AI-assisted STEMI triage system from ambulance to ER

China Medical University Hospital

Executive Summary

ST-segment elevation myocardial infarction (STEMI) is a medical emergency, and early reperfusion with primary percutaneous coronary intervention (PPCI) is essential to improve the clinical outcomes of patients with STEMI. Previous studies have demonstrated that shortened door-to-balloon (D2B) times for STEMI patients undergoing PPCI significantly reduced mortality and morbidity rates. The correct and immediate diagnosis of acute myocardial infarction is essential in emergency and prehospital ambulance settings, especially in patients with atypical presentations. To improve this clinical problem, we have introduced the following systems:

- ***In-hospital:***

Emergency intelligent myocardial infarction platform: An AI-assisted ECG diagnostic and high-risk scoring system used to calculate an "ASAP" score which identifies high-risk patients presenting with atypical symptoms.

- ***Prehospital:***

Remote AI STEMI detecting system for prehospital ambulance: An AI-assisted remote STEMI detection system used during ambulance to improve:

1. the proportion of patients with atypical symptoms who receive an ECG in a timely manner (within 10 minutes of arrival)
2. the timeliness and accuracy of diagnosing acute myocardial infarction in all emergency patients with an ECG
3. the rate of prehospital ECG performance and the accuracy of diagnosing acute myocardial infarction.

Our achievements:

- Prior to the introduction of AI, CMUH already had a shorter D2B time compared to other medical centers in Taiwan. The primary reason for integrating AI into our emergency department and prehospital environment is for self-improvement and to provide better medical services.
- The median D2B time decreased from 64.5 minutes to 53.2 minutes prior to Taiwan's major COVID-19 epidemic periods.
- The percentage of patients with an atypical presentation undergoing a 12-lead ECG examination within ≤10 min of their presentation steadily increased from 24.0% to 63.4%.
- Acute myocardial infarction (AMI) mortality has also dropped over the last three years from 7.7% to 5.5%.

- The percentage of prehospital ECGs successfully recorded in our system before arriving at the hospital is 100%. The percentage of prehospital ECGs recorded within 10 min of the initial medical contact is 80%.

Clinical Problem and Pre-Implementation Performance

ST-segment elevation myocardial infarction (STEMI) is a medical emergency. Early reperfusion with primary percutaneous coronary intervention (PPCI) is essential to improve the clinical outcomes of patients with STEMI. Shorter D2B times, or the interval between the patient's arrival in the emergency room (ER) and the time a catheter guidewire successfully crosses the offending lesion in the cardiac catheter lab, have been shown in previous studies to significantly lower mortality and morbidity rates for STEMI patients undergoing PPCI.

Individual components constituting the total D2B time are defined as follows:

I. Door-to-ECG time: The interval of time between the patient's arrival at the ER and the start of the ECG examination.
II. Catheterization laboratory activation time: The interval between performing an ECG and activating the catheterization team.
III. Door-to-activation time: The interval between the patient's arrival at the ER and the activation of the catheterization team.
IV. Catheterization laboratory preparation time: The time required for the catheterization team to prepare for PPCI.

The 2013 American College of Cardiology Foundation/American Heart Association Guideline gave a Class I recommendation that the first medical contact-to-device time should be less than 90 minutes for STEMI patients undergoing PPCI. In addition, the latest 2017 European Society of Cardiology (ESC) STEMI guidelines even recommend that the target time delay from STEMI diagnosis to wire crossing should be less than 60 minutes in PCI-capable institutes.

Before June 8, 2020, the mean D2B time at China Medical University Hospital (CMUH) was 64.5 minutes, and the percentage of D2B times <90 minutes was 87.2%. The mean D2B times during regular hours and off hours were 53.1 minutes and 70.4 minutes, respectively, and the percentage of D2B times <90 minutes during regular hours and off hours were 93.3% and 83.9%, respectively. Among the individual components of D2B time, the mean door-to-ECG time was 5.0 minutes, the catheterization laboratory activation time was 11.6 minutes, and the door-to-activation time was 16.1 minutes.

We have independently designed an ASAP score to identify patients who do not have chest discomfort but are at a high risk of STEMI (ASAP score ≥3) by retrospectively analyzing data from STEMI patients at CMUH. The data elements necessary for calculating the ASAP score were determined by the care coordinators and cardiologists associated with the Chest Pain Center based on data focused on various atypical presentations of ACS stored in the center's databse over the past five years. Before the ASAP score was implemented in the ER, a 12-lead ECG was performed on 24.0% of the patients within ≤10 min of their arrival.

To reduce the total D2B time and individual components of D2B time in patients with STEMI, and effectively identify high-risk patients requiring prompt ECG examination, we implemented an ASAP score and a 24/7 AI-based STEMI detection system in the ER. In addition, we then developed a prehospital AI-assisted remote detection system of STEMI to shorten the symptom-to-balloon (S2B) time.

Patients 20-100 years of age with STEMI and patients who arrived in the ER triage due to non-chest pain symptoms were enrolled. Patients who met the exclusion criteria at the ER included ischemic chest pain for >12 hours, out-of-hospital cardiac arrest, refractory ventricular tachyarrhythmias with prolonged cardiopulmonary resuscitation in the ER, acute respiratory failure and endotracheal intubation in the ED, and profound shock with intra-aortic balloon pump or extracorporeal membrane oxygenation placement in the ER. In addition, patients without significant angiographic coronary artery disease (CAD) were also excluded.

The ultimate goals were to provide real-world evidence by assessing how the AI-based triage system may impact chest pain triaging and clinical decision-making in our daily practice and how AI-assisted remote detection of STEMI may impact the timeliness and accuracy of prehospital ECG interpretation, important elements related to early diagnosis, and timely reperfusion in STEMI patients.

Design and Implementation Model Practices and Governance

The cardiology experts led by Vice Superintendent Dr. Kuan-Cheng Chang and the AI center for Medical Diagnosis led by Dr. Kai-Cheng Hsu cooperated to develop the 24/7 AI-assisted STEMI detection system. We also paired AI-assisted diagnosis software for acute myocardial infarction with a miniature 12-lead ECG machine (QT Medical, Diamond Bar, CA., USA) to be used at eight fire brigades in Taichung City and six fire brigades in Nantou County in central Taiwan.

The workflow design and solution selection, testing, and field testing process included (i) 12-lead ECG data collection and labeling, (ii) deep learning model selection and internal testing, (iii) comparison of ECG interpretation performance among AI, internists, ER doctors, and cardiologists, (iv) implementation the 24/7 AI-based STEMI detection system in the ER and the comparison between AI-based and conventional ER triage, (v) validation of 12-lead ECG signals between GE machines traditionally used in hospitals and the miniature portable ECG device (QT Medical), (vi) education and training of operators, (vii) implementation of AI-based STEMI detection on prehospital 12-lead ECGs, and (viii) real-world data collection after implementation and governance. Details of each step are described as follows.

I. 12-lead ECG data collection and labeling: Before the development of the remote AI, a core committee, including AI experts and cardiologists, identified the appropriate data elements required for capture. We first retrieved 12-lead ECG data from the digital ECG core laboratory database at CMUH between 2009 and 2018. The digital ECG was transmitted to and stored at the ECG core laboratory of CMUH. In total, 2907 12-lead ECGs were retrospectively retrieved and used to develop the AI model. These were labeled by three board-certified cardiologists simultaneously and their consensus served as the ground truth for model training (80%) and validation (20%).

