FUSSEK, Łukasz, NIEWIADOMSKA, Jagoda, BONDOS, Borys, STĘPIEŃ, Aleksandra, PALUCH, Alicja, SKRZYPEK, Jakub, NIEKRA, Aleksandra, KOCHAN, Robert, WIECZOREK, Ewelina and LEE, Kacper. Artificial Intelligence in ECG interpretation - review article. Journal of Education, Health and Sport. 2025;80:57853. eISSN 2391-8306.
https://doi.org/10.12775/JEHS.2025.80.57853
https://apcz.umk.pl/JEHS/article/view/57853

The journal has had 40 points in Minister of Science and Higher Education of Poland parametric evaluation. Annex to the announcement of the Minister of Education and Science of 05.01.2024 No. 32318. Has a Journal's Unique Identifier: 201159. Scientific disciplines assigned: Physical culture sciences (Field of medical and health sciences); Health Sciences (Field of medical and health sciences).
Punkty Ministerialne 40 punktów. Załącznik do komunikatu Ministra Nauki i Szkolnictwa Wyższego z dnia 05.01.2024 Lp. 32318. Posiada Unikatowy Identyfikator Czasopisma: 201159. Przypisane dyscypliny naukowe: Nauki o kulturze fizycznej (Dziedzina nauk medycznych i nauk o zdrowiu); Nauki o zdrowiu (Dziedzina nauk medycznych i nauk o zdrowiu). © The Authors 2025;
This article is published with open access at Licensee Open Journal Systems of Nicolaus Copernicus University in Torun, Poland
Open Access. This article is distributed under the terms of the Creative Commons Attribution Noncommercial License which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author (s) and source are credited. This is an open access article licensed under the terms of the Creative Commons Attribution Non commercial license Share alike.
(http://creativecommons.org/licenses/by-nc-sa/4.0/) which permits unrestricted, non commercial use, distribution and reproduction in any medium, provided the work is properly cited.
The authors declare that there is no conflict of interests regarding the publication of this paper.
Received: 16.01.2025. Revised: 02.03.2025. Accepted: 04.04.2025. Published: 06.04.2025.

Artificial Intelligence in ECG interpretation - review article

Łukasz Fussek [ŁF]
lukaszfussek@gmail.com
https://orcid.org/0009-0008-2185-399X
Medical University of Lublin, Poland
al. Racławickie 1, 20-059 Lublin, Poland

Jagoda Niewiadomska [JN]
malwatexass@wp.pl
https://orcid.org/0009-0003-2219-984X
Medical University of Lublin, Poland
al. Racławickie 1, 20-059 Lublin, Poland

Borys Bondos [BB]
borysb97@gmail.com
https://orcid.org/0009-0005-7971-4691
Medical University of Lublin, Poland
al. Racławickie 1, 20-059 Lublin, Poland

Aleksandra Stępień [AS]
stepienaleksandra00@gmail.com
https://orcid.org/0009-0004-9258-2294
Medical University of Lublin, Poland
al. Racławickie 1, 20-059 Lublin, Poland

Alicja Paluch [AP]
alapal123op@gmail.com
https://orcid.org/0000-0001-8233-3885
Medical University of Lublin, Poland
al. Racławickie 1, 20-059 Lublin, Poland

Jakub Skrzypek [JS]
jakub.skrzypek.00@gmail.com
https://orcid.org/0009-0004-1155-5818
Medical University of Lublin, Poland
al. Racławickie 1, 20-059 Lublin, Poland

Aleksandra Niekra [AN]
ola.niekra@gmail.com
https://orcid.org/0009-0007-0116-4882
Medical University of Lublin, Poland
al. Racławickie 1, 20-059 Lublin, Poland

Robert Kochan [RK]
robkochan2211@gmail.com
https://orcid.org/0009-0002-9796-9231
Medical University of Lublin, Poland
al. Racławickie 1, 20-059 Lublin, Poland

Ewelina Wieczorek [EW]
ewelinawieczorek1255@gmail.com
https://orcid.org/0009-0009-3763-0384
Medical University of Lublin, Poland
al. Racławickie 1, 20-059 Lublin, Poland

Kacper Lee [KL]
liosek17@gmail.com
https://orcid.org/0009-0005-4474-6140
Medical University of Lublin, Poland
al. Racławickie 1, 20-059 Lublin, Poland

Abstract

Introduction and purpose

Developments in medical and information technology are leading to improvements in the quality of medical care. This paper aims to show how the development of artificial intelligence can affect more effective interpretation of ECG, thus contributing to greater efficiency for clinicians, and to describe the limitations and potential for further development of artificial intelligence in ECG interpretation.

Material and methods

A review paper using articles describing the application of artificial intelligence in ECG interpretation from 1997 to 2024. The search terms used to find publications were “artificial intelligence”, “ecg”, “deep learning”, “machine learning”, “neural networks”, “arrhythmia”, “left ventricular dysfunction” and “cardiomyopathy” using the Pubmed and Google Scholar databases.

