Diagnostic accuracy of a prehospital electrocardiogram rule-based algorithm for ST-elevation myocardial infarction: results from a population-wide project

Joanne HY Lai *, CT Lui, Total WT Chan, Ben CP Wong, Matthew SH Tsui, Ben KA Wan, KL Mok

ABSTRACT

Introduction: This study reviewed the diagnostic accuracy of the prehospital electrocardiogram (PHECG) rule-based algorithm for ST-elevation myocardial infarction (STEMI) universally utilised in Hong Kong.

Methods: This prospective observational study was linked to a population-wide project. We analysed 2210 PHECGs performed on patients who presented to the emergency medical service (EMS) with chest pain from 1 October to 31 December 2021. The diagnostic accuracy of the adopted rule-based algorithm, the Hannover Electrocardiogram System, was evaluated using the adjudicated blinded rating by two investigators as the primary reference standard. Diagnostic accuracy was also evaluated using the attending emergency physician's diagnosis and the diagnosis on hospital discharge as secondary reference standards.

Results: The prevalence of STEMI was 5.1% (95% confidence interval [CI]=4.2%-6.1%). Using the adjudicated blinded rating by investigators as the reference standard, the rule-based PHECG algorithm had a sensitivity of 94.6% (95% CI=88.2%-97.8%), specificity of 87.9% (95% CI=86.4%-89.2%), positive predictive value of 29.4% (95% CI=24.8%-34.4%), and negative predictive value of 99.7% (95% CI=99.3%-99.9%) [all P<0.05].

Conclusion: The rule-based PHECG algorithm that is widely used in Hong Kong demonstrated high sensitivity and fair specificity for the diagnosis of STEMI.

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New knowledge added by this study

- The prehospital electrocardiogram (PHECG) diagnostic algorithm universally utilised in Hong Kong had high sensitivity for diagnosing ST-elevation myocardial infarction (STEMI) in a population-wide cohort of patients with chest pain.
- One in eight ECGs showed false-positive results for STEMI; the leading causes were early repolarisation, left bundle branch block, and extreme tachycardia.
- Evolving ECG patterns, subtle ST-segment elevation, and STEMI equivalents were responsible for false-negative diagnoses.

Implications for clinical practice or policy

- Primary diversion of STEMI patients to centres capable of primary percutaneous coronary intervention should not be implemented solely based on the algorithm's ECG diagnosis.
- ST-elevation myocardial infarction can be reasonably excluded by the PHECG diagnostic algorithm.
- Physicians should be aware of STEMI equivalents that are not identified by the algorithm.

Introduction

Heart disease is the third leading cause of death in Hong Kong. In 2019, an average of approximately 10.2 people died from coronary heart disease each day.[1] International guidelines recommend prehospital 12-lead electrocardiogram (ECG) for the assessment of patients with suspected acute coronary syndrome who present to emergency medical services (EMS).[2,3] Prehospital triage with direct transfer to the cardiac catheterisation laboratory for primary

院前心電圖規則式演算法診斷ST上升心肌梗塞的準確性：全港性研究結果

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引言：本研究評估於香港廣泛使用的院前心電圖規則式演算法對於診斷ST上升心肌梗塞的準確性。

方法：這是一項在全港進行的前瞻性觀察性研究。我們檢視了由2021年10月1日至12月31日期間全港緊急救護服務為胸痛患者進行的2210張院前心電圖，以評估此服務所採用的Hannover Electrocardiogram System規則式演算法對於診斷ST上升心肌梗塞的準確性。本研究的主要參考標準為兩名研究員各自判讀心電圖所作出的診斷，次要參考標準則為當值急症室醫生對相關患者作出的診斷，以及該患者出院的最終診斷來評估演算法的診斷準確性。

結果：ST上升心肌梗塞的發病率為5.1%（95%置信區間=4.2%-6.1%）。以研究員的判讀作為參考標準，院前心電圖規則式演算法的敏感性為94.6%（95%置信區間=88.2%-97.8%），特異性為87.9%（95%置信區間=86.4%-89.2%），陽性預測值為29.4%（95%置信區間=24.8%-34.4%），陰性預測值為99.7%（95%置信區間=99.3%-99.9%），所有p值均<0.05。

結論：香港廣泛使用的院前心電圖規則式演算法對ST上升心肌梗塞的診斷顯示出高敏感性和較好的特異性。

percutaneous coronary intervention is a strategy adopted by various healthcare systems to reduce reperfusion time in patients with ST-elevation myocardial infarction (STEMI).[4,5] Previous studies have investigated the diagnostic performances of prehospital electrocardiograms (PHECGs) for STEMI by various automated algorithms,[6-10] trained onsite EMS personnel,[11,12] and emergency department (ED) physicians remotely interpreting the tele-transmitted ECGs[13]; the findings have implications for policymakers involved in planning systems of care to minimise inappropriate resource mobilisation.

