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Integrative Use of Radiological Modalities for Early Detection and Risk Stratification in Coronary Artery Disease

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Abstract: Coronary Artery Disease (CAD) remains one of the leading causes of death globally. Early detection and risk stratification are very crucial for effective management as well as prognosis. Radiological imaging modalities such as the Coronary Computed Tomography Angiography (CCTA), Cardiac Magnetic Resonance Imaging (CMR, and Nuclear Imaging, play a pivotal role in non-invasive evaluation. This paper explores the integrative use of those radiological techniques to enhance diagnostic accuracy, guide clinical choice-making, and personalize treatment plans. The observer synthesizes current improvements, evaluates comparative effectiveness, and highlights future directions.

Keywords: *Coronary Artery Disease, CCTA, CMR, SPECT, Risk Stratification, Radiological Imaging.*

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I. INTRODUCTION

➢ *Background*

Coronary Artery Disease (CAD) remains one of the leading causes of death worldwide, accounting for millions of fatalities each year as well as placing an immense burden on the global healthcare systems (Roth et al., 2020). CAD occurs in the coronary arteries, responsible for supplying oxygen-rich blood to the heart muscle. They end up narrowed or blocked due to the buildup of atherosclerotic plaques. These plaques can be composed of fats, cholesterol and calcium in the blood, and their build-up can lead to reduced myocardial perfusion, myocardial infarction, or even sudden cardiac death (Libby et al., 2019).

Advancements in clinical cardiology as well as radiology, have extensively progressed, resulting in diagnosing and managing patients with CAD in a timely manner. Despite the advancements, sometimes patients are diagnosed with CAD after experiencing a major cardiac occasion, indicating that the sickness has spread unnoticed (Virani et al., 2021). This past-due detection reduces the window for preventive interventions and contributes to the morbidity and mortality related to CAD. Preventive cardiology focuses heavily on identifying individuals with risk factors earlier, way before signs and symptoms take place and permit the clinicians to provoke early treatment.

These risk factors can be divided into two groups: Modifiable and Non-Modifiable. Modifiable risks include hypertension, diabetes mellitus, smoking, sedentary life, and dyslipidaemia. Non-Modifiable risks include age, gender, family history, and race or ethnicity. However, despite these detections of risk factors, traditional risk evaluation cannot always accurately predict the presence or severity of the disease (D'Agostino et al., 2018). This underscores the necessity for imaging-based modalities which can locate CAD in its subclinical ranges.

➢ *Problem Statement*

Traditional diagnostic methods, including resting electrocardiograms (ECGs), treadmill stress tests, as well as basic blood markers, can sometimes fail to recognise subclinical or non-obstructive coronary artery disease, particularly in asymptomatic individuals (Greenland et al., 2018). While these methods provide important preliminary data, their sensitivity and specificity are constrained, especially when utilized in isolation. Moreover, anatomical assessment using invasive coronary angiography, while considered the gold standard, isn't always appropriate for full-size screening because its cost, invasiveness, and complications (Patel et al., 2015).

There is, therefore, an urgent need for diagnostic techniques which are non-invasive with high sensitivity and specificity, to be able to identify early pathologies in the coronary arteries and help in individualized risk stratification. Innovations in Coronary Computed Tomography Angiography (CCTA), Cardiac Magnetic Resonance Imaging (CMR), and nuclear imaging strategies along with Single-Photon Emission Computed Tomography (SPECT) and Positron Emission Tomography (PET) provide detailed

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anatomical and functional insights that go beyond conventional tests (Danad et al., 2014).

These imaging modalities often offer precise anatomical and useful insights into the coronary system, myocardial tissue viability, and plaque traits, facilitating evaluation that are way past what traditional diagnostic tests can offer. Importantly, the integrative use of those modalities may also facilitate diagnostic accuracy, lessen the incidence of unnecessary invasive approaches, and permit clinicians to tailor prevention and management primarily based on a patient's clinical profile (Nudi et al., 2013).

➢ *Research Objectives*

- *This Paper Aims to:*

✓ Evaluate the diagnostic performance of different radiological modalities in detecting CAD.
✓ Assess how integrated imaging approaches improve early detection and risk assessment.
✓ Propose a framework for using multi-modal imaging in clinical pathways.

