

## Advances in the Application of Artificial Intelligence in the Ultrasound Diagnosis of Vulnerable Carotid Atherosclerotic Plaque: A Systematic Review

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### Abstract

**BACKGROUND:** Carotid atherosclerosis is a leading cause of stroke, and early detection via ultrasound is vital. Artificial intelligence enhances ultrasound by improving plaque detection, measurement of intima-media thickness, and risk assessment. This review explores AI's role in advancing ultrasound-based diagnosis of carotid atherosclerosis and its potential to support clinical decision-making.

**METHODS:** The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta- Analyses) guidelines are adhered to in this systematic review. The purpose of the study is to use Artificial Intelligence role in ultrasound diagnosis of carotid plaques related to different AI tools ascertain the prevalence of stroke and CAD. The databases of PubMed, EMBASE, Scopus, and Cochrane were thoroughly searched.

**RESULTS:** AI models show strong potential in assessing carotid plaques using features like cIMT and TPA, often outperforming traditional approaches. However, challenges such as limited validation and clinical

application persist. Future research should emphasize real-time use and wider clinical integration.

**CONCLUSION:** AI improves the accuracy and efficiency of carotid ultrasound by automating plaque detection and risk assessment. Its integration into clinical practice may enhance early diagnosis and stroke prevention

## INTRODUCTION

About two-thirds of deaths from cardiovascular (CV) disease are caused by atherosclerotic cardiovascular disease (ASCVD), which is the main cause of mortality and morbidity worldwide.(1). The progressive condition known as atherosclerosis is typified by the buildup of lipids and fibrous components in the major arteries. Muller first proposed the idea of the "vulnerable plaque" in 1989, and because of its fragility and proneness to rupture, it has drawn attention from the medical community [7]. Significant structural characteristics of vulnerable plaques include thin fibrous caps, big lipid cores, active inflammatory responses, and surface ruptures, internal bleeding, or ulcers.(2). According to recent vascular research, the risk and progression of carotid plaques differ. Even in cases of mild-to-moderate stenosis, a fraction known as "vulnerable plaques (VPs)" are more susceptible to rupture or embolization, which can result in strokes or transient ischemic attacks (TIAs)(3).Atherosclerotic plaque is categorized by the American Heart Association into types based on increasing histomorphological complexity [9]: Type I macrophages have normal wall thickness or little intimal thickening, and some of them have foam cells or small lipid deposits; Type II, T-lymphocytes, uncommon mast cells, and extra smooth muscle cells with little lipid deposits; type III, elevated extracellular lipid (pre-atheroma); Type IV (atheroma), which is primarily covered by intima and consists of confluent lipid deposits (lipid core); type V, growing lipid deposits with a distinct fibroatheroma (type Va) fibrous (collagen) cap or calcifications that predominate (calcific, types Vbandc); Type VI is a complex lesion that has produced thrombotic deposits, hematoma or bleeding, and disruption of the lesion surface.(4). AI makes it possible to use human-like intelligence systems for the extraction and processing of quantitative data.(4).Certain hemodynamic and morphological traits are present in vulnerable carotid plaques. But traditional angiography methods, such computed tomography angiography (CTA), magnetic resonance angiography (MRA), and digital subtraction angiography (DSA), can only measure the extent of vascular stenosis.(5). Medical image analysis has advanced thanks to artificial intelligence (AI) technology. AI technology has greatly improved image analysis methods when paired with algorithms like Variational Autoencoders (VAEs) and Convolutional Neural Networks (CNNs). The substantial advancements in AI-based medical image segmentation and analysis, especially when considering deep learning approaches, have been brought to light by recent surveys. Deep learning algorithms are used by AI-based ultrasound image plaque segmentation technology to automatically segment and evaluate carotid plaques, improving the assessment's precision and effectiveness. Recent developments in ultrasonic picture segmentation using deep learning have demonstrated a great deal of promise for increasing diagnostic efficiency and accuracy.(2). One area of artificial intelligence is machine learning (ML), where computers or algorithms gather data from large datasets on their own to generate predictions without the need for explicit programming.(6). Semi- and fully automated analysis of vascular US images has been quickly adopted to overcome these constraints. Artificial intelligence (AI) techniques, in particular deep learning (DL), are used to increase accuracy, decrease inter-operator variability, and shorten analysis times. Because it offers an end-to-end solution and reduces the need for human interaction or preset parameters, DL-based image segmentation—which uses sophisticated neural networks for pattern identification from images—has grown in importance.(1)