Results

The present work has shown that artificial intelligence can be applied in the interpretation of ECGs for the following heart-related conditions: left ventricular dysfunction, atrial and ventricular arrhythmias, prediction of cardiovascular events, cardiomyopathy, valvular defect, monitoring of sleep quality, diagnosis of severe depression, presence of myocardial infarction, detection of the risk of transient myocardial ischemia, diagnosis of chronic maternal and fetal stress, and even determination of the age and sex of the subject. The biggest limitations of artificial intelligence are the need to verify the diagnosis made by the algorithm in order to detect possible errors. In addition, the use of personal data to train an artificial intelligence algorithm to diagnose specific medical conditions can be controversial, which can interfere with data protection rules. These data may contribute to a better understanding of artificial intelligence in ECG interpretation and its wider use in daily medical care practice.

Keywords: **“**Artificial Intelligence”, “Deep Learning”, “Machine Learning”, “Electrocardiography”, “Arrhythmias, Cardiac”.

1. Introduction

Correct interpretation of the ECG is essential for making correct clinical decisions and avoiding medical errors. Artificial intelligence can be used as a tool to facilitate the work of medical personnel and possible early detection of abnormalities. It can be used to obtain the following information through ECG analysis: left ventricular dysfunction [1-2, 12-14], atrial and ventricular arrhythmias [15-22], prediction of cardiovascular events [23], cardiomyopathy [27-28], valve defects [29-30], monitoring of sleep quality [31], diagnosis of severe depression [32], presence of myocardial infarction [3], detection of the risk of transient myocardial ischemia [4], in the diagnosis of chronic maternal and fetal stress [7], and even determination of the age and sex of the subject [8].

Various branches of artificial intelligence can be applied to ecg analysis, including machine learning [1], deep learning [2] and neural networks [3]. Neural networks use artificial neurons that form networks similar to the operation of the human brain. Machine learning is based on

the principle of looking for similarities in a large database and using them to recognize and predict specific parameters. Deep learning is a subset of machine learning and is characterized by the use of deep neural networks with multiple levels. This paper aims to present the potential benefits and drawbacks of using artificial intelligence in ECG analysis.

2. Purpose of the paper

The purpose of this paper is to present current applications of artificial intelligence in ECG interpretation.

3. A description of the state of the art

Artificial Intelligence

Artificial intelligence is defined as the ability of machines to learn and use that knowledge to perform a designated task, as well as creativity and planning. The term was introduced in 1956 by John McCarthy, and one of the earliest examples of its application in medicine was the MYCIN program, which was designed to assist doctors in identifying bacterial infections and suggest appropriate treatments [9].

In medicine, artificial intelligence has found many examples of application. One of them may be its use in the Da Vinci robot, which is used for patients in gastric cancer surgeries, among other things [10]. It is also being used in mammography, where researchers have shown effectiveness in interpreting a reading at a comparable level to a standard double reading [11]. These examples show that artificial intelligence has versatile applications in medicine.

Cardiology is a field where artificial intelligence can find many applications. It can be used in the interpretation of echocardiography [12], computed tomography [13], and electrocardiography [14]. In ecg equipment, it analyzes basic parameters and interprets cardiac abnormalities.

Machine learning

Machine learning is a subset of artificial intelligence and is characterized by the fact that it uses decision tree, linear regression or neural network algorithms to analyze data for classification purposes such as identifying the source of ventricular arrhythmias [11] or event prediction such as cardiovascular event prediction [17]. Because machine learning can be based on a variety of algorithms, it can have versatile applications.

Deep learning

Deep learning is a subset of machine learning. It uses deep neural networks as an algorithm to classify data and predict events.
Neural networks are algorithms that use data sets. Neural networks can be divided into: superficial neural network and deep neural network, which is used in deep learning, thus enabling artificial intelligence to solve complex tasks such as prediction of atrial fibrillation or left ventricular dysfunction and remodeling [5,6].

Artificial Intelligence in LV dysfunction

Machine learning as well as deep learning can be applied to predict left ventricular dysfunction based on ECG and clinical data, thus speeding up diagnosis and reducing the potential cost of testing. [1]. In a study by Nobuyuki Kagiyama published in 2020, a machine learning regression model was used to determine the effectiveness of artificial intelligence in estimating myocardial relaxation from ECG results, thereby detecting possible left ventricular dysfunction. Clinical data from 1202 patients were included in the analysis, and it was shown that artificial intelligence was able to predict the dimensions of left ventricular relaxation obtained by echocardiography with a mean absolute error of 1.46 and 1.96 cm/sec. These results indicate that artificial intelligence can be used to predict left ventricular dysfunction.

A study conducted by Jin-Yu Sun and published in the Journal of Cardiovascular Electrophysiology in 2021 also demonstrated the effectiveness of artificial intelligence in detecting left ventricular dysfunction using ECG analysis. The research group used a convolutional neural network approach to interpret 12-lead ECG and transthoracic echocardiogram along with left ventricular ejection fraction. The study analyzed 26,786 ECGs and echocardiograms and showed an accuracy of 73.19% for ECG-mediated prediction of left ventricular dysfunction, a sensitivity of 69.2%, a specificity of 70.5%, a positive predictive value of 70.1% and a negative predictive value of 69.9% [2]. These data indicate that the use of AI can be used as a low-cost screening test for early detection of left ventricular dysfunction, and thus for faster introduction of appropriate treatment and reduction of the risk of possible complications.