II. LITERATURE REVIEW

Recent studies have demonstrated that the integration of artificial intelligence (AI) with multimodal cardiovascular imaging has the ability to significantly enhance early diagnosis, risk assessment, as well as treatment monitoring of cardiovascular diseases. By incorporating AI, clinicians can now extract deeper insights from imaging data, improving diagnostic precision and permitting customized treatment plans (Zhou et al., 2023; Oikonomou et al., 2018). In a study by Betancur et al., 2018; Arsanjani et al., 2019, they emphasize the advantages of combining anatomical and practical imaging modalities, consisting of computed tomography, magnetic resonance imaging, and nuclear imaging, to provide disease progression.

Several recent systematic reviews and meta-analyses support the incremental value of AI-assisted imaging: (a) AI improves diagnostic accuracy and reduces interobserver variability for CCTA plaque characterization and stenosis grading (Zhou et al., 2023; Oikonomou et al., 2018), (b) radiomics features derived from perivascular fat and plaque correlate with markers of coronary inflammation and adverse outcomes (Oikonomou et al., 2018; Caristo/FAI studies), and (c) machine-learning models that integrate imaging parameters with clinical data achieve superior prognostic discrimination compared with imaging or clinical metrics alone (Motwani et al., 2017; Al'Aref et al., 2019).

