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ORIGINAL ARTICLE

High-resolution automated free-breathing coronary magnetic resonance angiography in comparison with coronary computed tomography angiography

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Abstract

Aims

Clinical implementation of coronary magnetic resonance angiography (CMRA) is limited due to variability in image quality. A protocol utilizing an image navigator (iNAV) integrated with automated scan planning has been developed to facilitate consistent diagnostic image quality. The aim of this study was to evaluate the agreement of automated iNAV CMRA compared with coronary computed tomography angiography (CCTA) using Coronary Artery Disease-Reporting and Data System (CAD-RADS) to classify coronary artery disease (CAD).

Methods and results

Ninety-five individuals underwent automated iNAV CMRA at a resolution of 0.7 mm^3 with a deep learning–assisted automated scan planning and trigger-delay detection protocol. CMRA and CCTA data sets were analysed using CAD-RADS to classify the per-patient severity of CAD. Additionally, the accuracy of both imaging modalities in predicting referral for invasive coronary angiography (ICA) and coronary revascularization was assessed. CMRA classification for CAD-RADS ≥ 1, ≥2, ≥3, and ≥4 agreed with CCTA for 80%, 73%, 63%, and 70% of cases, respectively. The area under the receiver operating characteristic curves with CAD-RADS ≥ 4 and ≥3 for CMRA and CCTA were comparable in predicting ICA referral (0.75 vs. 0.70, $P = 0.687$, and 0.70 vs. 0.70, $P = 0.945$) and revascularization (0.72 vs. 0.74, $P = 0.811$, and 0.68 vs. 0.76, $P = 0.089$).

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Conclusion A novel automated iNAV CMRA protocol was implemented, investigating individuals at risk of CAD. Using the CAD-RADS classification, there was moderate to good agreement between CMRA and CCTA. In patients with CAD-RADS ≥ 4 and ≥3, CMRA was as effective as CCTA in predicting ICA referral and revascularization.

Keywords coronary magnetic resonance angiography • coronary artery disease

Introduction

Coronary magnetic resonance angiography (CMRA) is a progressively developing modality to investigate coronary artery disease (CAD) in stable chest pain patients and is considered appropriate for use in female patients and younger patients (<55 years) according to the consensus statement.[1] However, clinical implementation has been challenging. Firstly, CMRA is technically complex, meaning that it has thus far only been performed by specialist academic centres with high levels of technical expertise.[2] Additionally, spatial resolution is lower and scan time is longer and unpredictable in comparison with coronary computed tomography angiography (CCTA). Thus, CMRA has only been used in a clinical setting to detect anomalous coronary arteries in patients with congenital heart disease and rarely for the detection of CAD.[3]

However, recent technological advances to improve the efficiency of CMRA have been implemented, encompassing both automated scan planning and accelerated image acquisition and motion correction. Deep learning (DL)–assisted automated CMRA has been shown to be as effective as an experienced operator for planning CMRA and finding the optimal cardiac rest period to acquire CMRA images with fewer motion artefacts.[4] The improvements in respiratory motion correction and associated scanning efficiency have reduced acquisition duration, facilitating an improved spatial resolution. Sub-millimetre isotropic coronary imaging has been shown to improve the diagnostic accuracy of CMRA as compared with both CCTA[5] and invasive coronary angiography (ICA),[6] relative to previous work.[7,8] However, an intrinsic spatial resolution of 0.5–0.7 mm^3 isotropic is considered necessary for accurate non-invasive evaluation of CAD with CCTA.[9] Thus, improvements in the spatial resolution of CMRA are likely necessary to ensure sufficient diagnostic accuracy for clinical use.

Whilst these technological developments have been shown to be effective,[4] they have never been integrated into a clinical workflow and tested within a clinical cohort. Therefore, this protocol needs to be tested within patients to establish the efficacy of this novel DL-assisted automated iNAV CMRA.

Finally, clinical implementation of CMRA requires systematic and standardized reporting for assessing CAD. The Coronary Artery Disease-Reporting and Data System (CAD-RADS) has been developed for CCTA in order to ease and standardize grading of CAD severity.[10] Assessment of the use of CAD-RADS with CMRA is needed to determine whether the current grading system can be directly translated from CCTA to CMRA, or whether modification is required.

As such, this study has three primary aims:

(1) To investigate whether increasing the spatial resolution of CMRA to an isotropic resolution of 0.7 mm^3 yields comparable diagnostic accuracy to CCTA
(2) To test the efficacy of DL-assisted automated iNAV CMRA for investigating patients suspected of having CAD
(3) To determine the agreement of the CMRA CAD-RADS classification to that of CCTA for evaluating CAD.

Methods

Study participants

Study participants were recruited among symptomatic individuals referred for a clinical CCTA at the Department of Cardiology, Aarhus University Hospital, under suspicion of CAD. Following CCTA, patients were approached and offered the opportunity to participate. Participants were not pre-screened to determine CAD severity or on the basis of any specific demographic characteristic. Inclusion and exclusion criteria are outlined in Supplementary data online, *Table S1*. Individuals underwent CMRA within 28 days of their CCTA. The study was approved by the research ethics committee of the Central Jutland Region, Denmark (1-10-72-57-22).