II. Deep learning model selection and internal testing: A new model that combined convolutional neural network and long short-term memory (CNN-LSTM) was used to facilitate STEMI ECG diagnosis. To evaluate the model's performance before its deployment, an additional 4,007 12-lead ECGs from ER patients were tested against the consensus (ground truth) formed by the three board-certified cardiologists as an internal test of the AI model.
III. Comparison of ECG interpretation performance among AI, internists, ER doctors, and cardiologists: We compared the diagnostic accuracy and labeling time between the model and physicians in order to investigate and confirm that the performance of our AI model was not inferior to that of cardiologists.
IV. Implementation the 24/7 AI-based STEMI detection system in the ER and a comparison between AI-based and conventional ER triage: We compared total D2B times, the individual components of D2B time, and percentages of D2B times <90 min between the AI-based triage period and the conventional triage period.
V. Validation of 12-lead ECG signals between devices: The proposed deep learning model for STEMI detection was based on the digital 12-lead ECG signals recorded using a computerized ECG machine (GE Healthcare MAC 2000/3500/5500, US). For the prehospital 12-lead ECG acquisition, we used a mini portable ECG device (QT Medical) with the proposed AI algorithm integrated within. To ensure the efficacy of AI-based STEMI detection using the mini-portable ECG device, we checked the consistency of the 12-lead ECG output signals between the two devices.
VI. Education and training of operators: Online courses were used to educate and train firefighters at each fire station how to properly operate the prehospital 12-leads ECG AI-based STEMI detection system during May 2022 to July 2022. The training was done online because of the COVID-19 pandemic.
VII. AI-assisted STEMI detection system implementation using prehospital 12-lead ECG: It was conducted in Taichung City and Nantou County in Central Taiwan between July 17 2021, and March 26 2022. There was a total of 14 pre-assigned fire stations which accounted for 19% of all the fire stations in the two administrative districts.
VIII. Real-world data collection following implementation and governance: All ECG signals were transmitted to the CMUH AI center. The false negative and false positive ECGs interpreted by AI were confirmed according to the consensus (ground truth) established by three board-certified cardiologists for model optimization.

The timetable from the initial data gathering to the final round of field testing is displayed in Figure 1.

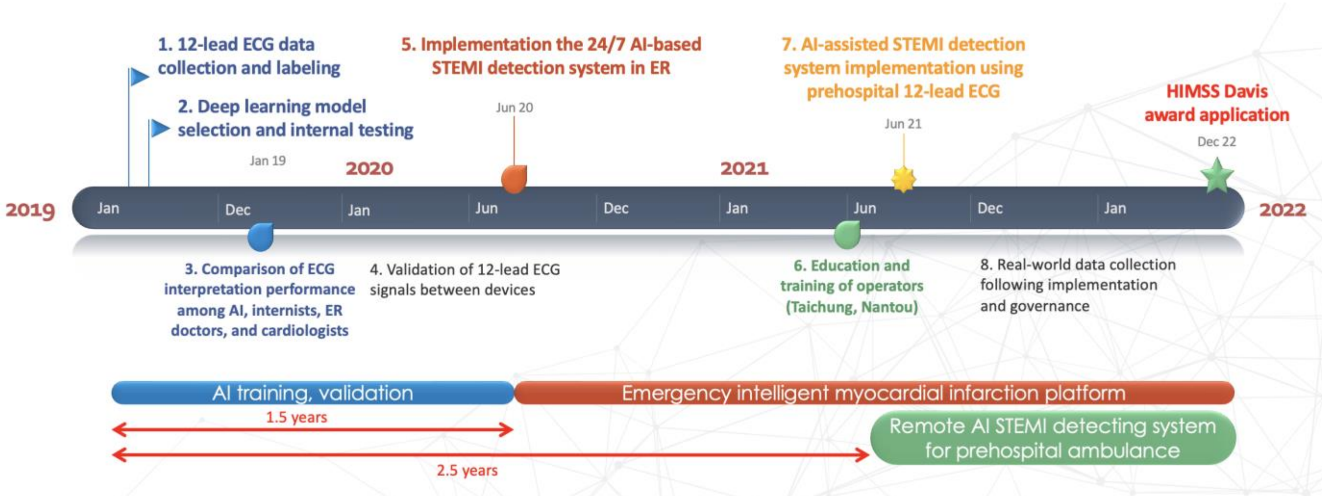


Figure 1. The timetable of developing AI-assisted STEMI triage system

Clinical Transformation enabled through Information and Technology

On June 9 2020, an All-Day AI-Based Triage System with ASAP scoring system was implemented in the CMUH ER, its workflow is shown in Figure 2. A digital 12-lead ECG examination was performed immediately for every patient who was triaged in the ER presenting with chest pain. Each ECG was instantly interpreted by AI. When the AI model detected a STEMI by ECG interpretation, the system automatically sent a warning message along with a link to the specific ECG to the mobile phones belonging to the ER physicians and on-duty cardiologists (Figure 3). Once STEMI was confirmed by a cardiologist on duty, he or she initiated PPCI treatment for the patients who were reporting an onset of ischemic chest pain within 12 hours of entering the ER.