In Hong Kong, the Hospital Authority, the local public healthcare service, and Hong Kong Fire Services Department, the primary EMS provider, jointly launched the Prehospital 12-Lead Electrocardiogram for Chest Pain Protocol on 1 February 2021. The Protocol covers the catchment areas of all EDs in Hong Kong and serves a population of 7.41 million. This study utilised data from a territory-wide audit of the Protocol to determine the diagnostic performance of the PHECG algorithm for STEMI.

Methods

Study design and setting

This prospective observational study analysed data from the territory-wide audit project regarding the Prehospital 12-Lead Electrocardiogram for Chest Pain Protocol, led by the Hong Kong Hospital Authority Coordinating Committee in Accident and Emergency. The Protocol was designed to include all patients with complaints of chest pain, excluding those <12 years of age; in cardiac arrest; with unmanageable airway or breathing; a Glasgow Coma Scale score of ≤13; a first systolic blood pressure of <90 mm Hg; a respiratory rate of <10 or >29 breaths per minute; or refusal or inability to give consent.

Ambulances were equipped with 12-lead ECG machines capable of automatic algorithm-based diagnosis. The selected machine model was a corpuls3 Monitor and Defibrillator (GS Elektromedizinische Geräte G Stemple GmbH, Kaufering, Germany), with the telemedicine application corpuls.mission (GS Elektromedizinische Geräte G Stemple GmbH, Kaufering, Germany). The selected ECG algorithm was the ECG diagnostic algorithm of the Hannover ECG System (Corscience GmbH & Co KG, Erlangen, Germany).

Upon encountering a patient who met the Protocol's criteria, the ambulance personnel performed a 12-lead ECG on scene or in the stationary ambulance compartment. The ECG was immediately analysed by the computer algorithm and classified as 'STEMI', 'Not STEMI', or 'N/A' (not interpretable due to suboptimal ECG quality). Additional ECGs were performed as necessary to improve quality. The ECG(s) were tele-transmitted to the ED serving the particular catchment area for reading and interpretation by the ED attending physician. If the ECG was classified as 'STEMI' by the computer algorithm, the EMS personnel also directly called to alert the ED. The ED prepared the resuscitation room for patient arrival if the ECG was classified as STEMI by the ED physician.

Study population and data collection

This study adhered to the STARD (Standards for Reporting of Diagnostic Accuracy Studies) 2015 reporting guideline. Patients with PHECGs performed in accordance with the Protocol throughout Hong Kong were prospectively recruited from 1 October to 31 December 2021.

Prehospital ECGs performed and tele-transmitted during the study period were obtained from corpuls.mission's online database and matched to clinical data from the Clinical Data Analysis and Reporting System and Accident and Emergency Information System (Information Technology and Health Informatics Division, Hospital Authority, Hong Kong). Electrocardiograms without matching patient data and those classified as 'N/A' by the algorithm were excluded from the analysis.

Three reference standards were used to investigate the diagnostic accuracy of the computer algorithm. The first reference standard, the primary

outcome, was adjudicated blinded rating of the ECG. Each ECG was de-identified and independently interpreted as 'STEMI', 'Not STEMI' or 'Not interpretable' by two investigators: an emergency physician with ≥5 years of experience in emergency medicine practice and a specialist in Emergency Medicine. Electrocardiograms for which there was disagreement between the interpretations of the two blinded raters were classified according to the blinded interpretation of an adjudicator (a second Emergency Medicine specialist). The diagnosis of STEMI was based on the Fourth Universal Definition of Myocardial Infarction[14] and the modified Sgarbossa criteria for left bundle branch block or ventricular paced rhythm.[15,16] ST-elevation myocardial infarction mimics[17] and STEMI equivalents, according to the 2022 ACC Expert Consensus Decision Pathway on the Evaluation and Disposition of Acute Chest Pain in the Emergency Department,[18] were regarded as 'Not STEMI'. 'Not interpretable' ECGs were those with substantial motion artefacts, wavering baseline, or disconnected lead(s); these ECGs were excluded from the analysis.

The second reference standard was the ED attending physician's diagnosis, which considered the patient's clinical condition, along with additional ECGs and other investigations performed upon arrival in the ED. Patients without ECGs performed in the ED were excluded from the analysis.

The third reference standard was the diagnosis on hospital discharge from the index admission. We excluded patients who died in the ED without an established diagnosis, who developed STEMI after admission, or were discharged with acknowledgement of medical advice and no definitive diagnosis.

Interrater agreement analysis was performed in three dimensions, namely, between the two blinded raters, between the adjudicated blinded rating and the ED diagnosis, and between the adjudicated blinded rating and the diagnosis on hospital discharge. If there was disagreement between the adjudicated blinded rating and the ED diagnosis, the prehospital and ED ECGs were reviewed by the principal investigator to differentiate between dynamic change or true disagreement. Dynamic change was defined as the lack of ST-segment elevation and ECG criteria fulfilment on the initial PHECG, with subsequent evidence on serial ECG performed in the ED.

