Gadobutrol-Enhanced Cardiac Magnetic Resonance Imaging for Detection of Coronary Artery Disease

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ABSTRACT

BACKGROUND Gadolinium-based contrast agents were not approved in the United States for detecting coronary artery disease (CAD) prior to the current studies.

OBJECTIVES The purpose of this study was to determine the sensitivity and specificity of gadobutrol for detection of CAD by assessing myocardial perfusion and late gadolinium enhancement (LGE) imaging.

METHODS Two international, single-vendor, phase 3 clinical trials of near identical design, “GadaCAD1” and “GadaCAD2,” were performed. Cardiovascular magnetic resonance (CMR) included gadobutrol-enhanced first-pass vasodilator stress and rest perfusion followed by LGE imaging. CAD was defined by quantitative coronary angiography (QCA) but computed tomography coronary angiography could exclude significant CAD.

RESULTS Because the design and results for GadaCAD1 (n = 376) and GadaCAD2 (n = 388) were very similar, results were summarized as a fixed-effect meta-analysis (n = 764). The prevalence of CAD was 27.8% defined by a ≥70% QCA stenosis. For detection of a ≥70% QCA stenosis, the sensitivity of CMR was 78.9%, specificity was 86.8%, and area under the curve was 0.871. The sensitivity and specificity for multivessel CAD was 87.4% and 73.0%. For detection of a 50% QCA stenosis, sensitivity was 64.6% and specificity was 86.6%. The optimal threshold for detecting CAD was a ≥67% QCA stenosis in GadaCAD1 and ≥63% QCA stenosis in GadaCAD2.

CONCLUSIONS Vasodilator stress and rest myocardial perfusion CMR and LGE imaging had high diagnostic accuracy for CAD in 2 phase 3 clinical trials. These findings supported the U.S. Food and Drug Administration approval of gadobutrol-enhanced CMR (0.1 mmol/kg) to assess myocardial perfusion and LGE in adult patients with known or suspected CAD.

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MR is a reference standard for assessing ventricular function (1) and for imaging myocardial infarction (MI) (2). In meta-analysis, stress perfusion CMR performs with high diagnostic accuracy, particularly when compared with invasive fractional flow reserve (FFR) (3). The MR INFORM (MR Perfusion Imaging to Guide Management of Patients with Stable Coronary Artery Disease) clinical trial (4) demonstrated that stress perfusion CMR can safely manage patients with stable angina with less revascularization but equivalent patient outcome to an invasive FFR-guided strategy. Large prospective single-center studies such as CE-MARC (Cardiovascular magnetic resonance and single-photon emission computed tomography for diagnosis of coronary heart disease) (5) and multicenter, multivendor studies such as MR-IMPACT (Magnetic Resonance Imaging for Myocardial Perfusion Assessment in Coronary artery disease Trial) (6) and MR-IMPACT II (Magnetic Resonance Imaging for Myocardial Perfusion Assessment in Coronary artery disease Trial II) (7) showed that stress perfusion CMR has good diagnostic performance and is superior or not inferior to single-photon emission computed tomography (SPECT) (5,6,8). Stress perfusion CMR and LGE imaging appear in multiple U.S. and international guidelines (9–11). Despite over 25 years of clinical trials and validations, there was no U.S. Food and Drug Administration (FDA) approval for gadolinium-based contrast agents (GBCAs) for stress perfusion CMR or LGE imaging in the United States prior to the current 2 clinical trials.

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GadaCAD1 and GadaCAD2 (Gadobutrol-enhanced CMR to detect Coronary Artery Disease) were phase 3 clinical trials (NCT01890421 and NCT01890434) designed to evaluate gadobutrol, a multipurpose GBCA, for the detection of CAD and to support regulatory approval for use in CMR in the United States, performed on Siemens CMR scanners (Erlangen, Germany). Gadobutrol (Gadavist Bayer Pharma AG, Leverkusen, Germany) was previously FDA approved for central nervous system magnetic resonance imaging, for magnetic resonance angiography in adult and pediatric patients including term neonates, and for breast magnetic resonance imaging in adult patients. Based on the chemical structure of the gadolinium chelate, gadobutrol is 1 of 3 macrocyclic GBCAs currently on the market. It provides high stability and high relaxivity (12,13).