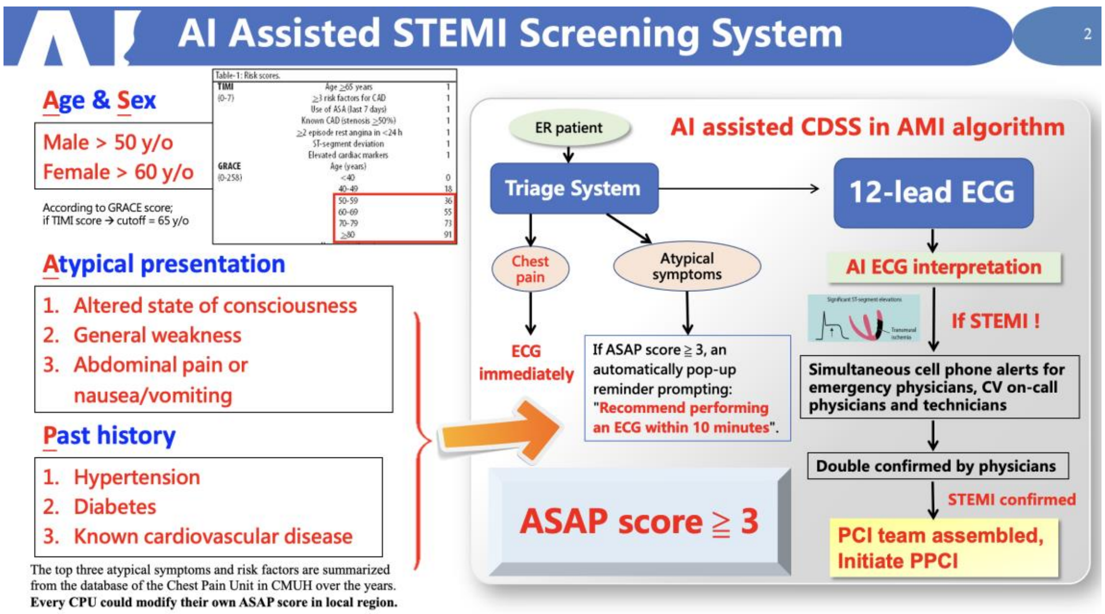


Figure 2

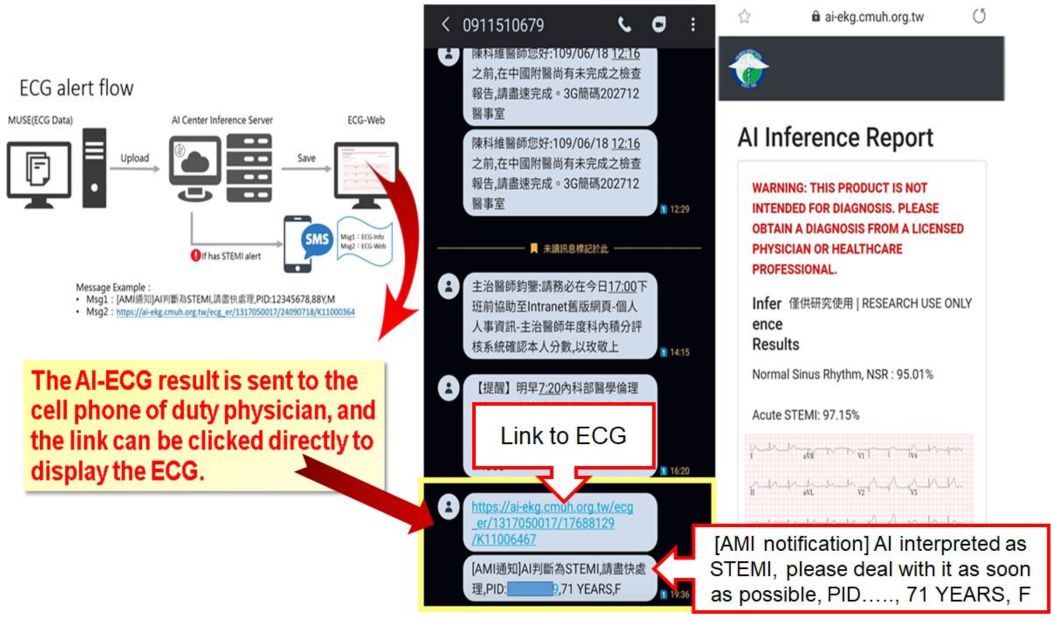


Figure 3

For those patients who were presenting with non-chest pain symptoms, we designed a scoring tool to identify high-risk patients requiring an immediate 12-lead ECG examination. After inputting clinical data including age, sex, clinical symptoms, and past medical history into an online triage system, a pop-up reminder for a prioritized 12-lead ECG examination to be taken immediately appeared on the screen when the computer-generated ASAP score was ≥3 points (Figure 4).

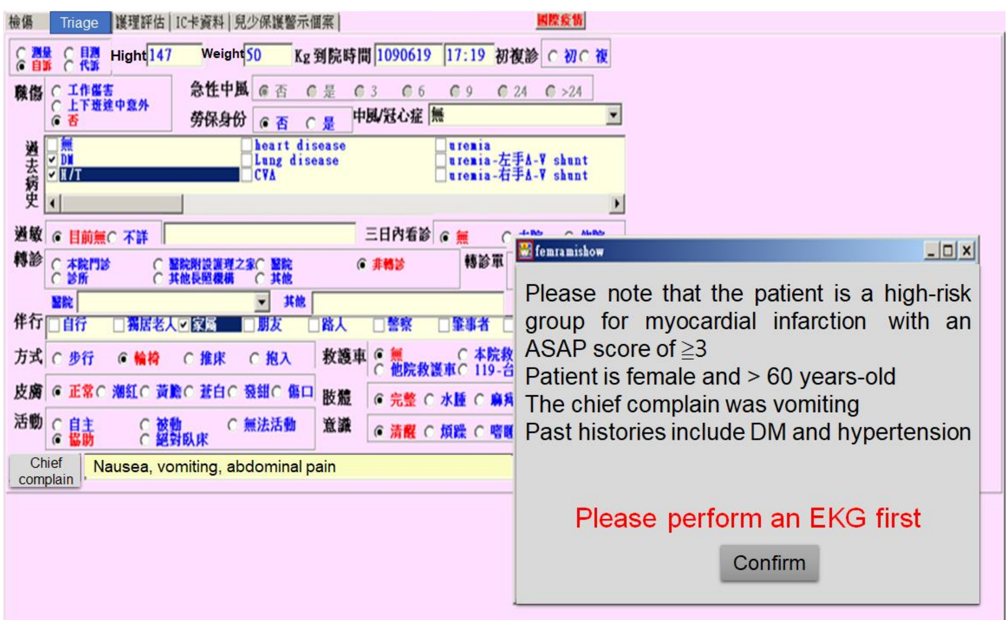


Figure 4

A new AI model combining a convolutional neural network and long short-term memory (CNN-LSTM) was used to facilitate STEMI ECG diagnosis. In this model, 6 chest leads were fed into one 1D CNN, and 6 limb leads were fed into another 1D CNN. The outputs of the two 1D CNNs were connected to two layers of LSTM, and the outputs of the two LSTMs were connected to a fully connected layer. The binary cross-entropy loss function and Adam optimizer were employed during model training. F1 scores, precision, and recall were monitored to retain the best model in the validation set (Figure 5).

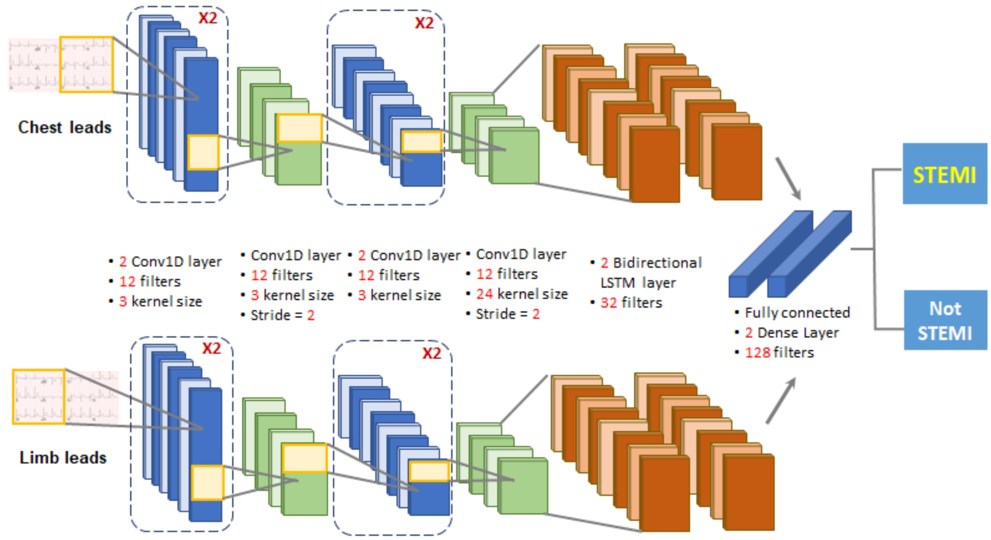


Figure 5

When the emergency department receives information indicating a 'possible STEMI', the following actions are triggered:
1) Cardiac team assembly: the attending physician, research physician, and technicians are notified to initiate emergency catheterization.
2) The catheterization lab located beneath the emergency department prepares for surgery.
3) The emergency team prescribes medications, including DAPT and anticoagulants.
4) The patient is transferred to the catheterization lab in the shortest possible time.