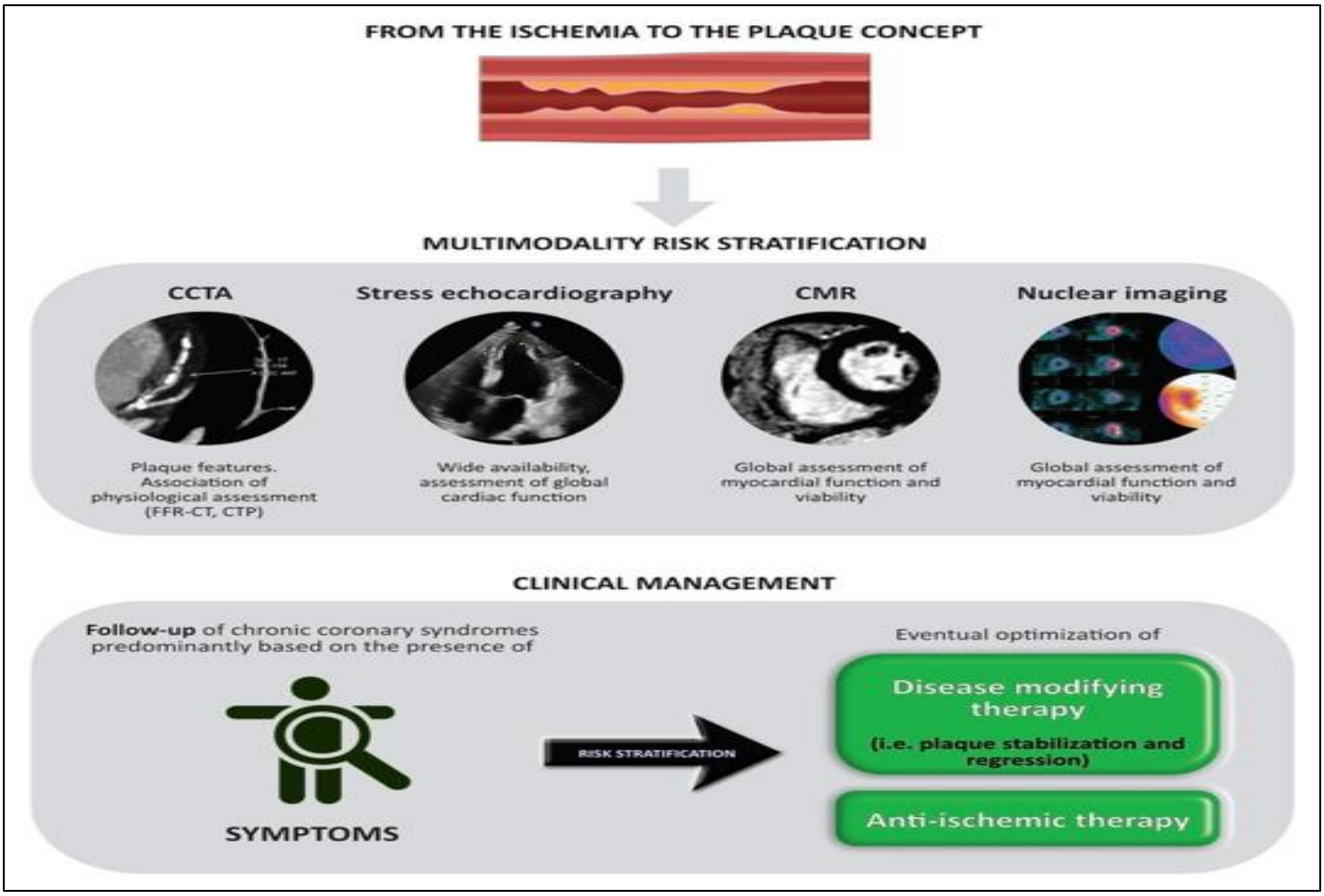

Fig 1 Risk Stratification of Patients with Coronary Heart Disease

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In the research done by Pompilio et al., 2021, the study outlines how contemporary cardiology has moved past conventional tools by embracing multimodal imaging strategies that permit visualization and characterization of cardiovascular illnesses. These approaches integrate anatomical, practical, and molecular imaging, resulting in improved diagnostic clarity, risk stratification, and treatment planning. They take a look at the significance of tailoring diagnostic strategies to patient profiles and scientific scenarios, enhancing accuracy by minimizing unnecessary approaches. Furthermore, it explores the synergistic cost of combining exceptional imaging modalities, together with echocardiography, cardiac computed tomography, magnetic resonance imaging, and nuclear imaging, each contributing unique strengths in identifying and assessing disease severity. The paper also reflects on the evolving function of synthetic intelligence in refining image interpretation, reducing human error, and helping proof-based decision-making in complicated cardiovascular illnesses.

Through clinical examples and case-based discussions, research underlines how integrated imaging contributes to early detection, tracking of favourable outcomes, and prediction of unfavourable cardiac events. Moreover, it advocates for established imaging protocols and standardized reporting to ensure consistency and reproducibility (Finke et al., 2021). The observer concludes that an imaging-oriented method in cardiology should try to embrace innovation, collaboration, and precision, by using imaging to enhance good patient outcomes and reshape cardiovascular care on diagnostic and therapeutic front.

Lin et al., 2021 particularly discusses the transformative role of artificial intelligence in enhancing the level of cardiovascular imaging, particularly for risk stratification in coronary artery disease. The studies highlight how gaining knowledge of and mastering techniques included in numerous non-invasive imaging modalities help to automate the extraction and quantification of essential prognostic biomarkers. These AI-driven systems allow for individualized risk assessments by means of analysing image-based information along medical variables. The study also emphasizes that technologies including coronary artery calcium scoring, coronary CT angiography, and nuclear myocardial perfusion imaging have drastically benefited from AI programs, leading to better predictions of ailment progression. By processing huge volumes of imaging statistics, AI not only increases efficiency but also improves diagnostic consistency across institutions and clinicians. Furthermore, the mixing of imaging parameters with scientific metrics allows for personalized profiles that enable better decision-making and optimize treatment planning. The study additionally underlines the significance of explainability in AI, which can objectively rank predictive variables, making their outputs transparent and clinically interpretable. Overall, the study takes a look at the AI as a powerful adjunct in cardiovascular medication, providing a statistics-based method that supports early detection, risk stratification, and long-term disease control. It concludes that the constant development in AI technologies, mixed with high-resolution imaging, is critical to reshaping the future of cardiovascular diagnostics and improving adverse patient outcomes.

Despite promising results, some challenges remain: model explainability, external validation across different vendors and populations, and integration into clinical workflows with clear regulatory and reimbursement pathways (Zhou et al., 2023). Ongoing 2023–2025 studies have addressed these issues by providing larger, multicenter datasets and by testing explainable AI approaches that highlight imaging features driving predictions (2023–2025 radiomics and digital PET studies referenced below).

III. METHODOLOGY

➢ *Research Design*

This study used an integrative review design to synthesize findings from peer-reviewed literature by following a study done by Whittemore & Knafl, 2005. This methodological approach was particularly selected to systematically synthesize already existing research findings on the use of radiological imaging modalities for early detection and risk stratification within Coronary Artery Disease (CAD). An integrative evaluation permits the inclusion of numerous methodologies, both qualitative and quantitative, thereby facilitating a comprehensive know-how of the topic under investigation (Infante et al., 2021). The goal of this design is to evaluate the collective evidence available in peer-reviewed literature published during the last decade and perceive styles, gaps, and emerging trends within the application of imaging technology consisting of Coronary Computed Tomography Angiography (CCTA), Cardiac Magnetic Resonance Imaging (CMR), and nuclear imaging modalities, along with Single-Photon Emission Computed Tomography (SPECT) and Positron Emission Tomography (PET), within clinical cardiology.

