ann Emerg Med.* 2012;**60**:766–776.
35. Meyers HP, Limkakeng AT Jr, Jaffa EJ, Patel A, Theiling BJ, Rezaie SR, *et al.* Validation of the modified Sgarbossa criteria for acute coronary occlusion in the setting of left bundle branch block: a retrospective case-control study. *Am. Heart J. [Internet]*. 2015;**170**:1255–1264.
36. From AM, Best PJM, Lennon RJ, Rihal CS, Prasad A. Acute myocardial infarction due to left circumflex artery occlusion and significance of ST-segment elevation. *Am. J. Cardiol. [Internet]* 2010;**106**:1081–1085.
37. Committee W, Kontos MC, de Lemos JA, Deitelzweig SB, Diercks DB, Gore MO, Jr, *et al.* 2022 ACC expert consensus decision pathway on the evaluation and disposition of acute chest pain in the emergency department: a report of the American College of Cardiology solution set oversight committee. *J. Am. Coll. Cardiol. [Internet]*. 2022;**80**:1925–1960.
38. Smith SW, Dodd KW, Henry TD, Dvorak DM, Pearce LA. Diagnosis of ST-elevation myocardial infarction in the presence of left bundle branch block with the ST-elevation to S-wave ratio in a modified Sgarbossa rule. *Ann. Emerg. Med. [Internet]* 2012;**60**:766–776.
39. Tamis-Holland JE, Abbott JD, Al-Azizi K, Barman N, Bortnick AE, Cohen MG, *et al.* SCAI expert consensus statement on the management of patients with STEMI referred for primary PCI. *J. Soc. Cardiovasc. Angiogr. Interv. [Internet]* 2024;**3**:102294.

40. Smith SW, Khalil A, Henry TD, Rosas M, Chang RJ, Heller K, *et al.* Electrocardiographic differentiation of early repolarization from subtle anterior ST-segment elevation myocardial infarction. *Ann. Emerg. Med. [Internet]* 2012;**60**:45–56.e2.
41. Fesmire FM, Percy RF, Bardoner JB, Wharton DR, Calhoun FB. Usefulness of automated serial 12-lead ECG monitoring during the initial emergency department evaluation of patients with chest pain. *Ann Emerg Med*. 1998;**31**:3–11.
42. Lehmacher J, Neumann JT, Sörensen NA, Goßling A, Haller PM, Hartikainen TS, *et al.* Predictive value of serial ECGs in patients with suspected myocardial infarction. *J. Clin. Med. Res. [Internet]* 2020;**9**:2303.
43. Scirica BM, Morrow DA, Budaj A, Dalby AJ, Mohanavelu S, Qin J, *et al.* Ischemia detected on continuous electrocardiography after acute coronary syndrome: observations from the MERLIN-TIMI 36 (metabolic efficiency with ranolazine for less ischemia in non-ST-elevation acute coronary syndrome-thrombolysis in myocardial infarction 36) trial. *J. Am. Coll. Cardiol. [Internet]* 2009;**53**:1411–1421.
44. O'Connor RE, Brady W, Brooks SC, Diercks D, Egan J, Ghaemmaghami C, *et al.* Part 10: acute coronary syndromes: 2010 American Heart Association guidelines for cardiopulmonary resuscitation and emergency cardiovascular care. *Circulation [Internet]* 2010; **122**:S787–S817.
45. Koechlin L, Strebel I, Zimmermann T, Nestelberger T, Walter J, Lopez-Ayala P, *et al.* Hyperacute T wave in the early diagnosis of acute myocardial infarction. *Ann. Emerg. Med. [Internet]* 2023;**82**:194–202.
46. Zorzi A, Marra MP, Migliore F, Tarantini G, Iliceto S, Corrado D. Interpretation of acute myocardial infarction with persistent "hyperacute T waves" by cardiac magnetic resonance. *European Heart Journal: Acute Cardiovascular Care [Internet]* 2012;**1**:344–348.
47. Verouden NJ, Koch KT, Peters RJ, Henriques JP, Baan J, van der Schaaf RJ, *et al.* Persistent precordial "hyper acute" T-waves signify proximal LAD artery occlusion. *Heart [Internet]* 2009;**95**:1701–1706.
48. Dressler W, Roesler H. High T waves in the earliest stage of myocardial infarction. *Am. Heart J. [Internet]* 1947;**34**:627–645.
49. Bozbeyoglu E, Aslanger E, Yildirimturk O, Simsek B, Karabay CY, Simsek MA, *et al.* A tale of two formulas: differentiation of subtle anterior MI from benign ST segment elevation. *Ann. Noninvasive Electrocardiol. [Internet]* 2018;**23**:e12568.
50. Smith SW. Upwardly concave ST segment morphology is common in acute left anterior descending coronary occlusion. *J. Emerg. Med. [Internet]* 2006;**31**:69–77.
51. Martí D, Mestre JL, Salido L, Esteban MJ, Casas E, Pey J, *et al.* Incidence, angiographic features and outcomes of patients presenting with subtle ST-elevation myocardial infarction. *Am. Heart J. [Internet]* 2014;**168**:884–890.
52. Hallén J, Jensen JK, Fagerland MW, Jaffe AS, Atar D. Cardiac troponin I for the prediction of functional recovery and left ventricular remodelling following primary percutaneous coronary intervention for ST-elevation myocardial infarction. *Heart [Internet]* 2010;**96**: 1892–1897.
53. Loutati R, Bruoha S, Taha L, Karmi M, Perel N, Maller T, *et al.* Association between peak troponin level and prognosis among patients admitted to intensive cardiovascular care unit. *Int. J. Cardiol. [Internet]* 2024;**417**:132556.
54. Macfarlane PW, Browne D, Devine B, Clark E, Miller E, Seyal J, *et al.* Modification of ACC/ESC criteria for acute myocardial infarction. *J. Electrocardiol. [Internet]* 2004;**37**: 98–103.