In a pre-hospital ambulance setting, we recommend that frontline emergency medical technicians (EMTs), upon suspecting potential cardiac conditions and if circumstances permit, should proceed directly with electrocardiogram examination. 12-lead ECG machines have been deployed in Taiwan's emergency response units. However, under emergency conditions, it's relatively challenging to utilize traditional 12-lead ECG machines that require proper connection of ten leads. This project employs a simplified patch-type 12-lead ECG machine, which is easier to operate and train on, and its compatibility with AI models further facilitates data collection. AI-assisted STEMI detection paired with prehospital 12-lead ECG was implemented in Taichung City and Nantou County. After the 12-lead ECG was recorded in the ambulance, the ECG signal was first transmitted to the CMUH AI center to be further classified as “STEMI” or “Not STEMI” (Figure 6). The AI-annotated ECG data was then posted on a messenger group to show the result to EMTs and for diagnostic confirmation by available online emergency physicians according to usual practice. The process, in most cases, is within 30 seconds.

Figure 6

When the AI model detected STEMI on a prehospital ECG and the result was confirmed by an online physician, EMT personnel contacted the nearest available interventional hospital to reduce ambulance transfer time for urgent reperfusion therapy. The most common and challenging issue raised by emergency responders involves situations where the patient or their family demands direct hospital transportation, or cases dealing with female patients.

On the CMUH APP, a health education system for patients with AMI has been built to help them follow their post-STEMI care plan outside of the hospital. Patients could use this interface to know how to prevent and monitor symptoms and signs of AMI. In addition, they can use the APP to communicate with their case manager online.

Improving Adherence to the Standard of Care

Timely ECG and catheterization lab activation:

In the early stages of system implementation (June - October 2020), we conducted a preliminary analysis: the percentage of patients with atypical presentation undergoing a 12-lead ECG examination within ≤10 min of their presentation steadily increased monthly from 24.0%, at baseline before introducing the ASAP score, to 43.4%, 56.2%, 62%, 57.8%, and 63.4% after incorporating the ASAP score for chest pain triage (Figure 7). Notably, the median door-to-ECG time decreased from 30 minutes to 6 minutes after introducing the ASAP score. Furthermore, in 8 of 1,011 patients with ASAP scores ≥3 who presented non-chest pain symptoms, a timely 12-lead ECG examination motivated by an alert from the AI system led to a prompt diagnosis of STEMI (n=3) and NSTEMI (n=5). Subsequently, the 3 STEMI patients received successful PPCI.

Since the implementation of the system to date, the door-to-ECG time has decreased significantly to an average of about 1 minute, and the ECG-to-call lab time (the time to activate PPCI) has also reduced to within 10 minutes. However, there was an exception from November 2020 to September 2021 when the complexity increased, and the ECG-to-call lab time exceeded the threshold. In addition, between May 2021 to October 2022, the epidemic in Taiwan was more severe, and the catheter activation time was affected because emergency patients required isolation for COVID-19 rapid PCR (Figure 8 and 9).

Consistence of AI accuracy

The accuracy rate of AI ECG interpretation in the emergency room and in out-of-hospital ambulance remained consistent.

In-hospital: The overall performance of the AI model in detecting STEMI from 21,035 ECGs assessed according to accuracy, precision, recall, the area under the receiver operating characteristic curve, F1 score, and specificity were 0.997, 0.802, 0.977, 0.999, 0.881, and 0.998, respectively, in a real-world setting.

Prehospital: The evaluation metrics including accuracy, precision, specificity, recall, the area under the receiver operating characteristic curve, and F1 score to assess the overall AI performance in the remote detection of STEMI from 362 prehospital 12-lead ECGs were 0.992, 0.889, 0.994, 0.941, 0.997, and 0.914, respectively (Figure 10).

The percentage of prehospital ECG successfully recorded before arrival at the hospital in our system was 100%, which was better than the FITT STEMI (Germany) rate of 97.1% and the MISSION Lifeline rate of 71.3%. The percent rate of prehospital ECG's performed within 10 min after the first medical contact was 80%, which was also better than the FITT STEMI (Germany) rate of 63.8%.

Regarding system scaling, we bundled the Emergency Intelligence Myocardial Infarction platform as a software package for other medical systems to learn the application and shorten the learning curve. In the out-of-hospital ambulance system, the core members of our team trained the EMTs participating in our system through physical or online education. As a result, it has increased the prehospital ECG completion rate, shortened the time needed to diagnose acute myocardial infarction, and optimized treatment time efficiency.

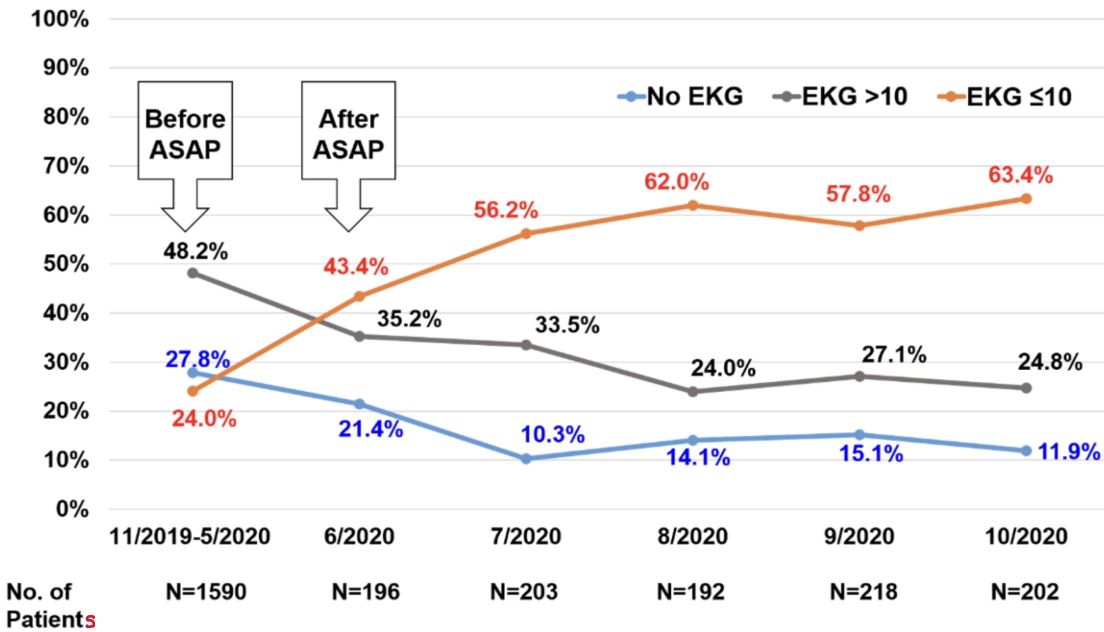


Figure 7. ECG ≤10 min increased from 24% to 63.4% after introducing ASAP scoring for non-chest pain patients who have an ASAP score ≥3.