Patient preparation

All participants were asked to abstain from caffeine on the day of scanning. Individuals were pre-treated with either oral and/or intravenous beta-blocker, as per standard CCTA protocols, to achieve a resting heart rate of ≤60 bpm. Sublingual nitroglycerine 0.8 mg was administered to patients just prior to commencement of the scanning protocol to improve coronary artery visualization.

CMRA

Images were acquired using a clinical 1.5 T scanner (MAGNETOM Sola, Siemens Healthineers, Erlangen, Germany) equipped with a 32-channel spine coil and an 18-channel body coil. Cardiac synchronisation was performed using a three-lead vector electrocardiogram (ECG). All CMRA scans were conducted by one of two investigators, both with limited prior experience in CMR acquisition (G.W. and A.U.P.).

First, an initial cardiac thoracic localizer was used for cardiac localization, planning, and acquisition of a cardiac localizer. A single-shot two-chamber balanced steady-state free precession (bSSFP) scan was employed to plan a free-breathing four-chamber CINE bSSFP, which was subsequently used to determine the trigger delay for automated positioning of the optimal acquisition window.[4,11] Placement of the 3D image volume and 2D image navigator was also automated; however, the operator was permitted to manually adjust these parameters if it was felt necessary.

High-resolution CMRA—image acquisition

High-resolution CMRA (HR-CMRA) was performed during free-breathing using iNAV-based respiratory motion correction.[12] The 0.7 mm^3 protocol is based upon a previously described sequence utilizing a spatial resolution of 0.9 mm^3.[4,5] This utilized an under-sampled, free-breathing 3D whole heart, prospectively gated ECG triggered bSSFP research protocol with a 3D variable density spiral-like Cartesian trajectory with golden angle rotation. A spectrally selective Spectral Presaturation with Inversion Recovery (SPIR) pre-pulse with a flip angle of 130° and a T2 preparation pulse of 40 ms was used. An acceleration factor of 4.5 was applied.

Field of view was 303–324 mm × 303–324 mm in coronal orientation, slices = 144–176, phase oversampling was 20%, slice oversampling was 25%, and TE/TR was 1.86/4.33 ms, with a flip angle of 90°.

HR-CMRA—image reconstruction

Image reconstruction of the non-rigid motion-compensated 3D CMRA images took place as previously described.[13,14] Reconstruction was performed in-line using work-in-progress scanner software provided by the

scanner manufacturer (Siemens Healthineers, Erlangen, Germany) if possible. In instances where there was insufficient memory to facilitate reconstruction, reconstruction was performed offline. PROST denoising[15] was then applied off-line in Matlab vR2022a.

CCTA

CCTA acquisition was performed with a 384-slice (2 × 192 slices) dual-source computed tomography scanner (Siemens Somatom Force; Siemens Healthcare, Forchheim, Germany) in accordance with best practice guidelines.[16] In brief, beta-blockers or ivabradine was given if necessary, targeting a heart rate < 60 bpm. All patients received sublingual nitroglycerine 0.8 mg before the scan. First, a non-contrast scan was performed for assessment of the Agatston score.[17] CCTA was performed using prospective ECG triggering. Automatic tube current modulation and tube voltage selection were used to adjust radiation exposure according to patient size.

CMRA and CCTA image analysis

Both the CMRA and CCTA 3D coronary data sets were analysed using a nine-segment coronary model.[7,15] Both data sets were assessed on the basis of the CAD-RADS classification[10] as well as coronary artery luminal stenosis grades ≥ 50% or ≥70%. The CMRA analysis was conducted through visual inspection using CVI42 (Circle Cardiovascular Imaging version 5.16) (see Supplementary data online, *Table S2*). Data were assessed on an intention-to-diagnose approach, with non-diagnostic images classified as CAD-RADS ≥ 4 for the purpose of data analysis. Analysis was performed twice, firstly by a single CMR expert reader (W.Y.K.) and then after 1 week by two CMR expert readers (W.Y.K. and C.A.F.) together to obtain a consensus reading.

Qualitative image quality assessment of CMRA was performed using the following scale as previously utilized by Hajhosseiny *et al.*[5]: 0, non-diagnostic; 1, poor; 2, average; 3, good; and 4, excellent.

The efficiency of the automated CMRA protocol was assessed by determining the number of times the free-breathing four-chamber CINE, which was used for the automated detection of the cardiac rest period, needed to be performed prior to CMRA acquisition. The time taken between completion of the initial planning and commencement of CMRA was also recorded.

For the direct comparison with CMRA, the CCTA CAD-RADS score was reported by one single CCTA expert reader (B.L.N.) who made the assessment of CAD-RADS by the use of a semi-automated quantitative assessment of luminal area stenosis with commercially available software (QCA module, Syngo.via, Siemens Healthcare).

Coronary artery calcium (CAC) score was calculated on a per-patient basis. This was grouped according to the following Agatston scores: 0, 1–100, 101–300, 301–999, and ≥1000.[10]

ICA and coronary revascularization

If individuals were referred to ICA, this was recorded, along with if they underwent coronary revascularization with percutaneous coronary intervention (PCI) or coronary artery bypass graft (CABG). The patient journal was reviewed, and the location and extent of the coronary disease were recorded, along with fractional flow reserve (FFR) and/or instantaneous wave-free ratio values, if available.