The specific aim of the GadaCAD clinical trials was to assess the diagnostic accuracy of gadobutrol-enhanced vasodilator stress perfusion CMR and LGE imaging to detect CAD in 2 nearly identical studies using an independent blinded read. The clinical trials had requirements from the FDA to meet or exceed specific diagnostic accuracy criteria for sensitivity and specificity. Gadobutrol-enhanced perfusion CMR had to have higher sensitivity than unenhanced stress cine CMR wall motion for CAD detection. The standard of reference defining CAD was invasive coronary angiography, but coronary computed tomography angiography (CTA) could be used to exclude CAD.

METHODS

STUDY POPULATION. Inclusion criteria required that subjects were undergoing evaluation for known or suspected CAD based on typical or atypical chest discomfort, were age ≥18 years, and were willing to undergo the study procedures. Female subjects of child-bearing potential had to agree to use medically approved birth control during the study. The main exclusion criteria were contraindications to CMR, contraindications to vasodilators, suspected clinical
instability during the study period, revascularization between CMR and coronary angiography, prior coronary artery bypass graft, acute coronary syndrome, or decompensated heart failure <14 days prior to inclusion, certain arrhythmias, uncontrolled hypertension, baseline hypotension <90 mm Hg, and estimated glomerular filtration rate <30 ml/min/m². Full inclusion and exclusion criteria are available in Supplemental Table 1.

All subjects signed written informed consent. The studies were conducted according to the Declaration of Helsinki, the principles of Good Clinical Practice, and were approved by the Health Authorities and local Ethics Committee of each participating institution.

**EFFICACY ENDPOINTS.** There were 3 coprimary endpoints regarding detection of CAD defined as a ≥50% and ≥70% QCA stenoses in 2 separate analyses: 1) the sensitivity for 2 of 3 readers had to be high enough that the lower bound of the 95% confidence interval (CI) was >60%; 2) the specificity for 2 of 3 readers had to be high enough that the lower bound of the 2-sided 95% CI was >55%; and 3) gadobutrol-enhanced stress/rest perfusion and LGE CMR had to have higher sensitivity than unenhanced wall motion CMR images performed at stress and rest. A CMR study was categorized as abnormal if either stress perfusion or LGE was abnormal with 1 exception. If stress and rest perfusion were abnormal but
LGE was normal, the perfusion finding was categorized as an artifact and the study as normal.

**Imaging and vasodilator stress methods.** The study-specific procedures are summarized in Figure 1 and Table 1. The study used Siemens 1.5- and 3.0-T CMR scanners running the “Cardiac Dot software” that assists with image acquisition. Imaging included segmented cine CMR, real-time cine CMR at baseline and during stress, vasodilator stress and rest first-pass perfusion CMR, and single-shot LGE imaging about 5 min after rest perfusion, followed by segmented LGE imaging (Table 1). Magnitude (14) and phase-sensitive inversion recovery LGE images were reconstructed (15). The inversion time suggested by protocol could be adjusted by the technologist. Gadobutrol 0.05 mmol/kg was injected at 4 ml/s during vasodilator stress and again about 10 min later for rest perfusion (total dose of 0.1 mmol/kg body weight). No additional contrast was given for LGE imaging. The vasodilator could be either adenosine (140 µg/kg/min infusion for up to 6 min) or regadenoson (0.4 mg intravenous injection) based on site specific availability or preference. The rationale for some of the CMR methods are detailed in the Supplemental Appendix.

**Core laboratory analyses.** CMR studies were read centrally, independently, and blinded to all non-imaging data by a total of 6 experts with 5 years of experience; 3 readers were assigned to each trial. Image analysis was through a study-specific image review program linked to the core laboratory image archive. Stress perfusion, rest perfusion, and LGE were summarized using the 17-segment American Heart Association model, but omitted the apical segment. Segments were read as normal, reversible perfusion defect (stress only), fixed perfusion (stress and rest), or mixed perfusion (reversible and fixed components). For each reader, a study was abnormal if ≥1 segment was not normal. Cine wall motion was interpreted on a different day.