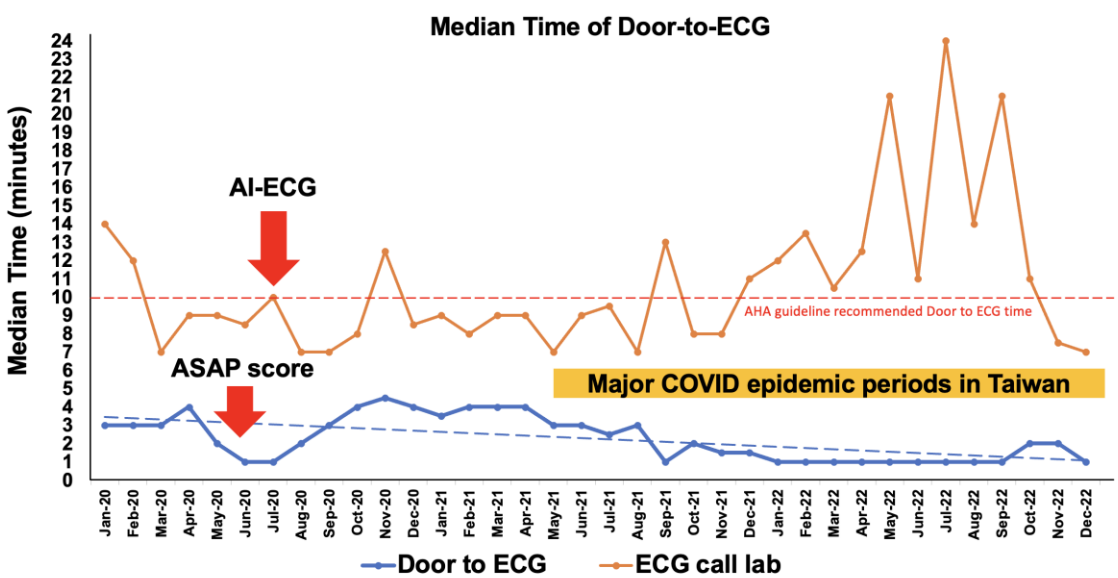


Figure 8. Median time of door-to-ECG and ECG-to-activation of emergent PCI

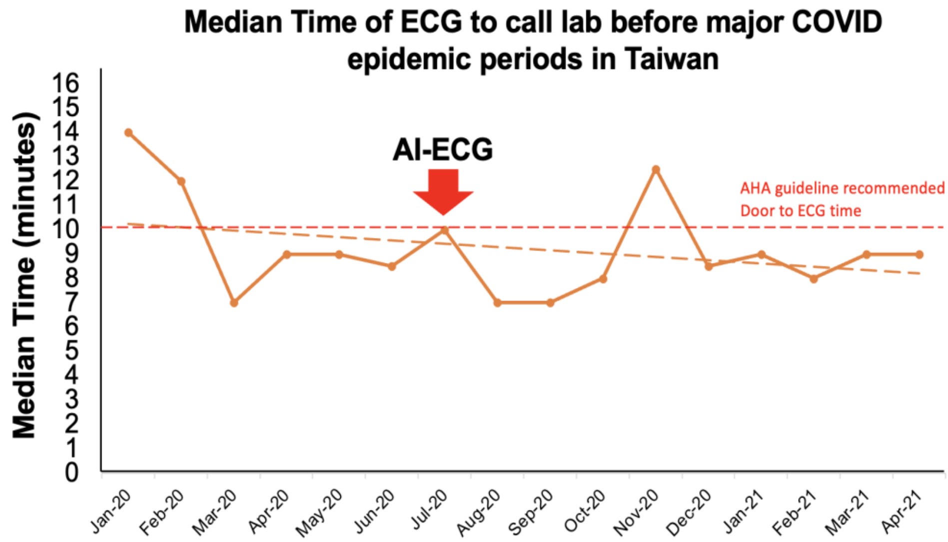
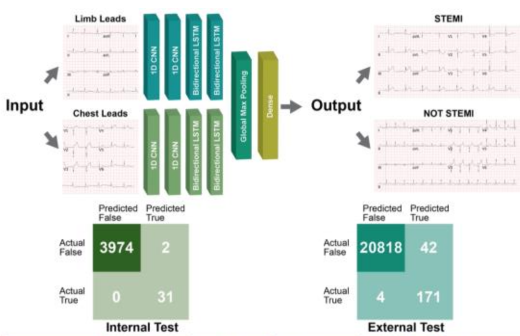


Figure 9. Median time of ECG-to-activation of emergent PCI before major COVID-19 epidemic periods in Taiwan



	F1	Recall	Precision	AUC	Accuracy
Internal test N=4007	0.968	1.0	0.939	0.986	0.999
External test N=21035	0.881	0.977	0.802	0.999	0.997

Left: in-hospital AI accuracy

Right: prehospital AI accuracy

N=362	Predict STEMI	Predict Not STEMI
Actual STEMI	16	1
Actual Not STEMI	2	343

	AUC	Accuracy	Specificity	Precision	Recall	F1
N=362	0.997	0.992	0.994	0.889	0.941	0.914

Figure 10. AI accuracy of the in-hosptal system and prehospital systems

Improving Patient Outcomes

The trend of the average D2B time after system introduction gradually decreased (from 64.5 minutes to 53.2 minutes) to become faster than the average D2B time of other medical centers in Taiwan (blue line) and lower than the 90 minutes international benchmark recommended by ACC/AHA guidelines. Even when the COVID-19 epidemic was more severe in Taiwan and strict emergency precautions were taken (rapid PCR screening before cardiac catheterization), our D2B time was still less affected than other medical centers in Taiwan (Figures 11 and 12). The mortality rate of AMI has also decreased to 5.5%-7.7% in the past three years.

We analyzed the overall D2B time and each component of time for the first year of system implementation: the mean D2B time, individual components of D2B time, and the percentage of D2B times <90 minutes are presented in Figure 13. Compared with those in the conventional group, the mean D2B time was shorter (53.2 ± 12.7 minutes vs. 64.5 ± 35.3 minutes, *P*=.007) and the percentage of D2B times <90 min was higher (98.5% vs. 87.2%, *P*=.009) in the AI group. During off-hours, the mean D2B time was shorter (54.6 ± 10.9 minutes vs. 70.4 ± 34.8 minutes, *P*=.002) and the percentage of D2B times <90 minutes was higher (100% vs. 83.9%, *P*=.003) in the AI group than in the conventional group. Among the individual components of D2B time, the mean door-to-ECG time (2.3 ± 2.2 minutes vs. 5.0 ± 10.8 minutes, *P*=.03), catheterization laboratory activation time (8.6 ± 6.5 minutes vs. 11.6 ± 11.8 minutes, *P*=.046) and door-to-activation time (10.5 ± 7.3 minutes vs. 16.1 ± 16.6 minutes, p=.006) were significantly shorter in the AI group than in the conventional group. From the monthly AMI patient mortality rates presented in Figure 14, we can see the difference before and after the introduction of the AI system. This system has indeed effectively improved the overall mortality rate of AMI patients.

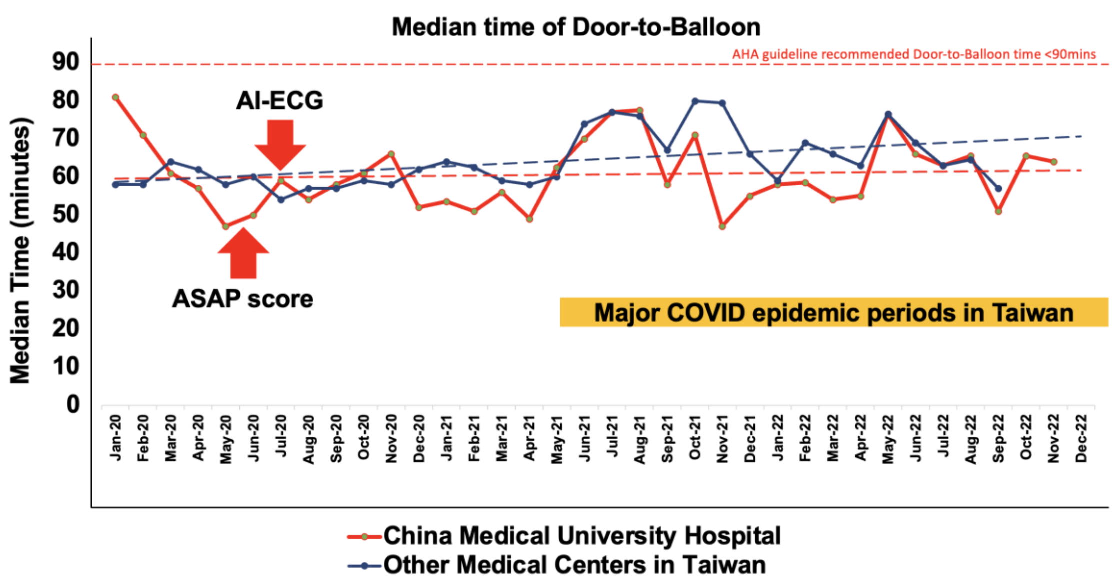


Figure 11. Median time of D2B in the recent two years following AI system implementation