False-positive and false-negative ECGs were reviewed and classified by the principal investigator. The following categories of ECG morphology were determined based on criteria described in existing literature: Brugada pattern,[19] early repolarisation,[20] left bundle branch block or paced rhythm not matching STEMI criteria,[15,16] left ventricular hypertrophy,[21] pericarditis,[22] and ventricular ectopics.[23]

Statistical analysis

Continuous variables were presented as mean ± standard deviation and were analysed with the independent *t* test. Categorical variables were reported as absolute frequencies and percentages and were analysed with the Chi squared test or Fisher's exact test. Interrater agreement regarding ECG diagnosis was analysed using Cohen's kappa. Sensitivity, specificity, and predictive values were derived from 2 × 2 contingency tables and analysed with the Chi squared test.

The threshold for statistical significance was regarded as P<0.05. All statistical analyses were performed using SPSS software (Windows version 26.0; IBM Corp, Armonk [NY], US).

Results

Baseline characteristics

During the study period, 2801 PHECGs were performed, one for each patient who presented with chest pain. Of these ECGs, 2437 were matched to electronic patient records. After the exclusion of 103 ECGs classified as 'N/A' by the computer algorithm, 2334 ECGs were included in the analysis (Fig 1).

The characteristics of the study population are presented in Table 1. Overall, 62.9% of the patients were men. The mean age of male patients, female patients, and both sexes were 63.9 years, 74.1 years, and 67.7 years, respectively. In total, 83.6% of patients were placed on stretchers upon arrival at the ED. Furthermore, 8.2% of patients were institutionalised in residential homes. Of the ECGs, 42.4% were performed during 0800 to 1559 hours, 35.4% were performed during 1600 to 2359 hours, and 22.3% were performed during 0000 to 0759 hours. A total of 405 (17.4%) PHECGs were classified as STEMI by the algorithm.

Primary outcome

The primary outcome was diagnostic accuracy based on the adjudicated blinded rating. The prevalence of STEMI was 5.1% (Table 2). There was good interrater observed agreement (96.9%) between the two blinded ECG assessors. Cohen's kappa was 0.84 (95% confidence interval [CI]=0.81-0.88; P<0.05) [Table 3]. The algorithm had a sensitivity of 94.6% (95% CI=88.2%-97.8%), specificity of 87.9% (95% CI=86.4%-89.2%), positive predictive value of 29.4% (95% CI=24.8%-34.4%), negative predictive value of 99.7% (95% CI=99.3%-99.9%), positive likelihood ratio of 7.8 (95% CI=6.9-8.8), and negative likelihood ratio of 0.06 (95% CI=0.03-0.13) [all P<0.05] (Table 2).