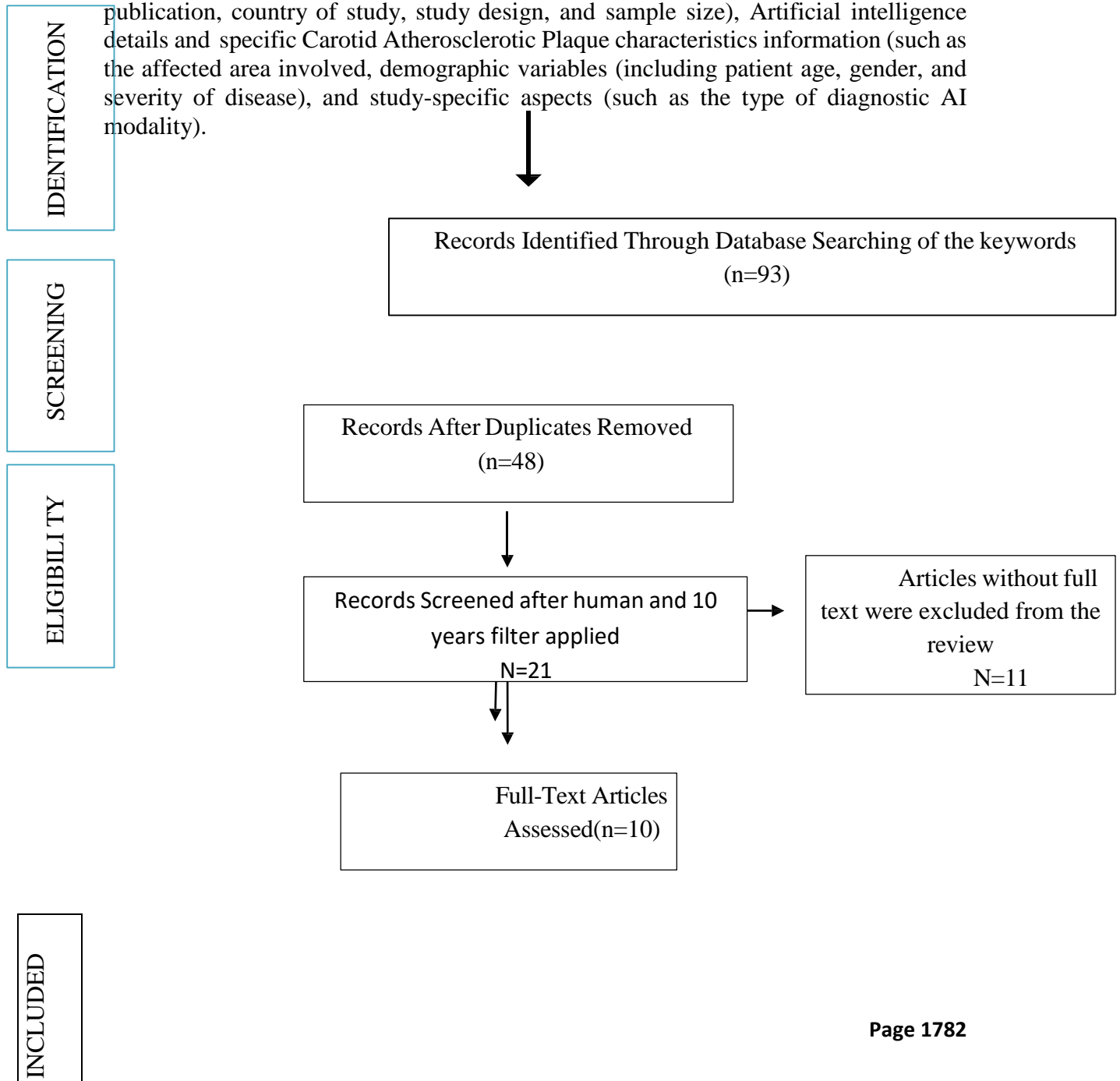
## METHODS AND MATERIAL

This systematic review follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The study aims to evaluate recent advances in applying AI to ultrasound for detecting vulnerable carotid atherosclerotic plaques

and improving stroke risk prediction. A systematic search was conducted in PubMed, EMBASE, Scopus, and Cochrane databases. Keywords included: "ADVANCES IN ARTIFICIAL INTELLIGENCE", "VULNERABLE CAROTID ATHEROSCLEROTIC PLAQUE" and "IN ULTRASOUND DIAGNOSIS". Studies that report the use of Artificial intelligence in diagnosing atherosclerotic plaque, Studies including human subjects, studies published in English, studies durations during last 10 years between 2015 to 2025 and report diagnostic performance studies e.g. accuracy and sensitivity were included in my systematic research and studies like that are non-ultrasound or non-AI, animal based studies, non-carotid or general atherosclerosis focus and no full text available, reviews, editorial, non-English articles were excluded from my research

**Data extraction**

A solo reviewer, MR extracted data independently, MR gathering relevant information from the selected papers using a consistent data extraction table based on predefined inclusion criteria. When disputes or uncertainties arose throughout the extraction process, SK rechecked the data to ensure accuracy and consistency. The extracted data included various key domains: study characteristics (such as the author's name, year of publication, country of study, study design, and sample size), Artificial intelligence details and specific Carotid Atherosclerotic Plaque characteristics information (such as the affected area involved, demographic variables (including patient age, gender, and severity of disease), and study-specific aspects (such as the type of diagnostic AI modality).