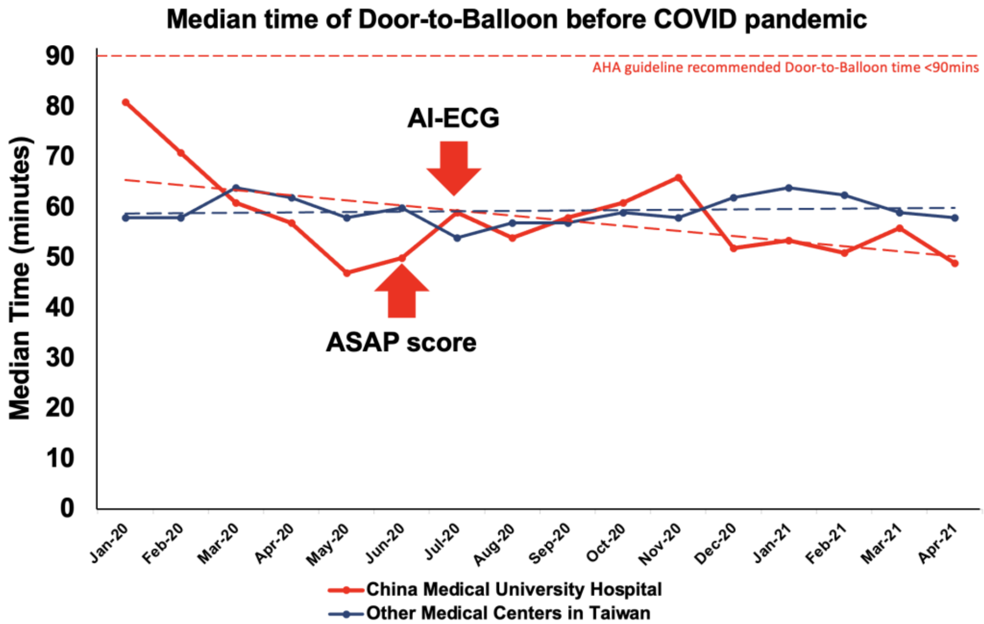


Figure 12. Median time of door-to-balloon before major COVID-19 epidemic periods in Taiwan

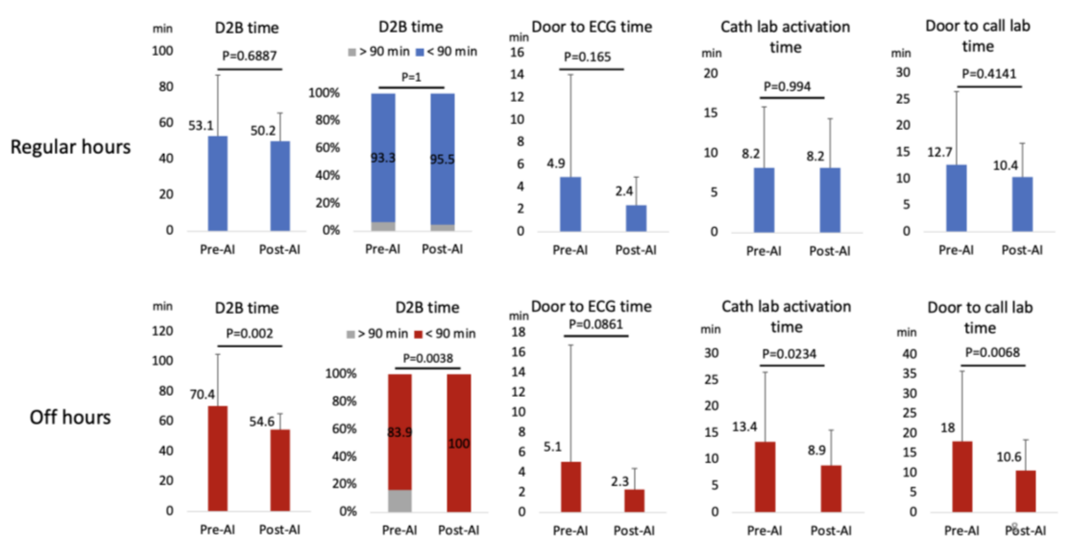


Figure 13. Comparisons of door-to-balloon time and its components between the AI-assisted triage group and the conventional triage group

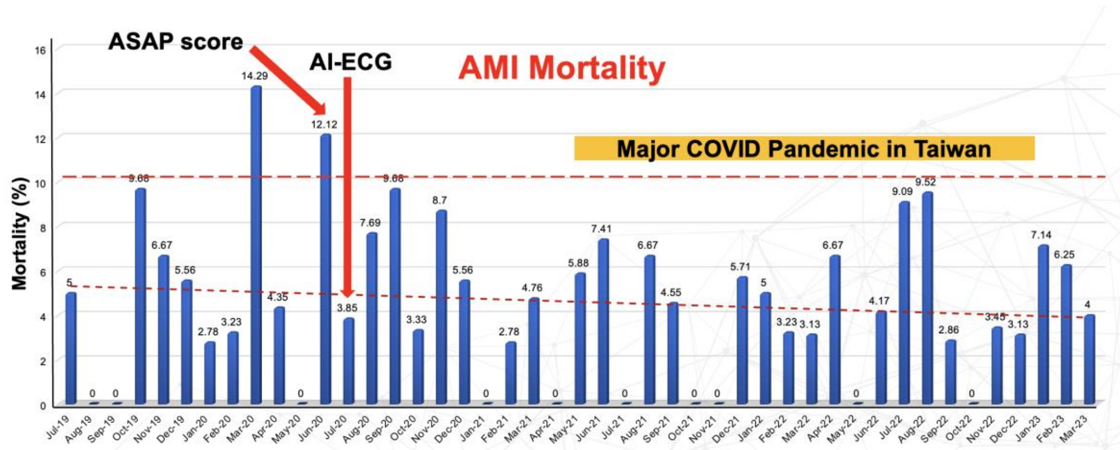


Figure 14. Monthly AMI patient mortality rates before and after AI systems implantation

Real-world case

A 64-year-old patient, Ms. Chen, was admitted to the emergency room with abdominal pain. Although Ms. Chen was admitted to the hospital with abdominal pain, her ASAP score exceeded 3 and therefore an ECG was immediately performed in the emergency room. The ECG revealed left main coronary artery disease, which could have resulted in sudden cardiac arrest or fatal arrhythmia if left undetected. After a week-long hospitalization, Ms. Chen recovered well and returned to her daily routine. (Figure 15) Prior to establishing an ASAP high-risk scoring mechanism and AI-assisted ECG interpretation, most patients with atypical symptoms of myocardial infarction were not identified due to the absence of the typical chest pain symptoms. Figure 16 shows another prehospital ECG case, with a first-medical-contact to door time of only 12 minutes.