This overview is descriptive in nature, meaning that it targets the characteristics, capabilities, and diagnostic performance of each imaging modality. This study does not try to establish new and relatively unknown research, as seen in experimental research, but is a review aimed to offer a dependent account of the already existing contemporary information. By integrating findings from a couple of research designs, which include randomized controlled trials, observational cohort studies, and systematic evaluations, this methodology supports a multifaceted exploration of the current issue. Furthermore, the integrative approach accepts the assessment of medical practices and points to specific healthcare systems and demographic settings, which is critical for the know-how of the global applicability of integrative imaging in CAD diagnosis and control.

➢ *Data Collection*

A systematic search was conducted in PubMed, Scopus, and Web of Science for studies published between 2015 and 2024 using combinations of keywords including “Coronary Artery Disease,” “CCTA,” “CMR,” “SPECT,” “PET,” “non-invasive imaging,” and “risk stratification.” Boolean operators (AND, OR, NOT) were used to refine results. These databases have been selected because of their vast indexing

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of peer-reviewed medical and scientific literature, in addition to their reputation to publish open-access journals within the fields of cardiovascular medicine, diagnostic radiology, and clinical imaging. The time body for the literature became limited to studies posted between January 2015 and December 2024. This 10-year window was selected to ensure that the overview meditated the maximum present-day developments in imaging technology, diagnostic protocols, and clinical evidence.

➤ *Inclusion and Exclusion Criteria*

To maintain the relevance and quality of the data analysed, specific inclusion and exclusion criteria were applied during the time of the screening as well as the selection process. Included research needed to be posted in English and appear in peer-reviewed journals listed in one or more of the chosen academic databases. Only authentic articles, medical trials, systematic opinions, and meta-analyses have been included. Editorials, opinion pieces, letters to the editor, and conference abstracts have been excluded because of their loss of peer-reviewed information and insufficient methodological detail.

Another important inclusion criterion was the focus of the observer. Only research that examined non-invasive radiological imaging modalities, especially CCTA, CMR, SPECT, or PET, inside the context of CAD prognosis and risk stratification had been covered. Studies that used those imaging strategies for purposes unrelated to CAD, such as heart failure or cardiomyopathies, were excluded except when CAD became a primary recognition.

In addition, research needed to involve adult human topics; paediatric research and animal studies have been excluded because the pathophysiology and diagnostic approaches in those populations differ notably from those in adult human patients.

Finally, studies had to document at least one of the following outcomes: diagnostic accuracy, sensitivity, specificity, prognostic factor, and scientific applicability of the imaging modality used. Studies that did not present any measurable clinical or diagnostic final results were excluded.

➤ *Data Analysis*

The collected data was analysed using thematic analysis, a qualitative method used to identify, analyse, and report patterns or the main themes within a dataset. This approach was suitable given the diverse styles of the research available and the exploratory nature of the studies question. Thematic evaluation allowed for the synthesis of findings from research with varying designs, sample populations, imaging protocols, and outcome measures.

The evaluation method began with familiarization, in which the content of the articles was gone through extensively, and key points had been highlighted. This change, accompanied by the generation of initial codes based totally on recurring ideas, terminologies, and conclusions mentioned in the studies. These codes were then grouped into broader thematic categories, such as "diagnostic performance," "comparative advantages," "clinical integration," "prognostic utility," and "limitations to implementation." Within each theme, findings were summarized and interpreted to decide the position and effectiveness of each imaging modality in early CAD prognosis and risk stratification.

The diagnostic performance was assessed based on reported sensitivity, specificity, and predictive values. Clinical applicability was evaluated in terms of the way imaging findings had been used in decision-making, which include treatment initiation, remedy control, and referrals for invasive methods. Risk stratification results were considered in terms of the capability of imaging modalities to discover high-risk features, together with plaque vulnerability, myocardial ischemia, and perfusion deficits.

A comparative lens was also implemented during the evaluation to decide how each modality performs with others. For example, CCTA's ability to provide anatomical assessment was compared with CMR's superior ability to assess myocardial viability. PET's advanced quantitative perfusion evaluation was compared with the wider availability and decreased cost of SPECT imaging (Blankstein et al,. 2021). These comparative insights have been essential for identifying the most desirable contexts in which every modality can be used correctly.

The final stage of the thematic analysis involved synthesizing those insights to expand an integrative framework that would guide clinicians and policymakers in the adoption and implementation of radiological imaging techniques for CAD. This framework considered technological abilities, diagnostic performance, cost-effectiveness, and medical application across diverse healthcare settings. The evaluation also took into consideration radiation exposure issues, variability in image interpretation, restrained admission to advanced imaging infrastructure in resource-negative settings, and the want for interdisciplinary learning and collaboration.