Zachi Attia and his research team, in a paper published in the journal Nature, demonstrated the effectiveness of artificial intelligence in identifying asymptomatic left ventricular dysfunction. The analysis included 97,829 ECGs, while the test group included the ECGs of 52,870 patients, yielding the following results: AUC = 0.93, specificity = 86.3%, sensitivity = 85.7% and accuracy = 85.7% [15]. This information indicates the applicability of artificial intelligence in the screening of left ventricular dysfunction.

Artificial intelligence also has applications in screening diagnosis of low ejection fraction. A 2021 publication by Xiaoxi Yao describes the use of deep learning in ECG analysis of 22,641 patients to identify low ejection fraction. The results indicate that the use of artificial intelligence increases the detection of this condition.When artificial intelligence was used, the detection rate of low ejection fraction was 2.1%, and in the control group, without the use of artificial intelligence, the detection rate was 1.6% [16]. This information indicates that ECGs can be analyzed with the help of artificial intelligence for early detection of low ejection fraction and thus earlier referral of the patient for transthoracic echocardiography to confirm left ventricular dysfunction. Another study performed by David Rushlow published 2022 also demonstrated the effectiveness of artificial intelligence in detecting low ejection fraction.It was also shown that clinicians with less complex patients tended to rely more heavily on the ECG analysis performed by artificial intelligence, compared to clinicians caring for more complex patients. ECGs from 11,573 patients were used for the analysis, and highly adaptive clinicians were twice as effective at detecting low ejection fraction based on artificial intelligence analysis compared to low-adaptive clinicians [17]. The above information suggests that these findings may contribute to more effective first medical care

AI in atrial and ventricular arrhythmia

Artificial intelligence may have applications in detecting atrial and ventricular arrhythmias. A study led by Dr. Masafumi Shimojo and reported in the journal 2023 successfully applied machine learning using a decision tree algorithm designed by the research team using ECG measurements to distinguish the left ventricular outflow tract from the right ventricular outflow tract as the source of ventricular arrhythmia. It was shown to have an efficiency of 94.4%, precision of 91.5%, sensitivity of 100% and an F1 index of 0.96 [18]. This information can contribute to the use of artificial intelligence algorithms to identify the source of ventricular arrhythmia and thus effectively perform ablation or apply appropriate drug treatment.

Artificial intelligence is also effective in detecting asymptomatic atrial fibrillation. A study conducted by Henri Gruwez and published in the journal JACC Clin Electrophysiol in 2023 demonstrated the effectiveness of artificial intelligence in detecting atrial fibrillation. The research group used a deep learning method to identify atrial fibrillation in asymptomatic patients. The study analyzed 494,042 ECGs belonging to 142,310 patients and showed an accuracy rate of 78.1% [19]. These data indicate that the use of artificial intelligence may help to increase the detection of asymptomatic AF, and with this, the introduction of appropriate treatment more quickly and reduce the risk of potential complications. Dr. Peter Noseworthy and his research team have shown that the use of artificial intelligence in ECG interpretation is associated with increased detection of atrial fibrillation. When artificial intelligence was used to analyze ECGs in patients at high risk of stroke, the detection rate of atrial fibrillation oscillated at 10.6% while in the low-risk group it was 2.4%, and for standard management in the high-risk group the values were in the range of 3.6% and in the low-risk group 0.9% [20]. These results show that artificial intelligence can significantly contribute to reducing the number of undiagnosed patients.
A similar study by Hongmin Wu describes the use of a convolutional neural network in detecting atrial fibrillation in sinus rhythm showing the following results: AUC = 0.82, sensitivity = 79.5%, specificity = 77.8% and precision = 78.2% and overall accuracy of 78.6% using 234 ECGs in an internal test set. An external test set consisting of 440 ECGs yielded similar results [21].

ECG analysis using artificial intelligence can be used in patients as a low-cost screening test. Nathan Hill's work has demonstrated the effectiveness of machine learning in identifying atrial fibrillation in high-risk patients. This information can be used to use artificial intelligence in AF screening and possibly reduce costs compared to traditional medical care [22].

Artificial intelligence can be effective in analyzing the rhythm from a portable ecg device, which can contribute to effective detection of paroxysmal atrial fibrillation and early initiation of treatment. A 2021 paper by Wenxia Fu and Ruogu Li described the use of a wrist-worn portable ECG device. Data from this device was uploaded to the Amazfit CardiDoc mobile app and analyzed by artificial intelligence. The ECGs of 114 users were analyzed, of which 53 patients were diagnosed with atrial fibrillation and 61 patients with sinus rhythm. In the supine position of the monitored patients, the accuracy of the test was 94.74%, sensitivity 88.68% and specificity 100%, and in the standing position 97.37%, 94.34% and 100%, respectively, results similar to those in the standing position were achieved after exercise [23]. These results suggest that the use of portable ECG devices with analysis performed by artificial intelligence can be effectively used to diagnose atrial fibrillation.