Secondary outcomes

Secondary outcomes were the algorithm's diagnostic

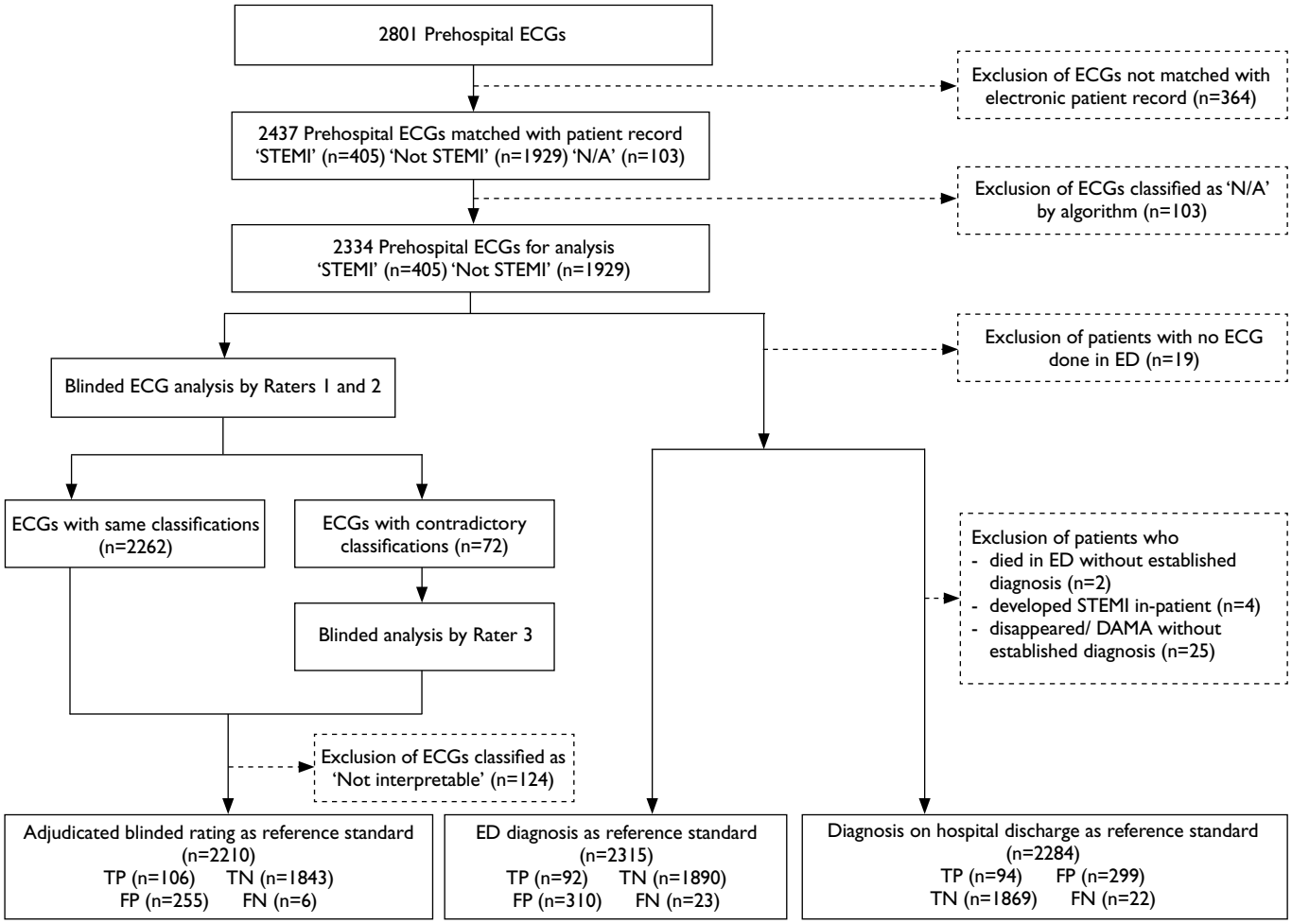

FIG 1. Patient selection for diagnostic accuracy analysis

Abbreviations: DAMA = discharged with acknowledgement of medical advice; ECG = electrocardiogram; ED = emergency department; FN = false negative; FP = false positive; N/A = not interpretable due to suboptimal ECG quality; STEMI = ST-elevation myocardial infarction; TN = true negative; TP = true positive

accuracy with reference to the ED attending physician's diagnosis and to the diagnosis on hospital discharge.

Substantial agreement was observed between the diagnosis based on the adjudicated blinded rating and these two reference standards. Discrepancies in agreement between the adjudicated blinded rating of ECGs and these two reference standards reflected the presence of dynamic ECG changes. Observed agreement between the adjudicated blinded rating and ED physician's diagnosis was 97.1%, with Cohen's kappa of 0.69. Excluding patients with dynamic ECG changes in the ED, the observed agreement was 98.2% and Cohen's kappa was 0.78. Observed agreement between the adjudicated blinded rating and final discharge diagnosis was 97.5%, with Cohen's kappa of 0.74. Excluding patients with dynamic ECG changes in the ED, the observed agreement was 98.4% and Cohen's kappa was 0.80 (Table 3). The diagnostic performance based on the three reference standards and the analysis of interrater agreement are summarised in Tables 2 and 3, respectively.

Characteristics of false-positive electrocardiograms

The 255 false-positive ECGs with the adjudicated blinded rating as the reference standard were reviewed and characterised as shown in Figure 2. The leading causes were early repolarisation (n=97; 38.0%), left bundle branch block (n=40; 15.7%), and tachycardia of >140 beats per minute (n=34; 13.3%). Excluding ECGs with suboptimal quality (classified as 'N/A' by the algorithm and 'Not interpretable' according to adjudicated blinded rating), false-positive ECGs due to artefacts constituted 8.6% (n=22).