QCA was performed at a central core laboratory by the consensus of 2 experts who were blinded to all other data. Coronary artery stenoses were measured in the left main, left anterior descending (LAD), circumflex, and right coronary arteries if ≥2 mm in diameter and were compared with corresponding proximal reference segments (Medis, Leiden, the Netherlands). The standard of reference was set at ≥70% and at ≥50% diameter QCA stenosis. A blinded, core laboratory assessment of coronary CTA could exclude CAD in the absence of significant coronary calcium and stenosis.

**Statistical analysis.** Generally, 2 adequate and well controlled trials are required to support FDA approval of medications. The sample size for stress perfusion CMR was determined by an assumed sensitivity of 75% with a lower bound of the 95% CI of 60% and an assumed specificity of 67% with a lower bound of the 95% CI of 55% and a 2-sided α-level of 0.05 and 90% power. These assumptions required a sample size that included 110 subjects with CAD and 180 subjects without CAD. Because the prevalence of disease could not be guaranteed, simulations were considered over a range of prevalence from 30% to 60% leading to estimates of 375 subjects per trial for approximately 80% power and assumed a disease prevalence of 40% to 55%.

Efficacy analysis used data from all subjects who underwent pharmacological stress, had complete electronic clinical report forms, had adequate

| TABLE 1 Typical CMR Image Acquisition Parameters |
|-----------------------------------------------|
| Field strength | 1.5-T | 1.5-T | 1.5- and 3-T | 1.5- and 3-T |
| Sequence | Saturation recovery, SSFP | Saturation recovery, FLASH | Inversion recovery* | Inversion recovery* |
| Parallel imaging | ePAT 2, GRAPPA with external reference lines | ePAT 2, GRAPPA with external reference lines | IPAT 2, GRAPPA, internal reference lines | IPAT 2, GRAPPA, internal reference lines |
| Slice orientation | Short axis x 3 slices | Short axis x 3 slices | Short and long axis views | Short axis views (with possible additional views) |
| Spatial resolution | 2.4 x 2.9 x 8.0 mm | 1.9 x 2.5 x 8.0 mm | 2.1 x 2.1 x 8.0 mm | 1.3 x 1.3 x 8.0 mm |
| Temporal resolution, ms | ~110 ms | ~110 ms | ~200 ms | ~160 ms |
| Echo time, ms | ~1.0 ms | ~1.0 ms | ~1.0 ms | ~2.0 ms |
| Repetition time, ms | ~2.7 ms | ~2.9 ms | ~2.8 ms | ~5.9 ms |
| Inversion time, ms | 100 ms | 100 ms | ~300-380 ms | ~300-380 ms, optimized per patient |
| Trigger pulse | Every heartbeat | Every heartbeat | Every other heartbeat | Every other heartbeat |

Typical acquisition parameters are listed; increases in field of view for larger patients will affect values for individual patients. Repetition time was estimated from temporal resolution and number of lines of k-space acquired. Inversion time ranges were modified during GadaCAD1 and thus have a broad range, but were generally longer at 3-T than for 1.5-T. *Magnitude and phase sensitive reconstruction (PSIR). ePAT = parallel image acceleration factor; FLASH = fast low angle shot; GRAPPA = Generalized Autocalibrating Partially Parallel Acquisitions; iPAT = parallel image acceleration factor; SSFP = steady state free precession.
TABLE 2 Demographics, Type of Stress, and Adverse Events