Artificial intelligence can also be used to analyze a patient's ECG after ablation on portable ECG devices to detect possible arrhythmias. Patients may experience asymptomatic arrhythmias after ablation. For this reason, Songqun Huang published a paper in 2021 on the use of a portable ECG monitor in patients after ablation. The 218 patients studied were divided into two groups. One group used the traditional procedure in monitoring patients after ablation, while the other group collected ECGs from patients via the BigThumb monitor and applied analysis with the help of artificial intelligence, an automated algorithm to detect atrial fibrillation and manually by cardiologists. In the group with BigThumb monitoring, no atrial fibrillation was detected in 64.2% of patients, and in the group with traditional management in 78.9% of patients. In the BigThumb group, 26133 ECGs were performed, of which 3299 were recorded as atrial fibrillation. The specificity of the test using artificial intelligence was 98.5% and the sensitivity was 94.4%, while using an automated algorithm to detect atrial fibrillation, the specificity was 96.2% and the sensitivity was 90.7% [24]. These results indicate the superiority of artificial intelligence in detecting atrial fibrillation over the automatic atrial fibrillation detection algorithm. The use of artificial intelligence to analyze ECGs in patients after ablation may contribute to better detection of AF and faster introduction of appropriate treatment and prevention of possible complications.

Artificial intelligence can be used to predict refractory ventricular fibrillation. Jason Coult conducted a cohort study of out-of-hospital cardiac arrest in patients with ventricular fibrillation using machine learning. Artificial intelligence analyzing a three-second ECG recording immediately before and one minute after the first shock was designed to predict treatment-resistant ventricular fibrillation. The following results were obtained: AUC = 0.85, specificity = 91%, sensitivity = 63% and positive likelihood factor = 6.7 [25]. This information indicates the effectiveness of machine learning in predicting refractory ventricular fibrillation, which can be used to implement appropriate therapy more quickly.

Use of artificial intelligence as a tool for detecting cardiovascular events

Patient monitoring is particularly important in patients with long-standing atherosclerosis. Machine learning can be used to predict cardiovascular events in these patients, which could help reduce mortality from the condition. A Bharath Ambale-Venkatesh research team using machine learning has demonstrated that artificial intelligence can improve the accuracy of cardiovascular event prediction in asymptomatic individuals compared to the traditional cardiovascular event prediction model. Using clinical data obtained from 6814 participants between the ages of 45 and 84, the researchers demonstrated using artificial intelligence an increased risk of tachyarrhythmias in people with a prolonged QT interval or left ventricular hypertrophy visible on the ECG. These were among the parameters most significant in the prediction of heart failure [26]. This information may contribute to the use of machine learning in the prediction of cardiovascular events in asymptomatic patients.

Artificial intelligence in detecting cardiomyopathies

Artificial intelligence may also have applications in detecting cardiomyopathies. Detecting these defects in pregnant or postpartum women could be of particular importance, as it could reduce possible pregnancy failure as well as mortality in the event of an adverse event. One study conducted by Demilade Adedinsewo showed that artificial intelligence can be effectively used in detecting left ventricular heart defects via ECG and digital stethoscope in peripartum women. The study was conducted with 1,232 women from Nigeria, who were

divided into two study groups. The intervention group used a digital stethoscope, 12-lead ECG, prediction of sex and age via artificial intelligence, prediction of left ventricular dysfunction made by artificial intelligence and an echocardiogram to confirm the prediction of left ventricular dysfunction made by artificial intelligence. The control trial used a 12-lead ECG, standard patient care, and artificial intelligence prediction of age and sex. When the 12-lead ECG alone was used, 20 left ventricular systolic dysfunctions were detected in the intervention trial and 12 in the control trial. When the digital stethoscope was used, 24 left ventricular dysfunctions were detected in the intervention trial and 12 in the control trial [27]. These results indicate the feasibility of using a digital stethoscope to more accurately diagnose left ventricular function, but also demonstrate the effectiveness of artificial intelligence in analyzing ECGs and results obtained from a digital stethoscope.

Artificial intelligence can also be used in the diagnosis of hypertrophic cardiomyopathy. A 2020 study by Wei-Yin Ko showed that deep learning diagnoses hypertrophic cardiomyopathy from a 12-lead ECG with high accuracy. The study included 2448 patients with verified cardiomyopathy and 51153 without. The area under the curve (AUC) was 0.96, specificity was 90%, and sensitivity was 87%. [28]. These results indicate the feasibility of using artificial intelligence in ECG interpretation for the screening diagnosis of hypertrophic cardiomyopathy.

Heart valve defects

Deep learning may be applicable to patients for ECG-mediated screening diagnosis of aortic valve stenosis. A study published in the European Heart Journal in 2021 by Michal Cohen-Shelly describes the use of convolutional neural networks identifying moderate to severe aortic valve stenosis. By analyzing 102,926 ECGs of patients in the test group, 3833 patients were diagnosed with aortic valve stenosis by artificial intelligence. The area under the curve (AUC) was 0.85, with a sensitivity of 78%, specificity of 74%, and accuracy of 74% [29].

The Gal Tsaban study demonstrated the effectiveness of artificial intelligence in detecting aortic stenosis, aortic regurgitation and mitral regurgitation. The study included 77,163 patients, with data from 21,048 patients used in a test group analyzed using deep learning. The performance of the model, defined as the area under the receiver-operating characteristic, was 0.84, sensitivity = 78%, and specificity = 73% [30]. This information can be used for the possible introduction of artificial intelligence in ECG interpretation toward early detection of aortic stenosis, aortic and mitral valve regurgitation.