TABLE 1. Characteristics of the study population*

	All (n=2334)	Adjudicated blinded rating (n=2210)			ED diagnosis (n=2315)			Diagnosis on hospital discharge (n=2284)		
		STEMI (n=112)	Not STEMI (n=2098)	P value	STEMI (n=115)	Not STEMI (n=2200)	P value	STEMI (n=116)	Not STEMI (n=2168)	P value
Age, y	67.7 (± 18.0)	64.8 (± 13.6)	67.4 (± 18.2)	0.05	62.1 (± 12.6)	68.0 (± 18.2)	<0.05	63.0 (± 12.0)	68.1 (± 18.2)	<0.05
Male	63.9 (± 18.1)	63.8 (± 13.9)	63.5 (± 18.4)	0.81	62.4 (± 12.3)	64.0 (± 12.3)	0.22	63.2 (± 11.7)	64.1 (± 18.4)	0.49
Female	74.1 (± 16.0)	69.6 (± 14.8)	74.0 (± 16.0)	0.22	60.6 (± 15.3)	74.5 (± 15.8)	<0.05	61.8 (± 15.2)	74.5 (± 15.8)	<0.05
Age >65 y	1410 (60.4%)	52 (46.4%)	1263 (60.2%)		42 (36.5%)	1357 (61.7%)		46 (39.7%)	1341 (61.9%)	
Male sex	1469 (62.9%)	93 (83.0%)	1308 (62.4%)	<0.05	101 (87.8%)	1358 (61.7%)	<0.05	103 (88.8%)	1334 (61.5%)	<0.05
Mobility status				<0.05			<0.05			<0.05
Ambulatory	76 (3.3%)	1 (0.9%)	73 (3.5%)		1 (0.9%)	69 (3.1%)		1 (0.9%)	68 (3.1%)	
Wheelchair	127 (5.4%)	0	122 (5.8%)		1 (0.9%)	125 (5.7%)		1 (0.9%)	123 (5.7%)	
Stretcher	1950 (83.6%)	94 (83.9%)	1753 (83.6%)		92 (80.0%)	1847 (84.0%)		93 (80.2%)	1819 (83.9%)	
Unknown	181 (7.8%)	17 (15.2%)	150 (7.2%)		21 (18.3%)	159 (7.2%)		21 (18.1%)	158 (7.3%)	
Institutionalised	191 (8.2%)	1 (0.9%)	172 (8.2%)	<0.05	0	189 (8.6%)	<0.05	1 (0.9%)	187 (8.6%)	<0.05
ECG time				0.74			0.26			0.27
0000-0759	520 (22.3%)	22 (19.6%)	472 (22.5%)		19 (16.5%)	499 (22.7%)		19 (16.4%)	493 (22.7%)	
0800-1559	989 (42.4%)	48 (42.9%)	895 (42.7%)		55 (47.8%)	925 (42.1%)		54 (46.6%)	917 (42.3%)	
1600-2359	825 (35.4%)	42 (37.5%)	731 (34.8%)		41 (35.6%)	776 (35.3%)		43 (37.1%)	758 (35.0%)	
Prehospital ECG algorithm classified as STEMI	405 (17.4%)	106 (94.6%)	255 (12.2%)	<0.05	92 (80.0%)	310 (14.1%)	<0.05	94 (81.0%)	299 (13.8%)	<0.05

Abbreviations: ECG = electrocardiogram; ED = emergency department; STEMI = ST-elevation myocardial infarction

* Data are shown as No. (%) or mean ± standard deviation, unless otherwise specified

TABLE 2. Diagnostic performance of the prehospital electrocardiogram algorithm according to respective reference standards*†

	Adjudicated blinded rating (n=2210)	ED diagnosis		Diagnosis on hospital discharge	
		All (n=2315)	Excluding dynamic changes (n=2283)	All (n=2284)	Excluding dynamic changes (n=2253)
STEMI prevalence	5.1% (4.2%-6.1%)	5.0% (4.1%-6.0%)	4.23% (3.5%-5.2%)	5.1% (4.2%-6.1%)	4.3% (3.5%-5.2%)
True positive	106	92	89	94	87
True negative	1843	1890	1888	1869	1866
False positive	255	310	298	299	291
False negative	6	23	8	22	9
Sensitivity	94.6% (88.2%-97.8%)	80% (71.4%-86.7%)	91.8% (83.9%-96.1%)	81.0% (72.5%-87.5%)	90.6% (82.5%-95.4%)
Specificity	87.9% (86.4%-89.2%)	85.9% (84.4%-87.3%)	86.4% (84.8%-87.8%)	86.2% (84.7%-87.6%)	86.5% (85.0%-87.9%)
Positive predictive value	29.4% (24.8%-34.4%)	22.9% (18.9%-27.4%)	23% (19.0%-27.6%)	23.9% (19.9%-28.5%)	23.0% (18.9%-27.7%)
Negative predictive value	99.7% (99.3%-99.9%)	98.9% (98.2%-99.2%)	99.6% (99.1%-99.8%)	98.8% (98.2%-99.3%)	99.5% (99.1%-99.8%)
Positive likelihood ratio	7.8 (6.9-8.8)	5.7 (5.0-6.5)	6.7 (6.0-7.6)	5.9 (5.1-6.7)	6.7 (5.9-7.6)
Negative likelihood ratio	0.06 (0.03-0.13)	0.23 (0.16-0.34)	0.1 (0.05-0.19)	0.22 (0.15-0.32)	0.11 (0.06-0.20)

Abbreviations: ED = emergency department; STEMI = ST-elevation myocardial infarction

* Data are shown as No. or % (95% confidence interval), unless otherwise specified

† All P<0.05

Characteristics of false-negative electrocardiograms

Using the diagnosis on hospital discharge as the reference standard, 22 STEMI cases were missed by the algorithm (Fig 3). Thirteen (59.1%) of the false-negative ECGs were due to the development of dynamic ECD changes in the ED; four (18.2%) of these had subtle ST-segment elevation. ST-segment