| Subcategory                           | GadaCAD1 | GadaCAD2 |
|---------------------------------------|----------|----------|
| Sample size                           | 376      | 388      |
| Age, yrs                              | 58.5 ± 12.0 | 58.9 ± 10.2 |
| Male                                  | 260 (69.1) | 239 (61.4) |
| Ethnicity                             |          |          |
| Hispanic                              | 5 (1.3)  | 22 (5.7) |
| Non-Hispanic                          | 365 (97.1) | 366 (94.1) |
| Other                                 | 6 (1.6)  | 1 (0.3)  |
| Race                                  |          |          |
| White                                 | 277 (73.7) | 261 (67.1) |
| Black                                 | 2 (0.5)  | 67 (17.2) |
| Asian                                 | 94 (25.0) | 48 (12.3) |
| Other                                 | 3 (0.8)  | 0 (0.0)  |
| Country/region                        |          |          |
| Europe                                | 256 (68.1) | None     |
| United States                         | 28 (7.4)  | 291 (75.0) |
| Korea                                 | 91 (24.2) | None     |
| Singapore                             | None     | 22 (5.7) |
| Canada                                | None     | 18 (4.6) |
| Australia/New Zealand                 | 1 (0.3)  | 57 (14.7) |
| Risk factors                          |          |          |
| Body mass index, kg/m²                | 27.1 ± 4.6 | 29.3 ± 5.3 |
| Hypertension                          | 228 (62.0) | 251 (65.2) |
| Diabetes                              | 89 (24.2) | 108 (28.1) |
| Dyslipidemia                          | 230 (62.5) | 271 (70.4) |
| Family history CAD                    | 143 (38.9) | 151 (39.2) |
| Smoking                               | 90 (24.5) | 53 (13.8) |
| eGFR, ml/min/1.73 m²                  | 84.2 ± 18.4 | 82.0 ± 18.7 |
| Prior CAD                             |          |          |
| MI                                    | 47 (12.8) | 63 (16.4) |
| PCI                                   | 10 (2.7)  | 24 (6.2)  |
| PCI with stent                        | 59 (16.0) | 74 (19.2) |
| CABG                                  | 0 (0.0)   | 0 (0.0)   |
| Type of stress CMR                    |          |          |
| 1.5-T                                 | 183 (48.7) | 275 (70.9) |
| 3.0-T                                 | 193 (51.3) | 113 (29.1) |
| Adenosine                             | 315 (83.8) | 201 (51.8) |
| Regadenoson                           | 61 (16.2) | 187 (48.2) |
| Adverse events prior to gadobutrol    |          |          |
| Any AE                                | 76 (17.8) | 142 (29.7) |
| Stressor-related AE                   | 64 (15.0) | 136 (28.5) |
| Adverse events <6 h after gadobutrol  |          |          |
| Any AE                                | 48 (11.3) | 82 (17.2) |
| Stressor-related AE                   | 20 (4.7)  | 49 (10.3) |
| Gadobutrol-related AE                 | 3 (0.7)   | 1 (0.2)   |

Values are n, mean ± SD, or n (%). Serious adverse events (AE) related to gadobutrol; death (0), anaphylaxis (1).

CABG = coronary artery bypass graft; CAD = coronary artery disease; CMR = cardiac magnetic resonance; eGFR = estimated glomerular filtration rate; GadaCAD = Gadobutrol-enhanced CMR to detect Coronary Artery Disease; MI = myocardial infarction; PCI = percutaneous coronary intervention.

unenhanced and gadobutrol-enhanced CMR as determined by the core laboratory, and had complete standard of reference images. The analysis was performed on a per-subject basis.

Subject characteristics are presented as mean ± SD if normally distributed, and median (25%, 75% CI) if not normally distributed. Diagnostic accuracy is summarized by sensitivity, specificity, area under the curve, positive predictive value, and negative predictive value. The 95% Clopper-Pearson CI were calculated. Receiver-operator characteristic (ROC) curves were determined from exact results at thresholds ranging from a 20% QCA stenosis to a 95% QCA stenosis. ROC curves were compared with the DeLong method (Supplemental Appendix).

Results were summarized at the individual reader level, the clinical trial level, and as a meta-analysis combining both clinical trials. To provide an overall summary result, a fixed-effect meta-analysis method was used to summarize diagnostic accuracy statistics for the 6 readers. This methodology was chosen as the 2 clinical trials had similar sensitivity and specificity, nearly identical methodology, the same study drug and dose, the same standard of reference methods and core laboratories, and populations with similar prevalence of CAD. At the clinical trial level, the majority read was used to determine whether the study was abnormal or normal on a patient-by-patient basis. Majority read meant the result by either 2 or 3 readers who came to the same determination of a study being normal or abnormal.

RESULTS

DEMOGRAPHICS. The GadaCAD studies were multicenter, multinational studies enrolling patients with an overall sample size for efficacy of 376 subjects in GadaCAD1 and 388 subjects in GadaCAD2. For GadaCAD1 and GadaCAD2, safety was assessed in the 426 and 478 subjects who received gadobutrol. Inadequate CMR image quality led to exclusion of 17 (4.0%) and 26 (5.4%) subjects in GadaCAD1 and GadaCAD2, respectively, while suitability of coronary angiography or CTA led to exclusion of 28 (6.6%) and 45 (9.4%) subjects, respectively (Supplemental Table 2). The demographic characteristics of the study participants are summarized in Table 2.