Others usage

Artificial intelligence has also found applications in monitoring emotional state via ECG. In Pritam Sarkar's 2021 study, deep learning was used to identify emotional state, which can be used to diagnose chronic stress in the mother and fetus. The study used maternal abdominal ecg containing maternal and fetal ECGs, which were analyzed by deep learning. The results were as follows AUROC = 0.982 ± 0.002, individual psychological test score R2=0.943 ± 0.009 FSI at 34 weeks of pregnancy R2=0.946 ± 0.013, maternal hair cortisol 0.931 ± 0.006 [7]. This information indicates the possibility of using deep learning in ECG analysis to determine emotional state. This offers the possibility of low-cost, non-invasive monitoring of fetal status during pregnancy.

Artificial intelligence may have applications in age and sex prediction. A study by Zachi Attia published in 2019 used deep learning trained on 499,727 patients to predict sex and age. The model was applied to 275,056 patients and showed an accuracy of 90.4% for gender detection with an AUC of 0.97. For age, the average error was 6.9 ± 5.7 years. These results indicate the effectiveness of artificial intelligence in gender classification and age estimation [8].

Assessment of sleep efficiency can be interpreted using actigraphy and ECG analyzed by artificial intelligence. In the Md study, Aktaruzzaman used machine learning to assess heart rate variability and chest and wrist actigraphy to classify sleep and wakefulness. He showed an accuracy of 78% when using ECG and chest actigraphy data interpreted by artificial intelligence, and 77% for wrist actigraphy and ECG [31]. This information indicates the potential of artificial intelligence in home sleep monitoring.

Artificial intelligence may have applications in the diagnosis of severe depression. Sangwon Byun using machine learning and data obtained from ECG based on linear and non-linear heart rate conducted a study to verify the effectiveness of artificial intelligence in diagnosing major depressive disorder. After analysis, he showed accuracy = 74.4%, sensitivity = 73% and specificity = 75.6% [32]. These results indicate the effectiveness of artificial intelligence in diagnosing major depression.

Disadvantages of using Artificial Intelligence

The use of artificial intelligence as demonstrated in the article can bring many benefits, however, potential drawbacks and risks should also be noted.
One must take into account the potential diagnostic errors made by artificial intelligence in interpreting ECGs. For this reason, any diagnosis made by artificial intelligence should be carefully checked by the physician caring for the patient in question. Different factors such as artifacts, conduction abnormalities or gender- and age-dependent variances in ECG morphology can contribute to an incorrect analysis of an ECG by artificial intelligence. In addition, the artificial intelligence algorithm must be trained on a large database, which may raise controversies relating to data protection rules.

4. Summary

Artificial intelligence, machine learning, deep learning and neural networks can be comprehensively used in medicine. The present work has shown that they can be used in the analysis of ECG such conditions as: left ventricular dysfunction [1-2, 12-14], atrial and ventricular arrhythmias [15-22], prediction of cardiovascular events [23], cardiomyopathy [27-28], valve defects [29-30], monitoring of sleep quality [31], diagnosis of severe depression [32], the presence of myocardial infarction [3], detecting the risk of transient myocardial ischemia [4], in the diagnosis of chronic maternal and fetal stress [7], and even determining the age and sex of the subject [8]. The introduction of artificial intelligence in ECG analysis could help increase the detection of these conditions. The drawbacks of artificial intelligence are the percentage of errors in the diagnosis of cardiac abnormalities caused by the presence of artifacts, conduction abnormalities or gender- and age-dependent variances in ECG morphology. There may also be controversy over the use of personal data to train the algorithm to correctly diagnose medical conditions, which may conflict with data protection rules. The potential development of artificial intelligence in ecg interpretation is to

use it on a large scale in screening, in ambulatory medical care, and to improve the accuracy of diagnoses made by artificial intelligence.

Disclosures

Author's Contribution

Conceptualisation: Łukasz Fussek, Ewelina Wieczorek, Alicja Paluch
Methodology: Jakub Skrzypek, Robert Kochan, Aleksandra Stępień
Formal analysis: Borys Bondos, Łukasz Fussek, Aleksandra Niekra
Investigation: Ewelina Wieczorek, Jagoda Niewiadomska, Kacper Lee
Writing - Rough Preparation: Łukasz Fussek, Robert Kochan, Jakub Skrzypek
Writing - Review and Editing: Kacper Lee, Aleksandra Stępień, Borys Bondos
Visualisation: Jagoda Niewiadomska, Aleksandra Niekra, Alicja Paluch
All authors have read and agreed with the published version of the manuscript.

Financial support No financial support was received.

Conflict of interest The authors declare no conflict of interest.

References

[1] Kagiyama N, Piccirilli M, Yanamala N, Shrestha S, Farjo PD, Casaclang-Verzosa G, Tarhuni WM, Nezarat N, Budoff MJ, Narula J, Sengupta PP. Machine Learning Assessment of Left Ventricular Diastolic Function Based on Electrocardiographic Features. J Am Coll Cardiol. 2020 Aug 25;76(8):930-941. doi: 10.1016/j.jacc.2020.06.061. PMID: 32819467.