Studies Included  
(n=10)

**Figure 1:** PRISMA flow diagram.

**RESULTS**

**STUDY SELECTION**

Database searches, including those from PubMed, turned up 93 results in all. There were 67 unique records left after 25 duplicates were eliminated. After 46 papers were eliminated through title and abstract screening, 21 publications remained for full-text evaluation. During this phase, a publication date filter spanning from 2015 to 2025 was used, 10 full-text studies out of the 21 articles were possibly qualified. Eleven, however, were excluded —three because they were not human research or did not use ultrasound guidance, and eight because the entire texts were not available. 10 papers thus satisfied all inclusion requirements and were incorporated into the final analysis. These studies examined artificial intelligence role in diagnosing carotid atherosclerotic plaques. An overview of each study's methodology is given in the table, which also includes information on the authors, sample sizes, ultrasound artificial intelligence techniques, and evaluation methods. The table also lists the different advantages and limitations of artificial intelligence in ultrasound diagnosis of carotid atherosclerotic plaques.

**TABEL1s:**

**METHODOLOGY AND**

**QUALITY ASSESSMENT OF INCLUDED STUDIES**

From 93 identified records, 10 studies met the inclusion criteria after screening.

These studies evaluated the artificial intelligence role in ultrasound diagnosis of carotid atherosclerotic plaques.

AUTHORS	YEAR	AREA	SAMPLE SIZE	STUDY DESIGN	METHOD OF AI APPLIED	VASCULAR SEGMENT	PLAQUE CHARACTERISTICS	OUTCOMES	LIMITATIONS