Statistics

Statistical analysis was performed using RStudio 2023.03.1. Continuous data are displayed as mean ± standard deviation. Ordinal data are displayed as median interquartile range (IQR). The agreement between CMRA and CCTA for CAD-RADS scores at thresholds of ≥1, ≥ 2, ≥ 3, and ≥4 was calculated as the percentage of cases where the two modalities agreed. Sensitivity, specificity, negative predictive value (NPV), positive predictive value (PPV), and area under the receiver operating characteristic curve (AUC) were calculated for the CAD-RADS for CMRA, using CCTA as the reference. The diagnostic performance of CMRA and CCTA for predicting referral for ICA and subsequent coronary revascularization in the form of PCI or CABG surgery was calculated. Furthermore, the agreement between CCTA and CMRA for ≥50% luminal stenosis and ≥70% luminal stenosis on a per-vessel and per-segment basis was assessed. Comparison of referral to ICA and revascularization between CMRA and CCTA was performed using McNemars test for sensitivity and specificity, using relative predictive values for PPV and NPV and comparing AUC using the DeLong method. The thresholds used for predicting referral to ICA and coronary revascularization were CAD-RADS ≥ 3 and CAD-RADS ≥ 4. The difference between the original and repeat CMRA readings was assessed using a weighted kappa test with squared weights. Additionally, the diagnostic performance of each reading was compared.

Results

Patient inclusion

One hundred and sixteen consecutive individuals referred for CCTA with suspicion of CAD were recruited to the project. A total of 95 individuals underwent the study protocol and data analysis (*Figure 1*).

Patient characteristics

Demographic data of the project participants are described in *Table 1*. Heart rate and CMRA scan duration as well as the beta-blocker administration are shown in *Table 2*. The median CAC score (IQR, range) per patient was 196 (IQR = 574, 16–590), including 17 individuals with CAC = 0, 20 individuals with CAC = 1–100, 19 individuals with CAC = 101–300, 23 individuals with CAC = 301–999, and 16 individuals with CAC ≥ 1000.

Classification of CCTA and CMRA using CAD-RADS

Classification of disease severity along with reclassification using CAD-RADS ≥ 3 and ≥4 between CCTA and CMRA is shown in *Figure 2* and *Table 3*. There were 21 individuals who were classified as CAD-RADS < 3 who were reclassified to ≥3 with CMRA and 14 who were reclassified to <3 on CMRA from ≥3 on CCTA. Using CAD-RADS ≥ 4 as a threshold, 7 individuals were reclassified to CAD-RADS < 4 on CMRA as compared with CCTA, whilst 22 were reclassified to ≥4. The median CCTA CAD-RADS was 2 whilst the median CMRA CAD-RADS was 3. Examples of CMRA and CCTA showing different CAD-RADS classifications are shown in *Figure 3*. Four individuals had CMRA judged to be non-diagnostic and thereby classified as CAD-RADS ≥ 4 in the analysis. A sensitivity analysis performed without these individuals included is included in the Supplementary data online, *Table S3*.

CMRA subjective image quality analysis

A total of 855 segments were assessed, of which 95 assessed the left mainstem, 285 the LAD, 190 the LCx, and 285 the RCA. The subjective image quality score for all segments assessed together, as well as on a per-vessel and per-segment basis, is shown in the Supplementary data online, *Table S4*.

Agreement between CMRA compared with CCTA according to CAD-RADS

Calculated on a per-patient basis, the proportion of CMRA that agreed with CCTA was 0.80 [95% confidence interval (CI): 0.51, 0.80] for CAD-RADS ≥ 1, 0.73 (95% CI: 0.63, 0.81) for CAD-RADS ≥ 2, 0.63 (95% CI: 0.53, 0.73) for CAD-RADS ≥ 3, and 0.70 (95% CI: 0.59, 0.79) for CAD-RADS ≥ 4 (*Table 3*).