We published our results in two papers: “Implementation of an All-Day Artificial Intelligence–Based Triage System to Accelerate Door-to-Balloon Times” in Mayo Clinic Proceedings, 2022, and “Artificial intelligence-assisted remote detection of ST-elevation myocardial infarction using a mini-12-lead electrocardiogram device in prehospital ambulance care” in Frontiers in Cardiovascular Medicine, 2022.

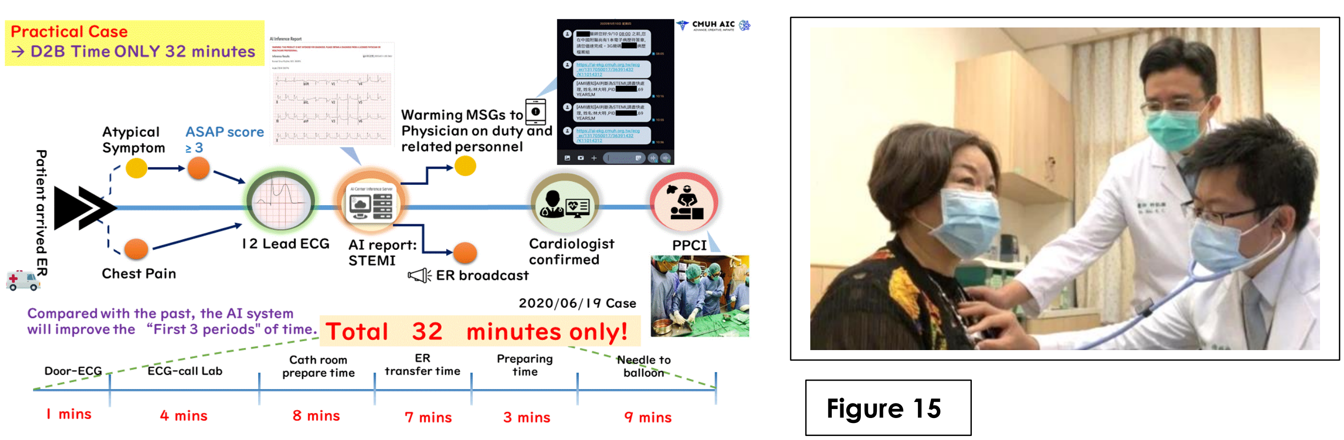


Figure 15

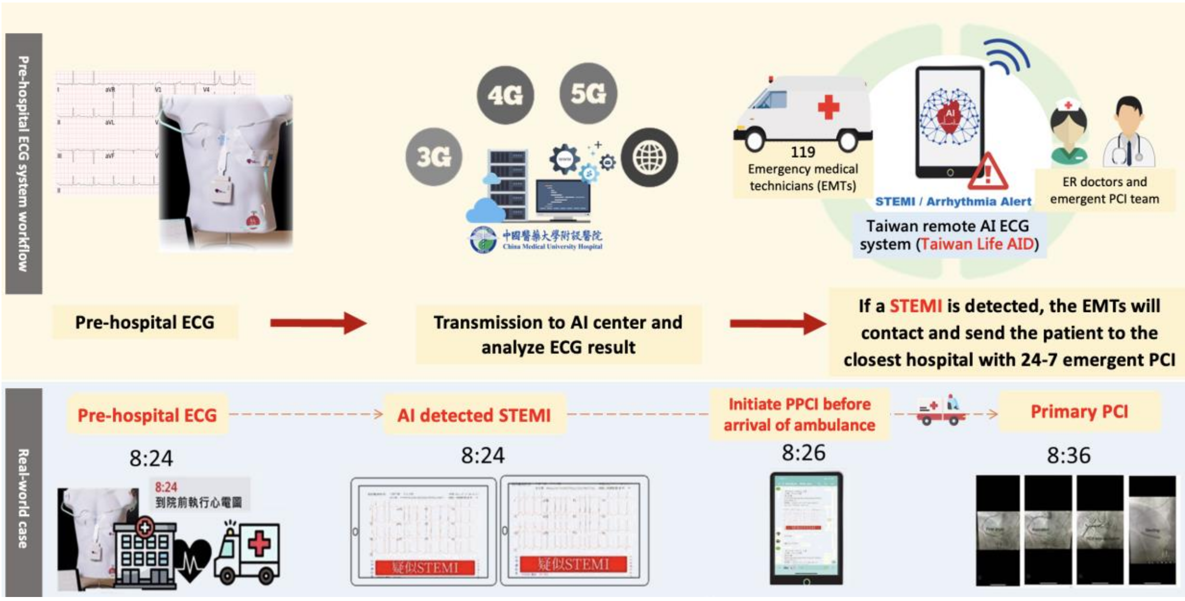


Figure 16. Prehospital ECG system workflow and a real-world case (first medical contact-to-door time is only 12 minutes)

Accountability and Driving Resilient Care Redesign

Workflow of the "Emergency intelligent myocardial infarction platform" (Figure 17):

- All patients who come to the emergency room are automatically analyzed using the ASAP high-risk score. In addition, AI diagnoses all ECGs performed in the emergency department in real-time. Suppose the AI system does not detect a STEMI ECG or does not immediately send a message to the on-call physician (which, in our experience, is less than 1%). In that case, the emergency physician will still reconfirm the ECG and decide whether to contact a cardiologist for emergency surgery.
- The accuracy of the AI system is verified by the AI Center and reviewed at a monthly meeting. If there is a discrepancy with clinical diagnosis, the core member cardiologists conduct a consensus meeting, and the data is incorporated into the AI algorithm training. The false negative rate is about 0.1-2% in case-by-case discussions monthly. Mostly it is due to false-positive cases, not false-negative cases. All these ECGs will eventually be re-confirmed by cardiologists and has not jeopardized patient safety.

Workflow and redesign of the "remote AI STEMI detecting system on the ambulance" (Figure 18):

- In the pre-hospital ECG section, our AI-assisted system is a failure mode prevention in the pre-hospital ECG diagnostic process, preventing labor shortages or diagnostic errors from occurring. The AI diagnoses the ECG performed on the ambulance in real time and communicates the results back to the instructor group using the communication software, which facilitates quicker diagnosis and prevents delays while obtaining reconfirmation by all online mentors. If there is a discrepancy, the core member cardiologists conduct a consensus meeting, and the data is incorporated into the next version of the AI algorithm training.
- During the epidemic, the system suffered a shock but also provided additional help that allowed us to maintain a better prognosis than other medical centers during the epidemic. In addition, remote ECG diagnosis and miniaturized ECG machines also provided a reduced contact monitoring approach during the epidemic. We used the remote system in the epidemic ward during that period. In the challenges ahead, we will continue improving AI interpretation accuracy through case reviews and adjusting our response plan during epidemics (e.g., early antigen screening in ambulances) to optimize the treatment of acute myocardial infarction.

As shown in Figure 19, our system indicates that the AI and physician diagnoses support each other and prevent the possibility of mutual errors. Furthermore, the AI system can continuously modify the algorithm and develop the next generation of AI based on the error report. Young physicians can also learn the diagnosis of ECG through this system.