Studies were appraised based on their readability of images, robustness of design, pattern size, appropriateness of statistical analyses, and transparency of reporting. This appraisal helped make sure that conclusions drawn from the thematic evaluation had been grounded in dependable and legitimate proof

IV. RESULTS

➤ *Coronary Computed Tomography Angiography (CCTA)*

- *Diagnostic Accuracy and Predictive Value*

Coronary Computed Tomography Angiography (CCTA) has particularly emerged as a pivotal non-invasive imaging modality within the evaluation of coronary artery disease (CAD). One of its biggest strengths lies in its negative predictive value (NPV), which is about 95% in various studies (Danad et al., 2014; Motoyama, S et al. (2015)). This high NPV indicates that CCTA is incredibly powerful in ruling out massive CAD, specifically in low to intermediate

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risk patients (Finke et al., 2021). The capacity to exclude obstructive CAD reduces the need for invasive diagnostic procedures, thereby minimizing complications associated with invasive procedures and healthcare costs.

- *Plaque Burden Quantification*

Beyond merely detecting luminal stenosis, CCTA provides detailed information on atherosclerotic plaque characteristics and the burden (Motoyama, S et al. (2015). Quantitative assessment of the plaque burden, inclusive of the assessment of non-calcified and atherosclerotic plaques, has been proven to correlate with unfavourable cardiovascular effects. Studies have confirmed that the extent and composition of coronary plaques, as visualized via CCTA, are predictive of future cardiac occasions, independent of luminal narrowing. This functionality permits nuanced risk stratification and personalized management strategies for sufferers with CAD. (Motoyama et al., 2015).

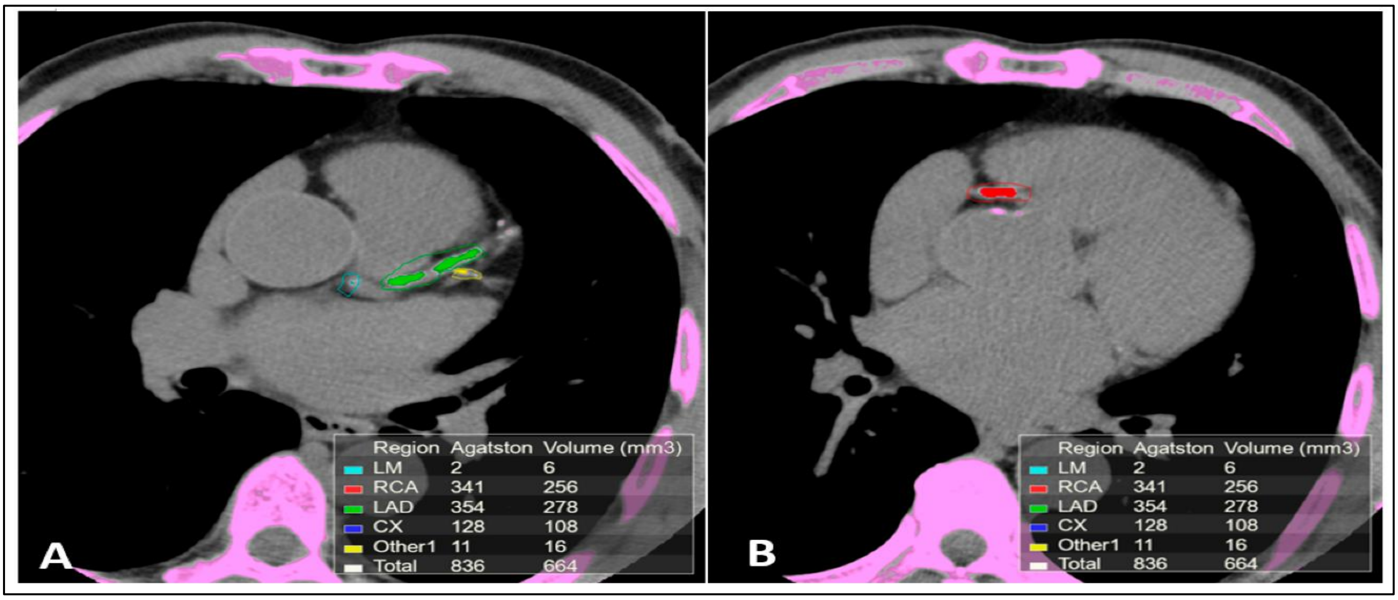

Fig 2 Coronary CT Images Showing Different Plaque Types in Atherosclerosis Imaging Review