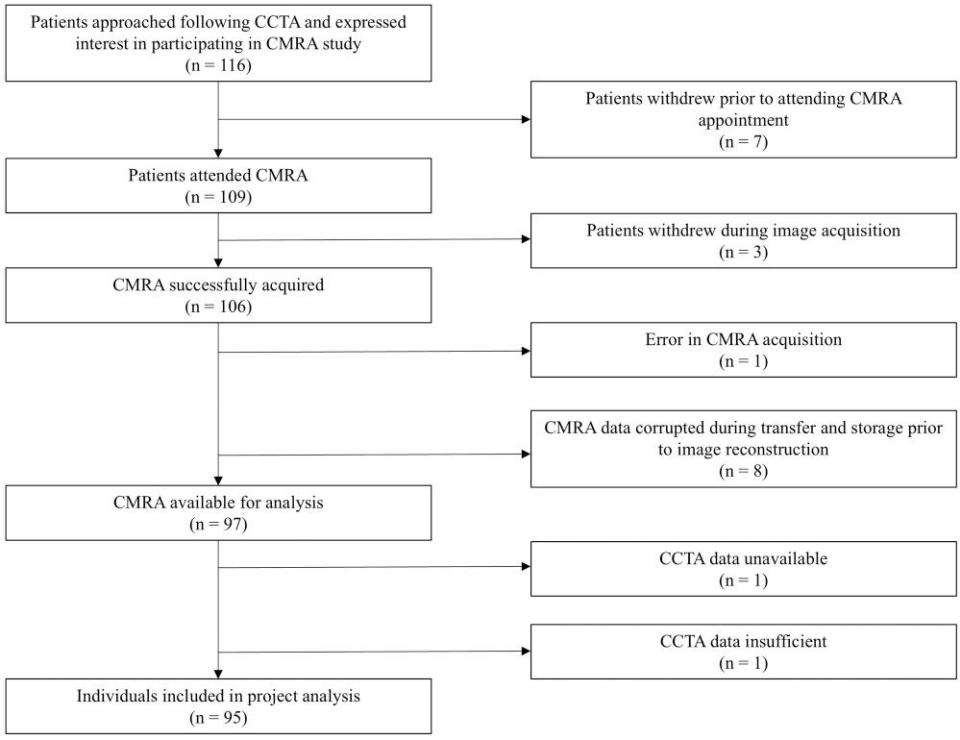

Figure 1 Patient inclusion and reasons for exclusion from the study.

Prediction of decision to refer to ICA and undergo revascularization

When comparing CMRA and CCTA on the ability to predict whether patients were referred to ICA using a CAD-RADS threshold of ≥4, there was no statistical difference in AUC between CMRA and CCTA ($P = 0.687$), nor for prediction of the patient to undergo coronary revascularization ($P = 0.811$) (*Table 4* and *Figure 4*). Using a CAD-RADS threshold of ≥3, there was no statistical difference in AUC for referral to ICA ($P = 0.945$), nor for predicting undergoing coronary revascularization, albeit there was a trend towards favouring CCTA ($P = 0.089$) (*Table 5*). At CAD-RADS threshold of ≥4, CCTA had higher specificity compared with CMRA for predicting referral to ICA and coronary revascularization; otherwise, there were no significant differences (*Table 4*).

The full description of the location and severity of CAD in each individual referred to ICA is reported in Supplementary data online, *Table S5*.

Diagnostic accuracy of CMRA compared with CCTA according to luminal stenosis degrees of ≥50% and ≥70%

On a per-patient, per-vessel, and per-segment basis, agreement between CCTA and CMRA for ≥50% stenosis was 0.66 (95% CI = 0.56–0.76), 0.80 (95% CI = 0.75–0.83), and 0.82 (95% CI = 0.79–0.85), respectively. For ≥70% stenosis, these were 0.66 (95% CI = 0.56–0.76), 0.88 (95% CI = 0.84–0.91), and 0.91 (95% CI = 0.89–0.93).

The per-segment and per-vessel analysis showed a tendency towards lower sensitivity and higher specificity for both degrees of luminal stenosis (see Supplementary data online, *Table S6*).

CMRA planning success rate

Planning of CMRA was successful at the first attempt in 76% of acquisitions, with a further 18% successful on the first repeat. A second repeat was required in 6% of scans. The average time taken between completion of the plan scanning and commencement of CMRA acquisition was 96 ± 46 s.

Reproducibility analysis

Reproducibility analysis of the CMRA images showed that the use of CAD-RADS on a per-patient basis showed a substantial agreement between the original and repeat readings (kappa = 0.70, $z = 6.87$). The CAD-RADS readings of CMRA from the two independent readings are shown in Supplementary data online, *Tables S7–S9*. Overall, there were no significant differences in diagnostic accuracy between the two repeat readings.

Discussion

This study is the first to evaluate free-breathing CMRA utilizing a novel iNAV-based CMRA protocol in concert with DL-assisted semi-automated scanning at a spatial isotropic resolution of 0.7 mm. Furthermore, CMRA was reported using the standardized CAD-RADS classification for comparison with CCTA.

Compared with a recent meta-analysis that compared pooled results from 1.5 T CMRA with ICA for the detection of significant CAD, the per-patient sensitivity was lower in our study being 71% for CAD-RADS ≥ 3 compared with the reported mean sensitivity of 86% with 95% CI of 80–90%.[18] The reported specificity of 73% (65–81%) was similar to our results being 60% and 70% for CAD-RADS ≥ 3 and ≥4, respectively. We acknowledge moreover

Table 1 Demographic data, including symptoms and the patient outcome following Coronary Computed Tomography Angiography

Demographics	
No. of participants	95
Female (*n*)	31 (33%)
Age (years)	67 [14]
Height (cm)	175.0 [11.0]
Weight (kg)	81.0 [19.5]
BMI (kg/m^2)	26.0 [4.9]
Hypertension (*n*)	57 (60%)
Hyperlipidaemia (*n*)	57 (60%)
Diabetes (*n*)	13 (14%)
Current smoker (*n*)	10 (11%)
Former smoker (*n*)	46 (48%)
Family history (*n*)	29 (31%)
Symptoms	
Chest pain on physical activity (*n*)	49 (52%)
Chest pain at rest (*n*)	35 (37%)
NYHA class 1	58 (61%)
NYHA class 2	30 (32%)
NYHA class 3	6 (6%)
NYHA class 4	0
Outcomes	
Referred to Invasive Coronary Angiography	25 (26%)
Revascularization	16 (17%)

Continuous data are presented as median and interquartile range. Percentages are expressed in brackets.
BMI, body mass index; NYHA, New York Heart Classification.