TABLE 3. Analysis of interrater agreement*

	Between adjudicated blinded raters (n=2210)	Between adjudicated blinded rating and ED diagnosis		Between adjudicated blinded rating and diagnosis on hospital discharge	
		All (n=2315)	Excluding dynamic changes (n=2283)	All (n=2284)	Excluding dynamic changes (n=2253)
Observed agreement	96.9%	97.1%	98.2%	97.5%	98.4%
Cohen's kappa (95% CI)	0.84 (0.81-0.88)	0.69 (0.62-0.77)	0.78 (0.72-0.85)	0.74 (0.67-0.81)	0.80 (0.74-0.87)

Abbreviations: 95% CI = 95% confidence interval; ED = emergency department
* All P<0.05

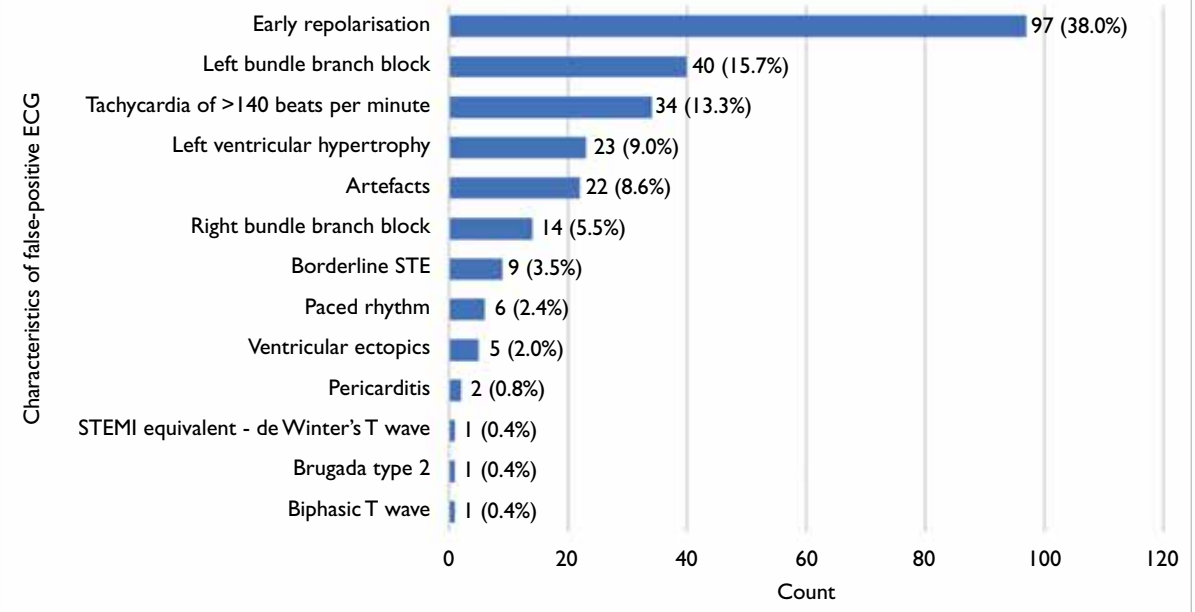

FIG 2. Electrocardiogram features of false-positive electrocardiograms with the adjudicated blinded rating as the reference standard (n=255)
Abbreviations: ECG = electrocardiogram; STE = ST-segment elevation; STEMI = ST-elevation myocardial infarction

elevation in lead augmented vector right and the STEMI equivalent morphology of de Winter's T wave were noted in two (9.1%) ECGs each. One ECG was classified as 'Not interpretable' according to the adjudicated blinded rating because of substantial artefacts.

Discussion

Implications on prehospital care systems for ST-elevation myocardial infarction

This prospective observational study examined the diagnostic performance of a rule-based PHECG algorithm universally utilised in Hong Kong, based on three levels of reference standards. The primary outcome, adjudicated blinded rating, closely reflects diagnostic performance without the addition of patient clinical history and presentation or any other diagnostic aids. The American Heart Association recommends three levels of PHECG diagnosis, namely, EMS interpretation, computerised algorithm diagnosis, and ECG transmission for remote interpretation.[24] However, in healthcare systems such as the Hospital Authority in Hong Kong, EMS are trained to perform but not interpret PHECGs. Thus, it is important to understand reliance on the computerised algorithm using the benchmark of physician-based remote interpretation; these data can guide the establishment and improvement of care systems.

One in eight of the PHECGs in this study showed false-positive results. Considering the fair specificity and positive predictive value of only 29.4% for the automated ECG diagnostic