[2] Sun JY, Qiu Y, Guo HC, Hua Y, Shao B, Qiao YC, Guo J, Ding HL, Zhang ZY, Miao LF, Wang N, Zhang YM, Chen Y, Lu J, Dai M, Zhang CY, Wang RX. A method to screen left ventricular dysfunction through ECG based on convolutional neural network. J Cardiovasc Electrophysiol. 2021 Apr;32(4):1095-1102. doi: 10.1111/jce.14936. Epub 2021 Feb 15. PMID: 33565217.

[3] Baxt WG, Shofer FS, Sites FD, Hollander JE. A neural computational aid to the diagnosis of acute myocardial infarction. Ann Emerg Med. 2002 Apr;39(4):366-73. doi: 10.1067/mem.2002.122705. PMID: 11919522.

[4] Polak MJ, Zhou SH, Rautaharju PM, Armstrong WW, Chaitman BR. Using automated analysis of the resting twelve-lead ECG to identify patients at risk of developing transient myocardial ischaemia--an application of an adaptive logic network. Physiol Meas. 1997 Nov;18(4):317-25. doi: 10.1088/0967-3334/18/4/005. PMID: 9413865.

[5] Mayourian J, La Cava WG, Vaid A, Nadkarni GN, Ghelani SJ, Mannix R, Geva T, Dionne A, Alexander ME, Duong SQ, Triedman JK. Pediatric ECG-Based Deep Learning to Predict Left Ventricular Dysfunction and Remodeling. Circulation. 2024 Mar 19;149(12):917-931. doi: 10.1161/CIRCULATIONAHA.123.067750. Epub 2024 Feb 5. PMID: 38314583; PMCID: PMC10948312.

[6] Khurshid S, Friedman S, Reeder C, Di Achille P, Diamant N, Singh P, Harrington LX, Wang X, Al-Alusi MA, Sarma G, Foulkes AS, Ellinor PT, Anderson CD, Ho JE, Philippakis

AA, Batra P, Lubitz SA. ECG-Based Deep Learning and Clinical Risk Factors to Predict Atrial Fibrillation. Circulation. 2022 Jan 11;145(2):122-133. doi: 10.1161/CIRCULATIONAHA.121.057480. Epub 2021 Nov 8. PMID: 34743566; PMCID: PMC8748400.

[7] Sarkar P, Lobmaier S, Fabre B, González D, Mueller A, Frasch MG, Antonelli MC, Etemad A. Detection of maternal and fetal stress from the electrocardiogram with self-supervised representation learning. Sci Rep. 2021 Dec 17;11(1):24146. doi: 10.1038/s41598-021-03376-8. PMID: 34921162; PMCID: PMC8683397.

[8] Attia ZI, Friedman PA, Noseworthy PA, Lopez-Jimenez F, Ladewig DJ, Satam G, Pellikka PA, Munger TM, Asirvatham SJ, Scott CG, Carter RE, Kapa S. Age and Sex Estimation Using Artificial Intelligence From Standard 12-Lead ECGs. Circ Arrhythm Electrophysiol. 2019 Sep;12(9):e007284. doi: 10.1161/CIRCEP.119.007284. Epub 2019 Aug 27. PMID: 31450977; PMCID: PMC7661045.

[9] McCarthy, J., Minsky, M. L., Rochester, N., & Shannon, C. E. (2006). A Proposal for the Dartmouth Summer Research Project on Artificial Intelligence, August 31, 1955. *AI Magazine*, *27*(4), 12. https://doi.org/10.1609/aimag.v27i4.1904

[10] Cheng, Qiangli, Dong, Yajun, Da Vinci Robot-Assisted Video Image Processing under Artificial Intelligence Vision Processing Technology, *Computational and Mathematical Methods in Medicine*, 2022, 2752444, 10 pages, 2022. https://doi.org/10.1155/2022/2752444

[11] Lång K, Josefsson V, Larsson AM, Larsson S, Högberg C, Sartor H, Hofvind S, Andersson I, Rosso A. Artificial intelligence-supported screen reading versus standard double reading in the Mammography Screening with Artificial Intelligence trial (MASAI): a clinical safety analysis of a randomised, controlled, non-inferiority, single-blinded, screening accuracy study. Lancet Oncol. 2023 Aug;24(8):936-944. doi: 10.1016/S1470-2045(23)00298-X. PMID: 37541274.

[12] Upton R, Mumith A, Beqiri A, Parker A, Hawkes W, Gao S, Porumb M, Sarwar R, Marques P, Markham D, Kenworthy J, O'Driscoll JM, Hassanali N, Groves K, Dockerill C, Woodward W, Alsharqi M, McCourt A, Wilkes EH, Heitner SB, Yadava M, Stojanovski D, Lamata P, Woodward G, Leeson P. Automated Echocardiographic Detection of Severe Coronary Artery Disease Using Artificial Intelligence. JACC Cardiovasc Imaging. 2022 May;15(5):715-727. doi: 10.1016/j.jcmg.2021.10.013. Epub 2021 Dec 15. PMID: 34922865.