Table 2 Characteristics of Coronary Magnetic Resonance Angiography scanning

CMRA scanning characteristics	
Heart rate (bpm)	58 ± 10
Scanning duration (secs)	746 ± 182
Delay between planning completion and commencement of CMRA (secs)	96 ± 46
Oral beta-blocker	54 (57%)
Intravenous beta-blocker	3 (3%)
Oral and Intravenous beta-blocker	3 (3%)
CMRA planning sequences required	
1	72 (76%)
2	17 (18%)
3	6 (6%)

Data are presented as mean and standard deviation. Percentages are expressed in brackets.
bpm, beats per minute; secs, seconds; CMRA, Coronary Magnetic Resonance Angiography.

that a previous study using the same protocol at a lower spatial resolution did show a sensitivity of 100%.[5] This difference in sensitivity may be due to differences in disease prevalence and burden between the two cohorts or variation in interpretation of both CMRA and CCTA. In the present study, the CCTA analysis was done by the use of a semi-automated quantitative assessment of luminal area stenosis, which is inherently more reproducible than visual inspection. Thus, automated detection and classification of CAD from both CMRA and CCTA would represent a significant advance facilitating more precise and observer independent diagnostics. The median CAD-RADS score of 3 for CMRA was greater than that of 2 for CCTA indicating a tendency for CMRA to overestimate CAD at the per-patient level. Thus, at CAD-RADS ≥ 4, it was shown that CCTA had higher specificity compared with CMRA in predicting referral to ICA and revascularization (*Table 4*). One possible explanation could be attributed to increasing the spatial resolution of CMRA to 0.7 mm^3, leading to a reduced signal-to-noise ratio. This reduction may consequently amplify signal drop in instances of luminal stenosis. With additional technical development, this issue may be alleviated, and it could be expected to improve diagnostic accuracy of CMRA further.[19]

Within this cohort, CMRA had a similar accuracy to CCTA at predicting referral to ICA and undergoing coronary revascularization at thresholds of CAD-RADS ≥ 3 and ≥ 4. This result is particularly notable as the clinical decision to refer to ICA was based on the clinical reading of CCTA, albeit the clinical reading would have considered additional factors, such as the location of the lesion and the patients' presenting symptoms, whilst our protocol assessed exclusively anatomical CAD severity. However, this limitation applies equally to both CMRA and CCTA, as both were assessed using exclusively anatomical measures.

As such, whilst decision regarding further downstream testing in clinical practice does not rely on CAD-RADS alone, this documents the high sensitivity and NPV of CMRA for detecting significant proximal CAD requiring revascularization. These findings support those of previous studies utilizing sub-millimetre CMRA.[5,6] In the 16 patients that subsequently underwent coronary revascularization, CMRA showed a CAD-RADS classification of <3 in two patients. In one patient (ID 77 in Supplementary data online, *Table S5*), an approximately 80% proximal LAD stenosis was not well visualized on CMRA despite excellent image quality whilst an approximately 50% stenosis more distal on the LAD was clearly visualized (see Supplementary data online, *Figure S1*). We hypothesize that the reason for this could be attributed to coronary plaque oedema, which would make it difficult to distinguish between the coronary vessel wall lesion and the luminal integrity on the T2-weighted CMRA scan unless combined with a black-blood pre-pulse preparation.[20] Furthermore, one patient in the study cohort underwent revascularization due to significant stenosis at the second diagonal branch with an FFR values of 0.65 (ID 110 in Supplementary data online, *Table S5* and *Figure S2*). Thus, whilst the stenosed segment was clearly visualized from both CMRA and CCTA, it was not included in the nine-segment model used in this study.

Automated CMRA acquisition, performed by two investigators (G.W. and A.U.P.) with limited prior experience, provided diagnostic image quality in 96% of patients and in 92% of all coronary segments (see Supplementary data online, *Table S4*). These results are comparable with those reported in previous non-automated iteration of the scanning protocol.[5,6] Additionally, the time delay between the completion of the automated CMRA planning scan and commencement of CMRA acquisition was similar to that found in a previous study,[4] demonstrating a time saving of approximately 60 s compared with an operator-determined trigger delay.

Using the CAD-RADS classification, the CMRA protocol demonstrated moderate to good agreement to CCTA. For CAD-RADS classifications ≥ 1, the agreement with CCTA was good being 80%, demonstrating that CMRA can recognize the absence of CAD. This