PREVALENCE OF CAD. In GadaCAD1, 12.8% of subjects had a history of MI compared with 16.4% in GadaCAD2 (Table 2). Fewer patients in GadaCAD1 had a history of prior percutaneous coronary intervention (PCI) (18.7%) than in GadaCAD2 (25.4%).

The post-testing prevalence of CAD was 28.7% in GadaCAD1 and 27.1% in GadaCAD2 (Table 2) as defined by the presence of at least 1 coronary artery stenosis ≥70% by core laboratory QCA. In GadaCAD1, the standard of reference was invasive angiography in 79.0% (297 of 376 subjects) and in GadaCAD2 was 68.0% (264 of 388 subjects) and coronary CTA in remaining subjects.

Of the 108 subjects in GadaCAD1 with a ≥70% QCA stenosis, 68 had single-vessel CAD and 40 had multivessel CAD defined as ≥70% QCA stenosis in 2 or more coronary arteries. Of the 105 subjects in GadaCAD2 with a ≥70% QCA stenosis, 58 had single-vessel
CAD and 47 had multivessel CAD. The proportions of subjects with significant CAD, without significant CAD, with single-vessel CAD, and with multivessel disease were similar for the 2 trials.

For participants with a \( \geq 50 \) QCA stenosis (Table 3), many patients had intermediate-severity stenoses in the range between 50% to <70% QCA stenosis. In GadaCAD1, 33 of 141 subjects (23.4%) had intermediate-severity stenoses and in GadaCAD2 the proportion was 45 of 150 subjects (30.0%).

**EXAMPLE OF IMAGE QUALITY.** Figure 2 depicts image quality from a participant who had no history of MI but was found to have 2 small subendocardial infarctions by LGE imaging and vasodilator-inducible perfusion defects that were more extensive than the MIs (Videos 1, 2, 3, 4, 5, and 6).

**DIAGNOSTIC ACCURACY VERSUS QCA STENOSIS.**

The meta-analysis (Table 4, Figure 3) of both clinical trials and all 6 readers provides a vantage point from which to compare other levels of analysis, including at the trial level and at the individual-reader level. Against a standard of reference of a \( \geq 70 \) QCA stenosis, the sensitivity was 78.9% with a lower limit of the 95% CI at 75.5% in the meta-analysis combining both clinical trials. The specificity was 86.8% with a lower limit of the 95% CI at 85.0%. The area under the curve was 0.871 and corresponded to positive predictive value and negative predictive value of 69.7% and 91.4%, respectively. The sensitivity for multi-vessel CAD was 87.4% (95% CI: 77.0% to 97.2%) and for single-vessel CAD was 73.05 (95% CI: 62.1% to 84.0%).

Overall, the combined results represented the sensitivity and specificity of the individual readers quite well (Figure 3). In general, the sensitivity for detecting a \( \geq 70 \) QCA stenosis was slightly higher in GadaCAD1 (81.5%) than GadaCAD2 (77.1%) as summarized by the majority read (Table 4). Individually, 5 of the 6 readers were within 2.9% of the meta-analysis sensitivity and were within 4.8% of the meta-analysis specificity. In pairwise comparisons of ROC curves, there were no significant differences between readers within either clinical trial. The Central Illustration summarizes the main study methods and main study results.

For detection of a \( \geq 50 \) QCA stenosis, the sensitivity of the meta-analysis decreased to 64.6%, while specificity was minimally different from the results using a \( \geq 70 \) QCA stenosis (Tables 4 and 5). For GadaCAD1 and GadaCAD2 analyzed as individual trials, sensitivity was within 2.1% and specificity was within 1.1% of the combined results. At the reader level, 5 of 6 readers had a sensitivity within 3.3% of the meta-analysis and all 6 readers had a specificity within 3.5% of the meta-analysis.