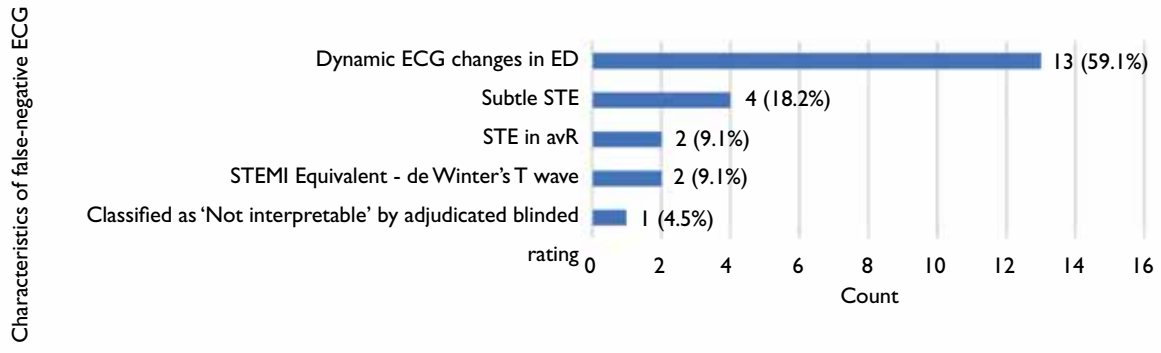

FIG 3. Electrocardiogram features of false-negative electrocardiograms with diagnosis on hospital discharge as the reference standard (n=22)

Abbreviations: avR = lead augmented vector right; ECG = electrocardiogram; ED = emergency department; STE = ST-segment elevation; STEMI = ST-elevation myocardial infarction

programme, this high false-positive rate reflected limitations in guiding prehospital treatment and streamlining care systems (eg, prehospital diversion to percutaneous coronary intervention–capable centres or prehospital triage for direct transfer to a cardiac catheterisation laboratory). A hybrid two-step ECG interpretation model, involving a physician's remote (ie, telemedicine-based) interpretation of ECGs that are classified as STEMI by the computerised algorithm, could be adopted to minimise overactivation and ensure prudent use of healthcare resources. Nonetheless, the algorithm exhibited good sensitivity in terms of identifying STEMI patients. Its high negative predictive value allowed STEMI to be reasonably excluded based on ECG results. Although remote PHECG interpretation is considered relatively accurate, it generally results in STEMI misdiagnosis rates of 6% to 8%.[13] Therefore, we included secondary outcomes, namely, the algorithm's diagnostic performance based on the ED attending physician's diagnosis and the final discharge diagnosis; we assessed interrater agreement between these reference standards. We adopted an operational approach focused on the 'appropriateness of cardiac catheterisation laboratory activation', rather than a strictly patient-centred approach based on primary percutaneous coronary intervention findings or cardiac biomarkers.

Diagnostic performance varies across electrocardiogram machine models and algorithms

The inclusion of three reference standards was intended to address the heterogeneous estimates of PHECG diagnostic performance for STEMI in existing literature. Prior studies have been based on various reference standards, including blinded physician rating,[25] ED attending physician's diagnosis,[6,26] hospital discharge diagnosis,[7] and the appropriateness of coronary angiography activation.[8] The results have varied according to STEMI prevalence in the study population, as well as the reference standard, ECG machine, and computerised algorithm. Using ED clinical diagnosis as the reference standard, a single-centre pilot study in Hong Kong by Cheung et al[6] utilising the X Series Monitor/Defibrillator and Inovise 12L Interpretive Algorithm (Zoll Medical Corporation, Chelmsford [MA], US) demonstrated a low sensitivity (53.8%) and high specificity (99.6%). Bhalla et al[26] utilised LIFEPAK 12 monitors (Physio-Control, Redmond [WA], US) equipped with a Marquette 12SL ECG analysis programme (General Electric Company, Fairfield [CT], US) to evaluate PHECGs from 100 STEMI patients and 100 control participants; they found a similarly low sensitivity (58%) and very high specificity (100%). Bosson et al[7] examined ECGs obtained with the LIFEPAK 15 monitor (Physio-Control, Inc, Minneapolis [MN], US) and analysed using the University of Glasgow 12-Lead ECG Analysis Programme (version 27); their results showed 92.8% sensitivity and 98.7% specificity, based on the reference standard of appropriateness for emergency coronary angiography.[7] The prevalence of STEMI was much lower in their study than in our study (1.4%[7] vs 5.1% [Table 2]) because their dataset also included PHECGs performed for symptoms other than chest pain. Using the same ECG machine model as the aforementioned study,[7] Fakhri et al[8] tested an automated analysis method with a high-specificity STEMI configuration. In a carefully selected STEMI population, the sensitivity and specificity were 69.8% and 51.5%, respectively, based on discharge diagnosis.[8] A meta-analysis conducted

by Tanaka et al[27] suggested that computer-assisted ECG interpretation had a high pooled specificity (95.4%; 95% CI=87.3%-98.4%) with an acceptable estimated number of false-positive results, whereas the pooled sensitivity was relatively low (85.4%; 95% CI=74.1%-92.3%), for identifying STEMI on PHECG. All of these studies utilised ECG machines and diagnostic algorithms that differed from our method, emphasising that diagnostic performance varies across models; evaluations of specific ECG machines and algorithms should be conducted by individual healthcare systems to suit their operational needs.