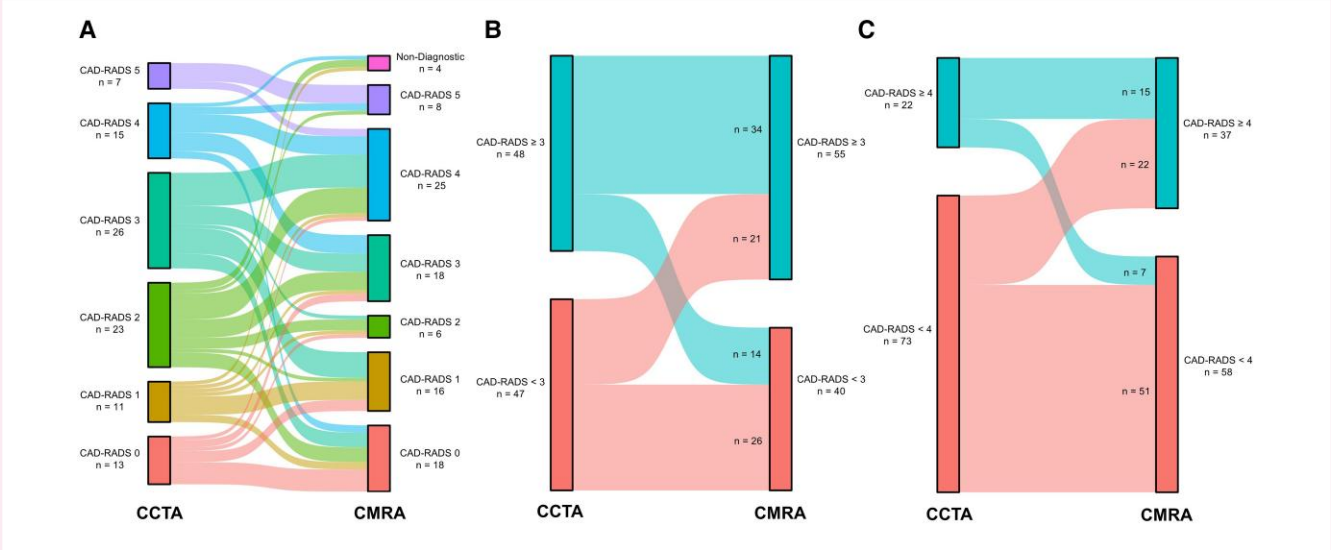

Figure 2 The CAD-RADS classifications for CMRA in comparison with CCTA. (*A*) The change for each CAD-RADS classification. (*B*) Reclassification using a CAD-RADS threshold of ≥3. (*C*) Reclassification using a CAD-RADS threshold of ≥4. CAD-RADS, Coronary Artery Disease-Reporting and Data System; CCTA, Coronary Computed Tomography Angiography; CMRA, Coronary Magnetic Resonance Angiography.

Table 3 Classification of Coronary Magnetic Resonance Angiography (CMRA) CAD-RADS scores as compared with Coronary Computed Tomography Angiography (CCTA), along with sensitivity, specificity, NPV, PPV, and AUC for CAD-RADS threshold ≥ 1, ≥ 2, ≥ 3, and ≥4 on a per-patient basis

Per-patient CAD-RADS analysis						
	Classification agreement	Sensitivity	Specificity	PPV	NPV	AUC
CAD-RADS ≥ 1	0.80 (0.71–0.88)	0.85 (0.76–0.92)	0.46 (0.19–0.75)	0.91 (0.82–0.96)	0.33 (0.13–0.59)	0.66 (0.51–0.80)
CAD-RADS ≥ 2	0.73 (0.63–0.81)	0.75 (0.63–0.84)	0.67 (0.45–0.84)	0.87 (0.76–0.94)	0.47 (0.30–0.65)	0.71 (0.60–0.82)
CAD-RADS ≥ 3	0.63 (0.53–0.73)	0.71 (0.56–0.83)	0.55 (0.40–0.70)	0.62 (0.48–0.75)	0.65 (0.48–0.79)	0.63 (0.53–0.73)
CAD-RADS ≥ 4	0.70 (0.59–0.79)	0.68 (0.45–0.86)	0.70 (0.58–0.80)	0.41 (0.25–0.58)	0.88 (0.77–0.95)	0.69 (0.58–0.80)

95% CIs are expressed in brackets.
AUC, area under the curve; CAD-RADS, Coronary Artery Disease-Reporting and Data System; NPV, negative predictive value; PPV, positive predictive value.

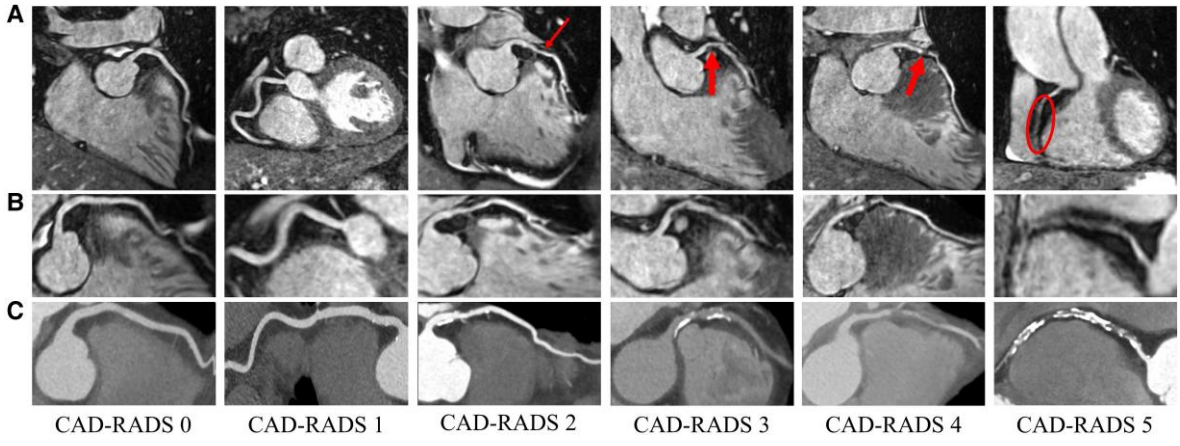

Figure 3 Examples of Coronary Magnetic Resonance Angiography (CMRA) in comparison with Coronary Computed Tomography Angiography (CCTA) at different CAD-RADS classifications. (*A*) CMRA images of the whole heart; red arrows show focal lesions. (*B*) A zoomed CMRA image of the coronary artery. (*C*) CCTA images of the same coronary artery. The LAD is visualized for CAD-RADS 0, 2, 3, and 4, whilst the right coronary artery is shown for CAD-RADS 1 and 5. CAD-RADS, Coronary Artery Disease-Reporting and Data System.