<p><b>Amer M. Johri(7)</b></p>	<p>2021</p>	<p>Canada</p>		<p>Prospectives</p>	<p>2 machine learning in RF &amp; RSF</p>	<p>Carotid plaques characteristi c for CAD &amp; CV Events</p>	<p>cIMT, MPH, &amp; TPA</p>	<p>Carotid imaging phenotype s and IPN were associated with CAD and CV events. The ML-based system is superior to the conventional statisti cally derived approaches for CAD prediction and survival analy sis</p>	<p>ML showed promise in high- risk CVD prediction. Future studies will validate it in broader, lower- risk populations.</p>
<p><b>Anjan Gudigar (4)</b></p>	<p>2021</p>	<p>India</p>	<p>122</p>	<p>Retro. S</p>	<p>DL techniques CNN based</p>	<p>CAD detects and classifies atherosclerotic plaque s by assessing their composition and high - risk features indicating vulnerabil it y</p>	<p>dense calcium (DC), necrotic core (NC), fibrotic tissue (FT), and fibrofatty tis sue (FFT)</p>	<p>Experimental results demonstrate that AI algorithms using ML and DL methods effectively identify plaques and serve as valuable tools in medical decision-making</p>	<p>The study is limited by English-only sources, unclear AI selection, and limited focus on post-treatment plaque grading.</p>

<b>Ankush Jamthikar (8)</b>	2020	India	208	Retro. S	ML-based algorithms	CVD	cIMT & Carotid Plaque	AI-based predictive risk models show superior performance over conventional cardiovascular risk calculators.	ML and imaging-based CVD risk assessment face challenges of cost, training, and clinical acceptance due to complexity and limited validation.
<b>Dandan Wang(9)</b>	2025	china	Variable Data type	Retro. S	AI, ANN, CNN, DL & ML	Carotid and Complex and variable including other organs	cIMT	AI-assisted ultrasound holds great potential in carotid plaque assessment, promising more accurate, consistent and timely diagnoses.	AI-assisted ultrasound shows promise but faces challenges in data quality, variability, and ethics. Future focus should be on multimodal, real-time, and adaptive diagnostic systems.

<b>Jiajia Song(2)</b>	2025	Nanjing Medical University	202	Retro. S	LASSO and SVM	Carotid Arteries	IMT, lumen, PSV, SV ratio	Study demonstrates better performance in evaluating plaque stability than the conventional clinical nomogram.	study is limited by reliance on image quality, use of static images, operator variability, and lack of external validation for broader applicability.
<b>G. Satyendra Ramnadh(3)</b>	2025	India	150	Retro. S	ML model YOLO v8	Carotid Arteries	VP features (IPH, LRNC, ulceration, and thin fibrous cap)	AI appears promising tool for analysis of US carotid images in the future	include operator dependence, unvalidated AI use, and limited generalizability to all patients.
<b>Pankaj K. Jain(10)</b>	2021	Japan	165	Retro. S	UNet-BaseD Deep Learning Architecture	Left and Right common carotid arteries	atherosclerotic plaque segmentation	We demonstrated that “Unseen AP” was in close proximity (<10%) to “Seen AP”, validating our DL model for low atherosclerotic wall	limited ethnic diversity, use of static images, lack of clinical outcome correlation, and untested performance in real-world settings.
								plaque segmentation.	

<b>Fitri Aprilian ty (11)</b>	2025	yama gu chi unive rsi ty	Data set of caroti d Doppl e r ultras o und	Retro. S	ML base d SVM , RF, KNN	CAS	Peak systolic velocity PSV,spect ral entropy, peal frequency shift	This research underscore s the potential of AI-driven diagnostic tools in enhancing non-invasive screening, facilitating early detection, and aiding in stroke preventi on	Not mention
<b>Na Han(5)</b>	2023	Lanz ho u China	1072	Cros.s	U- NET	Carotid Arteries	Qualitativ e and Quantitati ve Analysis of Vulnerabl e Carotid Plaques Based on VW- HRMRI	VW- HRMRI, 4D flow and artificial intelligenc e improve the efficiency and accu racy of vulnerable plaque assess ment	are high VW- HRMRI requirement s, limited 4D flow use, and lack of prospective radiomics validat ion.
<b>Ling-Jie Wang(12)</b>	2023	China	110	Retro. S	Five mach in e learn in g mode ls , XGB o	Common carotid artery	ID and FF values	The interpretab ility of the tree-based machine learning model was improved using the	include retrospective design, lack of external validation, limited D ECT availability, and no

					ost mode l			SHA method	P rect outcome correlat ion.	di
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**DISCUSSION**