[13] Zhang Y, Feng Y, Sun J, Zhang L, Ding Z, Wang L, Zhao K, Pan Z, Li Q, Guo N, Xie X. Fully automated artificial intelligence-based coronary CT angiography image processing: efficiency, diagnostic capability, and risk stratification. Eur Radiol. 2024 Aug;34(8):4909-4919. doi: 10.1007/s00330-023-10494-6. Epub 2024 Jan 9. PMID: 38193925.

[14] Hopkins CB, Suleman J, Cook C. An artificial neural network for the electrocardiographic diagnosis of left ventricular hypertrophy. Crit Rev Biomed Eng. 2000;28(3 - 4):435-8. doi: 10.1615/critrevbiomedeng.v28.i34.140. PMID: 11108211.

[15] Attia ZI, Kapa S, Lopez-Jimenez F, McKie PM, Ladewig DJ, Satam G, Pellikka PA, Enriquez-Sarano M, Noseworthy PA, Munger TM, Asirvatham SJ, Scott CG, Carter RE,

Friedman PA. Screening for cardiac contractile dysfunction using an artificial intelligence-enabled electrocardiogram. Nat Med. 2019 Jan;25(1):70-74. doi: 10.1038/s41591-018-0240-2. Epub 2019 Jan 7. PMID: 30617318.

[16] Yao X, Rushlow DR, Inselman JW, McCoy RG, Thacher TD, Behnken EM, Bernard ME, Rosas SL, Akfaly A, Misra A, Molling PE, Krien JS, Foss RM, Barry BA, Siontis KC, Kapa S, Pellikka PA, Lopez-Jimenez F, Attia ZI, Shah ND, Friedman PA, Noseworthy PA. Artificial intelligence-enabled electrocardiograms for identification of patients with low ejection fraction: a pragmatic, randomized clinical trial. Nat Med. 2021 May;27(5):815-819. doi: 10.1038/s41591-021-01335-4. Epub 2021 May 6. PMID: 33958795.

[17] Rushlow DR, Croghan IT, Inselman JW, Thacher TD, Friedman PA, Yao X, Pellikka PA, Lopez-Jimenez F, Bernard ME, Barry BA, Attia IZ, Misra A, Foss RM, Molling PE, Rosas SL, Noseworthy PA. Clinician Adoption of an Artificial Intelligence Algorithm to Detect Left Ventricular Systolic Dysfunction in Primary Care. Mayo Clin Proc. 2022 Nov;97(11):2076-2085. doi: 10.1016/j.mayocp.2022.04.008. PMID: 36333015.

[18] Shimojo M, Inden Y, Yanagisawa S, Suzuki N, Tsurumi N, Watanabe R, Nakagomi T, Okajima T, Suga K, Tsuji Y, Murohara T. A novel practical algorithm using machine learning to differentiate outflow tract ventricular arrhythmia origins. J Cardiovasc Electrophysiol. 2023 Mar;34(3):627-637. doi: 10.1111/jce.15823. Epub 2023 Jan 24. PMID: 36651347.

[19] Gruwez H, Barthels M, Haemers P, Verbrugge FH, Dhont S, Meekers E, Wouters F, Nuyens D, Pison L, Vandervoort P, Pierlet N. Detecting Paroxysmal Atrial Fibrillation From an Electrocardiogram in Sinus Rhythm: External Validation of the AI Approach. JACC Clin Electrophysiol. 2023 Aug;9(8 Pt 3):1771-1782. doi: 10.1016/j.jacep.2023.04.008. Epub 2023 Jun 21. PMID: 37354171.

[20] Noseworthy PA, Attia ZI, Behnken EM, Giblon RE, Bews KA, Liu S, Gosse TA, Linn ZD, Deng Y, Yin J, Gersh BJ, Graff-Radford J, Rabinstein AA, Siontis KC, Friedman PA, Yao X. Artificial intelligence-guided screening for atrial fibrillation using electrocardiogram during sinus rhythm: a prospective non-randomised interventional trial. Lancet. 2022 Oct 8;400(10359):1206-1212. doi: 10.1016/S0140-6736(22)01637-3. Epub 2022 Sep 27. PMID: 36179758.

[21] Wu H, Sawada T, Goto T, Yoneyama T, Sasano T, Asada K. Edge AI Model Deployed for Real-Time Detection of Atrial Fibrillation Risk during Sinus Rhythm. J Clin Med. 2024 Apr 11;13(8):2218. doi: 10.3390/jcm13082218. PMID: 38673490; PMCID: PMC11051059.

[22] Hill NR, Groves L, Dickerson C, Boyce R, Lawton S, Hurst M, Pollock KG, Sugrue DM, Lister S, Arden C, Davies DW, Martin AC, Sandler B, Gordon J, Farooqui U, Clifton D, Mallen C, Rogers J, Camm AJ, Cohen AT. Identification of undiagnosed atrial fibrillation using a machine learning risk prediction algorithm and diagnostic testing (PULsE-AI) in primary care: cost-effectiveness of a screening strategy evaluated in a randomized controlled trial in England. J Med Econ. 2022 Jan-Dec;25(1):974-983. doi: 10.1080/13696998.2022.2102355. PMID: 35834373.