Table 4 Diagnostic performance of Coronary Magnetic Resonance Angiography (CMRA) and Coronary Computed Tomography Angiography (CCTA) using a threshold of CAD-RADS ≥4 (severe stenosis) to determine threshold to invasive coronary angiography and coronary revascularization

Referral to invasive coronary angiography (CAD-RADS ≥ 4)						
	Sensitivity	Specificity	PPV	NPV	Diagnostic accuracy	AUC
CMRA	0.76 (0.55–0.91)	0.74* (0.62–0.84)	0.51 (0.34–0.68)	0.90 (0.79–0.96)	0.75 (0.65–0.83)	0.75 (0.66–0.84)
CCTA	0.56 (0.35–0.76)	0.89* (0.79–0.95)	0.64 (0.41–0.83)	0.85 (0.75–0.92)	0.80 (0.71–0.88)	0.70 (0.58–0.82)
Undergo coronary revascularization (CAD-RADS ≥ 4)						
	Sensitivity	Specificity	PPV	NPV	Diagnostic accuracy	AUC
CMRA	0.75 (0.48–0.93)	0.68* (0.57–0.78)	0.32 (0.18–0.50)	0.93 (0.83–0.98)	0.69 (0.59–0.79)	0.72 (0.61–0.84)
CCTA	0.62 (0.35–0.85)	0.85* (0.75–0.92)	0.45 (0.24–0.68)	0.92 (0.83–0.97)	0.81 (0.72–0.88)	0.74 (0.67–0.80)

CAD-RADS, Coronary Artery Disease –Reporting and Data System; CCTA, Coronary Computed Tomography Angiography; CMRA, Coronary Magnetic Resonance Angiography; NPV, Negative Predictive Value; PPV, Positive Predictive Value.
* Indicates a statistically significant difference.

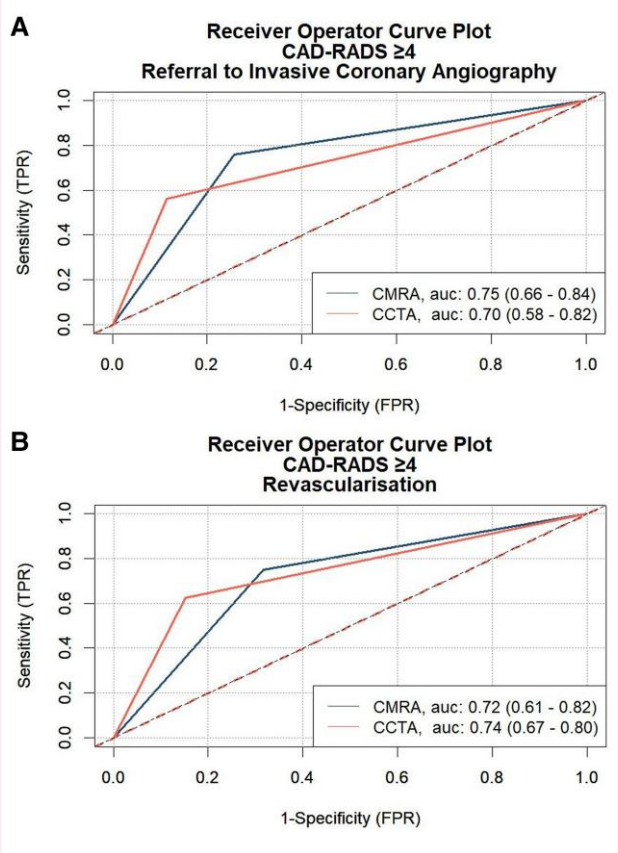

Figure 4 The receiver–operator curves for Coronary Magnetic Resonance Angiography (CMRA) and Coronary Computed Tomography Angiography (CCTA) with respect to referral for invasive coronary angiography (*A*) and coronary revascularization (*B*) using a threshold for referral of severe Coronary Artery Disease (CAD-RADS ≥ 4). CAD-RADS, Coronary Artery Disease-Reporting and Data System

is important towards clinical implementation since a key advance of coronary artery imaging is the ability to not only diagnose obstructive CAD but also to provide reassurance to symptomatic patients in the absence of CAD.