- *Clinical Implications*

The integration of CCTA into the clinical process has converted the diagnostic approach to CAD. Its non-invasive nature, blended with high-resolution imaging, enables early detection of subclinical atherosclerosis. Moreover, the complete anatomical facts acquired from CCTA aid in guiding therapeutic selections, along with the initiation of antiplatelet/statin therapy or lifestyle modifications, even in the absence of large stenosis. Thus, CCTA serves not only as a diagnostic tool but also as a means to put into effect preventive measures.

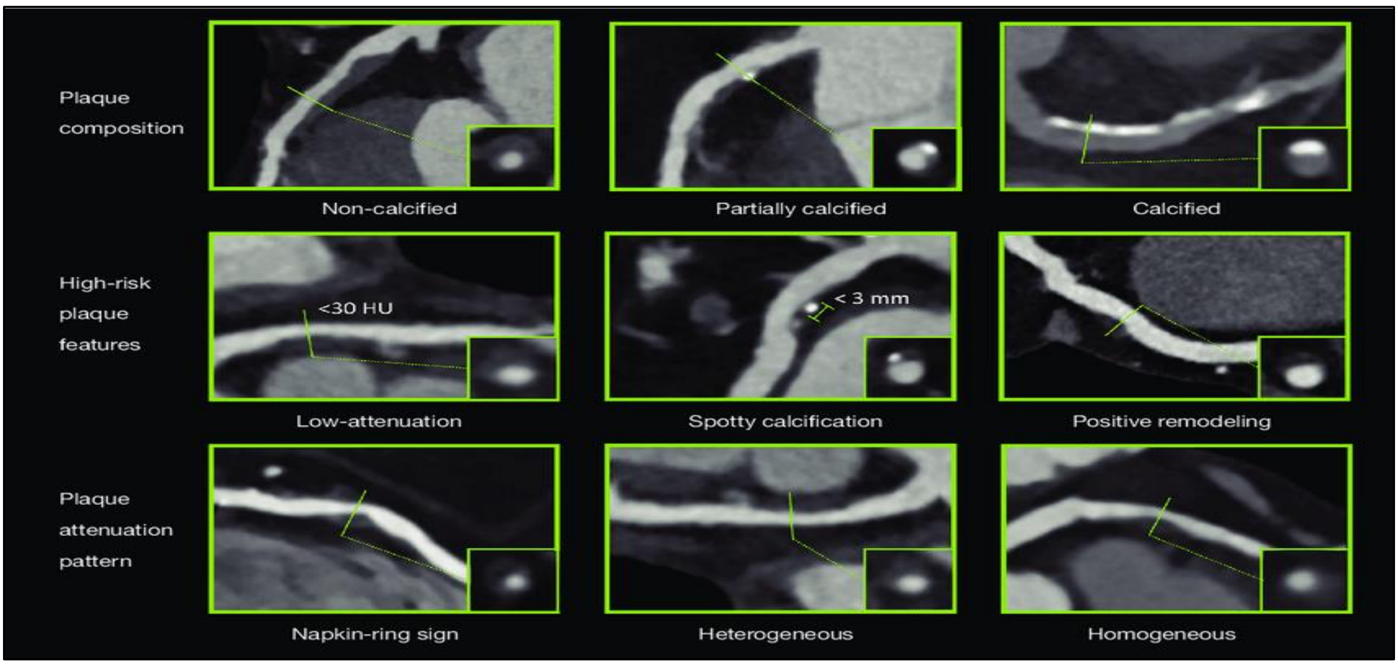

Fig 3 Representative Images of Plaque Characteristics (Non-Calcified, Mixed, Calcified) with Colour Overlays from CT

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➢ *Cardiac Magnetic Resonance Imaging (CMR)*

- *Comprehensive Cardiac Assessment*

Cardiac Magnetic Resonance Imaging (CMR) offers a multifaceted evaluation of the cardiac structure and its function without the use of ionizing radiation. It gives precise measurements of ventricular volumes, mass, and ejection fraction, which can be vital parameters in the evaluation of cardiac health (Kramer et al., 2014, Pontone et al., 2021). Furthermore, CMR can examine myocardial perfusion and viability, enabling the detection of ischemia and infarction. This complete assessment is helpful in the analysis and management of various cardiac pathologies, which include CAD.