Researchers employed two machine learning models, Random Forest (RF) and Random Survival Forest (RSF), to evaluate carotid plaque features for the purpose of forecasting coronary artery disease (CAD) and cardiovascular (CV) events in a prospective study carried out in Canada by Amer M. Johri in May 2021. The study examined carotid imaging characteristics, including intraplaque neovascularization (IPN), total plaque area (TPA), maximum plaque height (MPH), and carotid intima-media thickness (cIMT). Future CV events and CAD were substantially correlated with these characteristics. The ML-based system showed great promise in assessing high-risk CVD and beat traditional statistical techniques in both CAD prediction and survival analysis. The study's concentration on a high-risk population, however, is a drawback; more validation in larger, lower-risk groups is required.(7)Anjan Gudigar and associates assessed the application of deep learning (DL) methods, more especially convolutional neural networks (CNN), for identifying and categorizing atherosclerotic plaques linked to coronary artery disease (CAD) in 2021 retrospective research carried out in India. With a sample size of 122 cases, the study examined many plaque components, including fibrotic tissue (FT), fibrofatty tissue (FFT), necrotic core (NC), and dense calcium (DC), as well as characteristics that point to susceptible plaques. The findings showed that AI systems that employ both machine learning (ML) and deep learning (DL) techniques may assist in clinical decision-making and are successful in identifying plaque. Never the less, the study had a number of drawbacks, such as its dependence on English-language sources, its unclear AI model selection process, and its little assessment of plaque properties following therapy. These limitations draw attention to the necessity of more comprehensive and consistent methodologies in further studies.(4)Ankush Jamthikar and associates investigated the application of machine learning (ML)-based algorithms to evaluate cardiovascular disease (CVD) risk in 2020 retrospective research conducted in India. With a focus on carotid plaque (CP) and carotid intima-media thickness (cIMT) as important imaging indicators, the study examined data from 208 individuals. According to the results, AI-driven prediction models performed better than conventional cardiovascular risk calculators, providing higher risk stratification accuracy. Not with standing these encouraging results, the research recognized many drawbacks, including exorbitant expenses, the requirement for specific training, and restricted clinical adoption because of the intricacy and lack of validation of machine learning and imaging-based methods. These elements could prevent widespread adoption in standard clinical procedures.(8)Dan-dan Wang and

associates investigated the use of several AI techniques, such as artificial neural networks (ANN), convolutional neural networks (CNN), deep learning (DL), and machine learning (ML), in the evaluation of carotid plaque using ultrasound imaging in a 2024 retrospective study carried out in China. Measurements of carotid intima-media thickness (IMT) and plaque throughout carotid and other vascular segments were investigated in this study, which included variable data kinds. The findings showed that