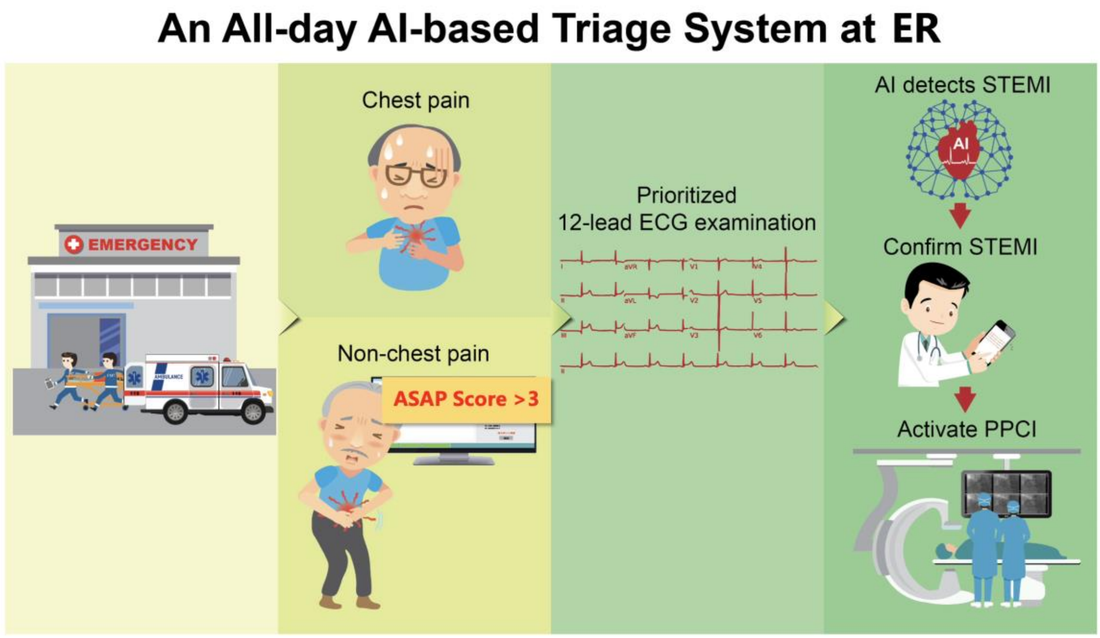


Figure 17. Workflow of the "Emergency intelligent myocardial infarction platform"

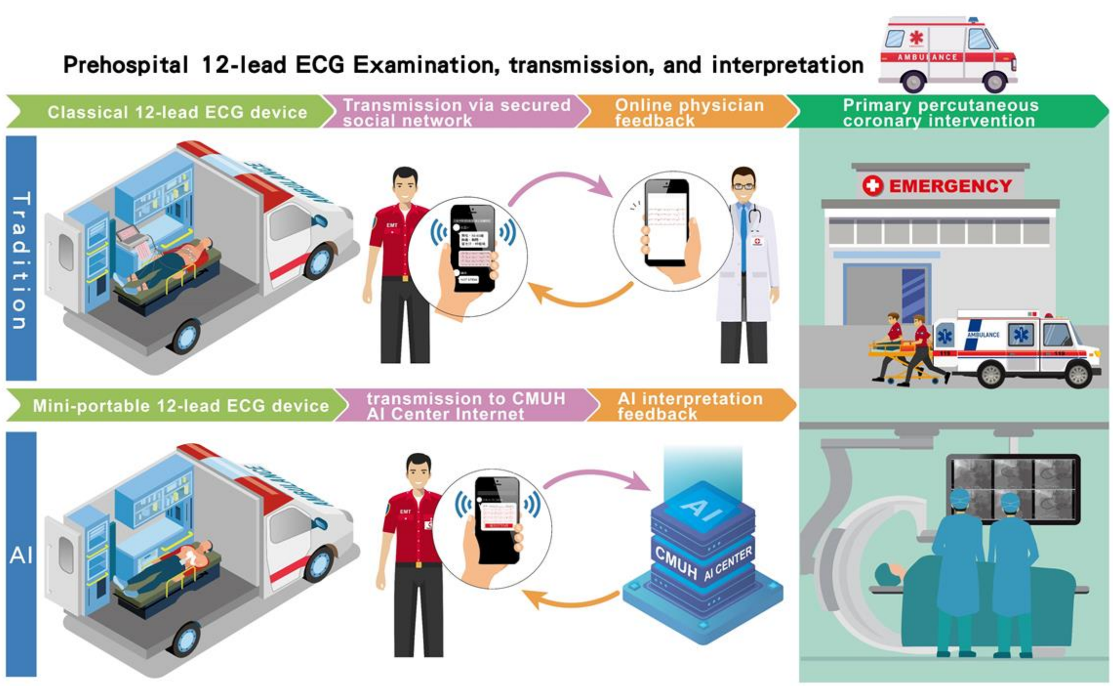


Figure 18. Workflow and redesign of the "remote AI STEMI detecting system on the ambulance"

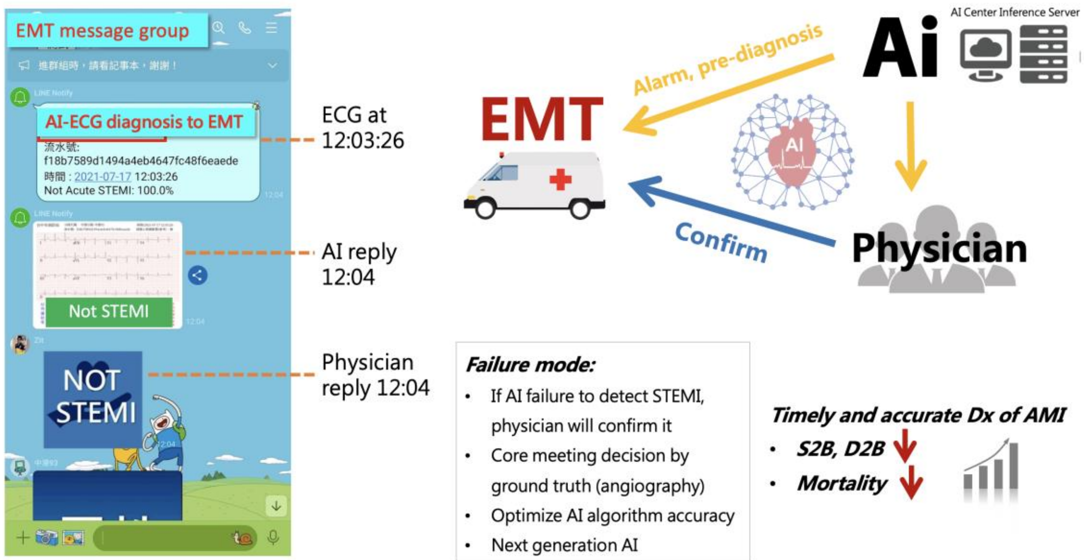


Figure 19. Prevention of failure mode.

The AI algorithm quickly diagnoses and displays the results to the guidance group, where EMTs can promptly judge. At the same time, the online guidance physician also receives and reconfirms the results and gives further medical instructions. If there is a discrepancy between AI and physician diagnoses, a decision meeting of cardiologists makes the final determination and feeds the results into the next-generation AI model.

The current version of the AI model in STEMI detection has evolved from its previous versions and lessons learned from its deployment:

1) The AI architecture was modified from the original solely LSTM-based 12-lead system to the current LSTM-CNN and 6-by-6 lead system.

2) We exclude the ECGs with marked baseline drifting or pacing rhythm that may mimic STEMI ECG changes.

3) In the future, we plan to optimize the model to be able to discriminate the location of STEMI as well as making multiple diagnoses with add-on cardiac arrhythmias detection based on our previous experience.