- *Late Gadolinium Enhancement and Myocardial Fibrosis*

A unique function of CMR is its capability to detect myocardial fibrosis through Late Gadolinium Enhancement (LGE). LGE imaging identifies regions of myocardial scarring by highlighting areas where gadolinium accumulates inside the extracellular area, indicative of fibrosis or necrosis. Presence and extent of LGE are independently predictive of mortality and major adverse cardiac events (MACE) in CAD patients (Neilan et al., 2011; Gul et al., 2013). In sufferers with CAD, LGE can differentiate between viable and non-viable myocardium, which drives revascularization choices.

- *Risk Stratification and Prognostication*

The prognostication of CMR extends beyond its structural assessment. By figuring out myocardial fibrosis and assessing perfusion deficits, CMR contributes to risk stratification in sufferers with CAD. Studies have shown that the extent of LGE correlates with the chance of future cardiac events, independent of different scientific variables. (Chan, R. H., Maron, B. J et al,. 2024), Halliday, B. P., et al,. 2023).

Therefore, CMR is not the most effective aid in prognosis but it helps for risk stratification of CAD by long-term analysis.

➢ *Nuclear Imaging: SPECT and PET*

- *Single-Photon Emission Computed Tomography (SPECT)*

SPECT myocardial perfusion imaging (MPI) has long been one of the cornerstones in the non-invasive evaluation of CAD. It assesses myocardial blood flow at relaxation and at some stage of stress, identifying areas of ischemia and infarction. SPECT is extensively available and has a properly installed function in diagnosing obstructive CAD, in particular in patients with intermediate to high predictive risk. However, its spatial decision is limited in comparison to more modern modalities, and attenuation artefacts can have an effect on image quality (Nudi et al., 2013).

- *Positron Emission Tomography (PET)*

PET imaging offers superior spatial and high-resolution images compared to SPECT, along with the ability to quantify absolute myocardial blood flow and flow reserve. This quantitative capability complements the detection of multivessel disease and microvascular disorder, which may be underestimated through other imaging techniques (Giubbini, R., & Milan, E. et al., 2024). PET's better diagnostic accuracy makes it particularly useful in complicated instances and in patients with equivocal findings on other tests. However, its confined availability and higher value can restrict wider use (Woodhead, R. C., Tong, X et al., (2024).

- *Comparative Diagnostic Performance*

When comparing SPECT and PET, studies have continuously proven PET's advanced diagnostic performance in detecting CAD. PET's capability to offer absolute quantification of myocardial perfusion allows for greater correct identification of ischemic regions, leading to higher risk stratification and treatment choices (Nudi et al., 2013). Despite these benefits, SPECT remains a valuable tool because of its accessibility and significant clinical validation.

➢ *Integration and Complementarity of Imaging Modalities*

- *Combining Anatomical and Functional Imaging*

The integration of anatomical imaging (such as CCTA) with the various functional imaging modalities (like CMR or PET) has been proven to improve diagnostic accuracy and decision-making in CAD. Hybrid imaging strategies, including PET/CT and PET/MRI, have evolved to simultaneously gather anatomical and functional statistics. These modalities provide the advantage of co-relating images, enhancing spatial alignment, and decreasing general scan time. Clinical research has established that hybrid imaging can improve diagnostic accuracy, especially in instances with intermediate findings on a single-modality imaging. Moreover, hybrid imaging can aid in identifying patients who might benefit most from revascularization processes, thereby optimizing treatment plans. (Zhou et al., 2023). This blended method also allows for greater diagnostic accuracy of CAD, figuring out both the presence of atherosclerotic plaques and their impact on myocardial perfusion.

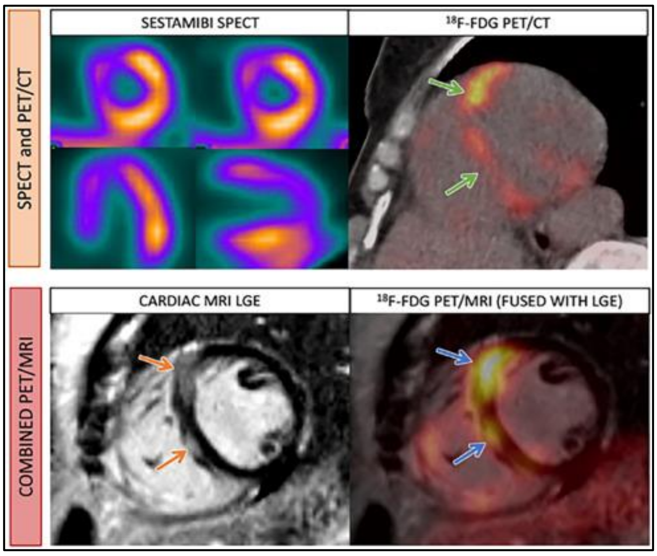

Fig 4 FDG PET/MR Fusion in Cardiac Inflammation or Viability Imaging: MRI Anatomical Overlay with Metabolic FDG Uptake Map Showing Focal Uptake in Myocardium