[23] Fu W, Li R. Diagnostic performance of a wearing dynamic ECG recorder for atrial fibrillation screening: the HUAMI heart study. BMC Cardiovasc Disord. 2021 Nov 20;21(1):558. doi: 10.1186/s12872-021-02363-1. PMID: 34800984; PMCID: PMC8606080.

[24] Huang S, Zhao T, Liu C, Qin A, Dong S, Yuan B, Xing W, Guo Z, Huang X, Cha Y, Cao J. Portable Device Improves the Detection of Atrial Fibrillation After Ablation. Int Heart J. 2021 Jul 30;62(4):786-791. doi: 10.1536/ihj.21-067. Epub 2021 Jul 17. PMID: 34276021.

[25] Coult J, Yang BY, Kwok H, Kutz JN, Boyle PM, Blackwood J, Rea TD, Kudenchuk PJ. Prediction of Shock-Refractory Ventricular Fibrillation During Resuscitation of Out-of-Hospital Cardiac Arrest. Circulation. 2023 Jul 25;148(4):327-335. doi: 10.1161/CIRCULATIONAHA.122.063651. Epub 2023 Jun 2. PMID: 37264936.

[26] Ambale-Venkatesh B, Yang X, Wu CO, Liu K, Hundley WG, McClelland R, Gomes AS, Folsom AR, Shea S, Guallar E, Bluemke DA, Lima JAC. Cardiovascular Event Prediction by Machine Learning: The Multi-Ethnic Study of Atherosclerosis. Circ Res. 2017 Oct 13;121(9):1092-1101. doi: 10.1161/CIRCRESAHA.117.311312. Epub 2017 Aug 9. PMID: 28794054; PMCID: PMC5640485.

[27] Adedinsewo DA, Morales-Lara AC, Afolabi BB, Kushimo OA, Mbakwem AC, Ibiyemi KF, Ogunmodede JA, Raji HO, Ringim SH, Habib AA, Hamza SM, Ogah OS, Obajimi G, Saanu OO, Jagun OE, Inofomoh FO, Adeolu T, Karaye KM, Gaya SA, Alfa I, Yohanna C, Venkatachalam KL, Dugan J, Yao X, Sledge HJ, Johnson PW, Wieczorek MA, Attia ZI, Phillips SD, Yamani MH, Tobah YB, Rose CH, Sharpe EE, Lopez-Jimenez F, Friedman PA, Noseworthy PA, Carter RE; SPEC-AI Nigeria Investigators. Artificial intelligence guided screening for cardiomyopathies in an obstetric population: a pragmatic randomized clinical trial. Nat Med. 2024 Oct;30(10):2897-2906. doi: 10.1038/s41591-024-03243-9. Epub 2024 Sep 2. PMID: 39223284; PMCID: PMC11485252.

[28] Ko WY, Siontis KC, Attia ZI, Carter RE, Kapa S, Ommen SR, Demuth SJ, Ackerman MJ, Gersh BJ, Arruda-Olson AM, Geske JB, Asirvatham SJ, Lopez-Jimenez F, Nishimura RA, Friedman PA, Noseworthy PA. Detection of Hypertrophic Cardiomyopathy Using a Convolutional Neural Network-Enabled Electrocardiogram. J Am Coll Cardiol. 2020 Feb 25;75(7):722-733. doi: 10.1016/j.jacc.2019.12.030. PMID: 32081280.

[29] Cohen-Shelly M, Attia ZI, Friedman PA, Ito S, Essayagh BA, Ko WY, Murphree DH, Michelena HI, Enriquez-Sarano M, Carter RE, Johnson PW, Noseworthy PA, Lopez-Jimenez F, Oh JK. Electrocardiogram screening for aortic valve stenosis using artificial intelligence. Eur Heart J. 2021 Aug 7;42(30):2885-2896. doi: 10.1093/eurheartj/ehab153. PMID: 33748852.

[30] Tsaban G, Lee E, Wopperer S, Abbasi M, Yu HT, Kane GC, Lopez-Jimenez F, Pislaru SV, Nkomo VT, Deshmukh AJ, Asirvatham SJ, Noseworthy PA, Friedman PA, Attia Z, Oh JK. Using Electrocardiogram to Assess Diastolic Function and Prognosis in Mitral Regurgitation. J Am Coll Cardiol. 2024 Dec 3;84(23):2278-2289. doi: 10.1016/j.jacc.2024.06.054. PMID: 39603748.

[31] Aktaruzzaman M, Rivolta MW, Karmacharya R, Scarabottolo N, Pugnetti L, Garegnani M, Bovi G, Scalera G, Ferrarin M, Sassi R. Performance comparison between wrist and chest

actigraphy in combination with heart rate variability for sleep classification. Comput Biol Med. 2017 Oct 1;89:212-221. doi: 10.1016/j.compbiomed.2017.08.006. Epub 2017 Aug 8. PMID: 28841459.

[32] Byun S, Kim AY, Jang EH, Kim S, Choi KW, Yu HY, Jeon HJ. Detection of major depressive disorder from linear and nonlinear heart rate variability features during mental task protocol. Comput Biol Med. 2019 Sep;112:103381. doi: 10.1016/j.compbiomed.2019.103381. Epub 2019 Aug 4. PMID: 31404718.