Major patterns of false-positive and false-negative electrocardiograms

The Hannover ECG System algorithm utilised in our study was one of nine computer programmes investigated in the international Common Standards for Quantitative Electrocardiography Diagnostic Study,[28] using clinical diagnosis as the reference standard. This statistics-based algorithm exhibited one of the highest sensitivities (79.0%) for detecting myocardial infarction compared with all algorithms combined (72.2%); its sensitivity also was similar to that of the combined independent ratings of eight cardiologists (80.3%). However, its ability to correctly classify normal ECGs (86.6%) was lower than that of the combined ratings of cardiologists (97.1%) and the combined algorithms (96.7%). Our findings are consistent with the results of the Common Standards for Quantitative Electrocardiography Diagnostic Study. The presence of artefacts contributed to 8.6% of false-positive ECGs; this rate could be improved by enhancing ECG technique. The major patterns of misdiagnosis were early repolarisation (38.0%), left bundle branch block (15.7%), and tachycardia of >140 beats per minute (13.3%) [Fig 2]. Artefacts on ECG were responsible for the largest proportion of false-positive ECGs[8]; they contributed a smaller proportion in our dataset because we excluded ECGs considered 'Not interpretable' by the algorithm or blinded raters. Early repolarisation remained a leading cause of false-positive ECGs, and existing consensus papers on early repolarisation may help guide future algorithm development.[20,29] Further collaboration with the software provider to optimise the algorithm may enhance its accuracy.

Among cases of STEMI missed by the algorithm using diagnosis on hospital discharge as the reference standard, more than half were caused by ECG changes after patient arrival in the ED. False-negative ECGs due to subtle ST-segment elevation represented only 3.45% of all STEMI patients. Remote physician interpretation of these PHECGs would likely be equivocal and uncertain. It presumably would not be beneficial to adjust the algorithm to correct this margin of error, considering the potential for additional false-positives. However, it might be useful to refine the algorithm for enhanced detection of STEMI equivalents, which were missed in the current cohort.

The rise of artificial intelligence

Although the diagnostic limitations of rule-based algorithms are recognised, Zhao et al[9] described an artificial intelligence diagnostic algorithm that showed promising results (96.8% sensitivity and 99% specificity) using coronary angiography findings as the reference standard. The potential role of artificial intelligence in PHECG diagnosis merits further exploration to increase accuracy.

Paradigm shift in classifying myocardial infarction

Meyers et al[30] proposed a new paradigm of occlusion myocardial infarction (OMI) vs non-OMI, which they compared with the conventional STEMI vs non-STEMI paradigm. Occlusion myocardial infarction refers to type 1 myocardial infarction that involves acute total or near-total occlusion of a major epicardial coronary vessel with insufficient collateral circulation, causing acute infarction. Meyers et al[30] showed that 38% of OMI patients did not meet ECG-based STEMI criteria, as stated in the 4th Universal Definition of Myocardial Infarction.[14] Compared with OMI patients who met STEMI criteria, patients not meeting the criteria experienced significant delays in cardiac catheterisation but exhibited similar adverse outcome profiles. These findings highlight the need to re-evaluate classification strategies for acute coronary syndrome, with a focus on rapidly recognising this underserved and poorly understood subgroup of patients who would benefit from emergent reperfusion therapy. Future research should emphasise identifying ECG features of OMI beyond the STEMI criteria.

Limitations

First, 13% of PHECGs were not matched to electronic patient records, resulting in the loss of data for interpretation. Second, during adjudicated blinded rating of the ECGs, STEMI equivalents were not included in the definition of STEMI because the algorithm was not designed to include these characteristics. This exclusion differs from real-world scenarios in which the recognition of STEMI equivalents would prompt ED physicians to implement STEMI management. Third, this study evaluated a single rule-based algorithm combined with a single ECG machine model utilised by a single urban EMS service provider serving a predominantly ethnic Chinese population. Fourth, intraobserver variability was not assessed for each ECG reviewer. Finally, ECGs considered 'Not interpretable' by

ECG reviewers due to substantial artefacts were excluded from data analysis, which might lead to underestimation regarding the contributions of artefacts to false positivity.

Conclusion

In this territory-wide study, a rule-based PHECG algorithm demonstrated good sensitivity and fair specificity for the diagnosis of STEMI.

Author contributions

Concept or design: JHY Lai, CT Lui.
Acquisition of data: JHY Lai, TWT Chan, BCP Wong.
Analysis or interpretation of data: JHY Lai, CT Lui.
Drafting of the manuscript: JHY Lai.
Critical revision of the manuscript for important intellectual content: CT Lui, TWT Chan, BCP Wong, MSH Tsui, BKA Wan, KL Mok.

All authors had full access to the data, contributed to the study, approved the final version for publication, and take responsibility for its accuracy and integrity.

Conflicts of interest

All authors have disclosed no conflicts of interest.

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Ethics approval

The research was approved by the New Territories West Cluster Research Ethics Committee of Hospital Authority, Hong Kong (Ref No.: NTWC/REC/21097). The requirement for patient consent was waived by the Committee because the study was conducted within a preexisting prehospital clinical service.

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