- *Implications for Patient Management*

The complementary use of various imaging modalities enables a more personalized technique for patient care. By integrating statistics on coronary anatomy, plaque burden, myocardial perfusion, and tissue viability, clinicians can take better decisions regarding clinical therapy, lifestyle interventions, and the need for invasive techniques. This integrative approach aligns with the standards of precision medicine, aiming to tailor interventions primarily based on person characteristics and disease profiles.

V. CONCLUSION

➢ *Summary of Findings*

This research has mainly emphasized the actual growing significance of the non-invasive radiological modalities in the early detection as well as the risk stratification of Coronary Artery Disease (CAD). CAD remains a main purpose of morbidity and mortality internationally, with subclinical and asymptomatic patients often escaping conventional diagnostic processes. Through an integrative evaluation of present literature and scientific statistics, it's obvious that the strategic use of imaging modalities consisting of Coronary Computed Tomography Angiography (CCTA), Cardiac Magnetic Resonance Imaging (CMR), and nuclear imaging techniques which include Single-Photon Emission Computed Tomography (SPECT) and Positron Emission Tomography (PET) affords a sturdy framework for diagnosing CAD at its earliest stages.

The review has revealed that CCTA possesses a good negative predictive value, making it especially powerful for ruling out obstructive CAD in patients with low to intermediate danger. In addition to visualizing coronary anatomy, CCTA gives the capability to evaluate atherosclerotic plaque burden, consisting of traits that are predictive of future cardiovascular activities (Santangelo et at., 2021). Complementing this, CMR sticks out for its comprehensive tissue characterization, useful evaluation, and perfusion imaging which can be achieved without the usage of ionizing radiation. The capability to diagnose myocardial fibrosis through late gadolinium enhancement (LGE) offers prognostic data that goes beyond structural abnormalities. Nuclear imaging modalities, especially PET, similarly aid diagnostic precision by way of presenting absolute quantification of myocardial blood flow and uncovering microvascular dysfunction. SPECT, though more restricted in spatial resolution, continues to play a valuable role because of its availability and clinical familiarity.

Importantly, the integration of anatomical imaging from CCTA with myocardial viability assessed from CMR/PET results in a more desirable diagnostic acumen and allows for tailored clinical decisions. This multimodal approach helps in risk stratification and well-timed initiation of therapeutic interventions.

➢ *Recommendations*

Based on the findings of this review, several practical recommendations emerge for the purpose of clinical practice. First, CCTA needs to be taken into consideration as a frontline diagnostic modality for patients with intermediate risk factors to look for a chance of CAD. Its non-invasive nature and diagnostic accuracy make it a great first step in assessing coronary anatomy and figuring out individuals at risk. Second, in cases wherein anatomical imaging produces ambiguous effects or in patients with diagnosed CAD requiring further assessment, CMR/PET must be done. These modalities provide a deeper perception of myocardial viability, ischemia, and fibrosis, permitting clinicians to determine the want for revascularization or aggressive medical control. Third, healthcare institutions should expand multidisciplinary imaging protocols that combine anatomical and functional modalities. Such protocols might promote regular, evidence-based decision-making and facilitate communication between radiologists, cardiologists, and referring physicians. Implementing integrative imaging pathways can optimize diagnostic performance and streamline patient control in acute and outpatient setting.

➢ *Future Research*

While the present-day evidence supports the integrative use of imaging modalities in CAD control, future studies have to be aware of lengthy-time period effects and cost-effectiveness. Longitudinal, multicentre studies are necessary to decide whether or not multi-modal imaging strategies lead to sustained changes in cardiovascular diseases, enhancements in lifestyles, and financial costs. Additionally, technological advances including artificial intelligence (AI) -push picture interpretation and device learning algorithms for risk stratification give exciting opportunities for boosting the diagnostic overall performance of current imaging gear. Future investigations should additionally discover how such innovations can be incorporated into contemporary imaging workflows to similarly refine CAD evaluation.

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