AI-assisted ultrasonography holds great promise for improving carotid plaque assessment speed, accuracy, and consistency. The study did identify some significant drawbacks, though, such as issues with data quality, unpredictability, and ethical considerations. The authors underlined that in order to increase clinical integration and reliability, future research must concentrate on multimodal, real-time, and adaptive AI diagnostic systems.(9)Jiajia Song and colleagues used data from 202 individuals in a 2025 retrospective study from Nanjing Medical University to evaluate plaque stability in the carotid arteries using LASSO and support vector machine (SVM) models. Intima-media thickness (IMT), lumen diameter, peak systolic velocity (PSV), and PSV ratio were among the important plaque features that were examined. When assessing plaque stability, the AI-based method performed better than traditional clinical Nomo grams. The study's wider relevance was constrained by its shortcomings, which included operator variability, reliance on image quality, the use of static images, and the lack of external validation.(2)G. Satyendra Ramnadh and associates assessed the application of the YOLOv8 machine learning model for interpreting carotid artery ultrasound images in 150 patients in an Indian prospective study conducted in 2025. The goal of the study was to identify characteristics of vulnerable plaque (VP), such as ulceration, thin fibrous cap, lipid-rich necrotic core (LRNC), and intraplaque hemorrhage (IPH). Results indicate that AI has potential as a carotid ultrasonography analysis tool in the future. However, the study's limitations include limited generalizability across various patient populations, operator dependency, and a lack of AI validation.(3)Pankaj K. Jain and associates evaluated the effectiveness of a UNet-based deep learning (DL) architecture for the segmentation of atherosclerotic plaques in the left and right common carotid arteries in a 2021 retrospective study carried out in Japan. By comparing the model's accuracy on "Unseen AI" (data not previously used during training) with "Seen AI" (training data), the study introduced a novel approach using data from 165 patients. The model was found to have strong generalizability for low-burden plaque segmentation, with a difference of less than 10%.Notwithstanding the encouraging outcomes, the study included a number of drawbacks. Among these were the dataset's low level of ethnic diversity, its reliance on static images rather than dynamic imaging, its lack of association with clinical outcomes, and the model's performance not having been evaluated in actual clinical settings. These factors suggest the need for broader validation before clinical application.(10)Fitri Aprilianty and associates investigated the application of machine learning (ML) methods, including Support Vector Machine (SVM), Random Forest (RF), and k-Nearest Neighbors (KNN), to the analysis of carotid artery stenosis (CAS) using Doppler ultrasound data in a 2021 retrospective study conducted at Yamaguchi University. Important plaque-related traits such peak frequency shift, spectral entropy, and peak systolic velocity (PSV) were the focus of the investigation. These parameters were used to train machine learning models intended to identify and classify CAS.The results demonstrated the great potential for non-invasive screening techniques to be enhanced by AI-driven diagnostic tools. Such tools can be extremely helpful in clinical decision-making and stroke prevention by improving the precision and effectiveness of early detection. For improved risk classification and prompt intervention, this study backs the use of machine learning (ML) into standard carotid ultrasonography evaluations.(11)In a 2022 cross-sectional study from Lanzhou, China, Na Han and associates examined 1,072 patients' susceptible carotid plaques using the U-NET deep learning model. Vessel wall high-resolution MRI (VW-HRMRI) was used in the study to evaluate plaque features both qualitatively and quantitatively. Assessing susceptible plaques became much more accurate and efficient when VW-HRMRI, 4D flow imaging, and artificial intelligence were combined. The high technical requirements of VW-HRMRI, the restricted use of 4D flow imaging, and the lack of prospective

validation by radiomics were some of the study's drawbacks, which could have an impact on generalizability and clinical adoption.(5) Ling-Jie Wang and colleagues assessed plaques in the common carotid artery by examining 110 cases using five machine learning models, including XGBoost, in a 2023 Chinese retrospective study. The SHAP technique improved model interpretability, and the study focused on ID and FF values obtained via imaging. The study was limited by its retrospective methodology, lack of external validation, restricted access to dual- energy CT (DECT), and lack of a direct association with clinical outcomes.(12)

## CONCLUSION

The reviewed studies highlight the growing role of AI—particularly machine learning and deep learning—in evaluating carotid plaques for cardiovascular risk prediction. Across various global settings, AI models such as Random Forest, CNN, UNet, YOLOv8, SVM, and XGBoost have demonstrated superior accuracy, interpretability, and diagnostic efficiency compared to traditional methods. Key plaque features like cIMT, TPA, PSV, and tissue composition were commonly used inputs. Despite promising results, limitations such as retrospective designs, lack of external validation, operator dependency, and limited clinical integration remain consistent challenges. Future research should aim for larger, diverse populations, multimodal imaging, real-time systems, and validation in clinical workflows to ensure broader applicability and trust in AI-assisted cardiovascular diagnostics.

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## APPENDICES

Search strategy details

Quality assessment forms

Extra data tables

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**Line spacing:** 1.5 or double (2.0)

**Font:** Times New Roman

**Font size:**

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**12 pt bold/italic** for subheadings

**Text alignment:** Justified

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