The use of CAD-RADS in CMRA implicitly requires high sub-millimetre spatial resolution to accurately differentiate between the CAD-RADS classifications. Previous studies of CMRA have focussed on coronary stenosis grading, which is not as useful in guiding patient management.[21] In the current era of more restricted use of coronary revascularization and precision medicine, the application of luminal stenosis cut-off values appears less suitable for reporting CMRA findings. As such, use of CAD-RADS should be considered in future studies of CMRA, since its use in CCTA has been shown to offer a clinically useful categorization of CAD with high diagnostic accuracy when compared with ICA[22] and a beneficial impact on medical management.[23] A previous study of CMRA with CAD-RADS has recently been completed, using a spatial resolution of 1.5 mm^3 demonstrating even greater correlation between CCTA and CMRA than shown in our study.[24] Whilst this supports the argument that CAD-RADS can be effectively implemented with CMRA, an improved resolution is likely required for clinical implementation, as has been recommended with CCTA.[16] This will likely require the integration of additional DL-based image reconstruction. This has recently been demonstrated for whole-heart image of paediatric patients, acquired using increased under-sampling and vastly accelerated reconstruction, whilst preserving and perhaps even improving image quality as compared with previous iterations.[19]

More recent CAD-RADS classification using CCTA also incorporates factors such as coronary calcium and total plaque burden, which only to some extent can be investigated with the current iteration of CMRA. However, T1-weighted magnetic resonance coronary plaque imaging has evolved with the promise of detecting high-risk coronary plaque features such as intraplaque haemorrhage, thrombus, and lipid.[25,26] These high-risk plaques provide a high degree of value in predicting future myocardial infarction.[27,28] Therefore, a modification of CAD-RADS to describe the plaque characteristics as visualized using CMRA could be necessary and may improve the predictive value of CAD-RADS beyond that shown in this study. An additional approach may be to integrate other MR-based techniques such as myocardial perfusion imaging and late gadolinium enhancement to provide physiological data and evidence of chronic disease, to better stratify risk and need for onward referral. If this proves

Table 5 Diagnostic performance of Coronary Magnetic Resonance Angiography (CMRA) and Coronary Computed Tomography Angiography (CCTA) using a threshold of CAD-RADS ≥ 3 (moderate stenosis) to determine threshold to invasive coronary angiography and coronary revascularization

Referral to invasive coronary angiography (CAD-RADS ≥ 3)						
	Sensitivity	Specificity	PPV	NPV	Diagnostic accuracy	AUC
CMRA	0.88 (0.69–0.97)	0.53 (0.41–0.65)	0.40 (0.27–0.54)	0.92 (0.80–0.98)	0.62 (0.52–0.72)	0.70 (0.58–0.82)
CCTA	0.80 (0.59–0.93)	0.60 (0.48–0.72)	0.42 (0.28–0.57)	0.89 (0.77–0.96)	0.65 (0.55–0.75)	0.70 (0.59–0.81)
Undergo coronary revascularization (CAD-RADS ≥ 3)						
	Sensitivity	Specificity	PPV	NPV	Diagnostic accuracy	AUC
CMRA	0.88 (0.62–0.98)	0.48 (0.37–0.60)	0.25 (0.15–0.39)	0.95 (0.83–0.99)	0.55 (0.44–0.65)	0.68 (0.55–0.80)
CCTA	0.94 (0.70–1.00)	0.58 (0.47–0.69)	0.25 (0.15–0.39)	0.98 (0.89–1.00)	0.64 (0.54–0.74)	0.76 (0.65–0.87)

CAD-RADS, Coronary Artery Disease–Reporting and Data System; CCTA, Coronary Computed Tomography Angiography; CMRA, Coronary Magnetic Resonance Angiography; NPV, Negative Predictive Value; PPV, Positive Predictive Value.

successful, cardiovascular magnetic resonance has the potential to offer a single comprehensive examination to investigate patients presenting with stable chest pain.

Limitations

Despite improvement in overall image quality, CMRA remains inferior to CCTA in robustness since the image quality was deemed non-diagnostic in 8% of segments of which the distal segments had the highest number of non-diagnostic segments. This is unsurprising given that vessel segments with smaller diameters impose greater demands for both spatial resolution and motion correction to achieve adequate image quality. However, CMRA appears able to visualize comparatively small stenoses within the more proximal segments.

Direct comparison of two non-invasive imaging modalities such as CMRA and CCTA is not optimal and should be interpreted with caution. Although CCTA is considered the preferred first-line non-invasive imaging modality for evaluating CAD, there are challenges in accurately assessing luminal stenosis, especially in those with a high calcium score.[29] Therefore, to further determine the clinical efficacy of CMRA, comparison with invasive angiography as well as larger cohort studies with clinical endpoints is required.

Conclusions

Automated CMRA acquisition with predictable scan times, developed using DL-assisted scan planning, produced high diagnostic image quality in a cohort of patients at risk of CAD. Using CAD-RADS, the CMRA protocol demonstrated moderate to good agreement compared with CCTA. In patients with CAD-RADS ≥ 4 and ≥3, CMRA was as effective as CCTA in predicting referral for ICA and subsequent coronary revascularization.

Supplementary data

Supplementary data are available at *European Heart Journal – Imaging Methods and Practice* online.

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Conflict of interest: K.P.-K. is employed by Siemens Healthcare Limited, Camberley, UK. J.W. is employed by Siemens Healthcare GmbH, Erlangen, Germany.

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Data availability

Data will be made available upon reasonable request from the corresponding author in accordance with the applicable local, national, and European regulations.

Lead author biography

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