**SENSITIVITY ANALYSIS FOR INTERMEDIATE STENOSIS (50% TO <70% BY QCA).** By ROC analysis, the optimal threshold for detecting CAD was a \( \geq 67 \) QCA stenosis in GadaCAD1 and a \( \geq 63 \) QCA stenosis in GadaCAD2 (Supplemental Table 3). To further analyze the decrease in sensitivity between a \( \geq 70 \) QCA stenosis and a \( \geq 50 \) QCA stenosis, 78 subjects had an intermediate-severity stenosis defined as \( \geq 50 \) to <70% QCA stenosis (Table 3). In GadaCAD1, 18% of subjects with an intermediate stenosis had an abnormal CMR, whereas in GadaCAD2, 29% of subjects with an intermediate stenosis had an abnormal CMR.

**SUMMARY OF STUDY ENDPOINTS.** The meta-analysis combining results from the 6 readers met all study endpoints for both definitions of CAD: \( \geq 70 \) QCA stenosis and \( \geq 50 \) QCA stenosis (Table 4). The lower bound of the 95% CI exceeded the pre-defined thresholds for both sensitivity and specificity. In addition, the sensitivity of gadobutrol-enhanced perfusion and LGE CMR was better than vasodilator-induced wall motion abnormalities (Supplemental Table 4). With significant CAD defined by a 70% QCA stenosis, all 6 readers met every endpoint for sensitivity, specificity, and the comparison with stress cine wall motion (Supplemental Table 4). When defining CAD at a 50% QCA stenosis, 5 of 6 readers did not meet or exceed the lower limit of the sensitivity endpoint but all readers met all other study endpoints (Table 5).

**ADVERSE EVENTS.** The great majority of adverse events were stressor-related (Table 2). There were no deaths. Of the 4 adverse events related to gadobutrol, only 1 was considered serious: an anaphylactic reaction.
This patient had multivessel coronary stenoses and no clinically recognized prior myocardial infarction (MI), a 95% right coronary artery stenosis, 70% diagonal stenosis, and a 50% obtuse marginal stenosis. Nonmotion-corrected stress perfusion images (bottom) show an obvious inferior and inferolateral perfusion defect (green arrows) and a second less severe anterolateral perfusion defect (red arrows). The perfusion defects were more extensive than the small subendocardial MI detected with LGE imaging (middle). See Videos 1, 2, 3, 4, 5, and 6, including the cine CMR (top), which showed a subtle inferior wall motion abnormality and perfusion images. Abbreviations as in Figure 1.
The GadaCAD1 and GadaCAD2 studies were pivotal, phase 3 clinical trials that led to FDA approval of gadobutrol-enhanced CMR to assess stress and rest myocardial perfusion and LGE in adult patients with known or suspected CAD. The GadaCAD studies had high diagnostic accuracy for detection of CAD. The results were consistent at the individual reader level, the clinical trial level, and at the meta-analysis level.

### TABLE 4

| Study                  | Data Level       | Sample Size | CAD(+) | CAD(-) | Sensitivity, % (95% CI) | Specificity, % (95% CI) | AUC   | PPV, % | NPV, % | TP     | TN     | FP     | FN     |
|------------------------|------------------|-------------|--------|--------|-------------------------|-------------------------|-------|--------|--------|--------|--------|--------|--------|
| GadaCAD1 and 2         | Meta-analysis    | 764         | 213    | 551    | 78.9 (75.5–82.0)         | 86.8 (85.0–88.3)         | 0.871 | 69.7   | 91.4   | 168    | 478    | 73     | 45     |
| GadaCAD1               | Clinical trial   | 376         | 108    | 268    | 81.5 (72.9–88.3)         | 89.6 (85.3–92.9)         | 0.880 | 75.9   | 92.3   | 88     | 240    | 28     | 20     |
| GadaCAD2               | Clinical trial   | 388         | 105    | 283    | 77.1 (67.9–84.8)         | 86.6 (82.0–90.3)         | 0.861 | 68.1   | 91.0   | 85     | 245    | 38     | 24     |
| GadaCAD1               | Reader 1         | 376         | 108    | 268    | 89.8 (82.5–94.8)         | 82.8 (77.8–87.2)         | NA    | 67.8   | 95.3   | 97     | 222    | 46     | 11     |
| GadaCAD1               | Reader 2         | 376         | 108    | 268    | 79.6 (70.8–86.8)         | 91.0 (87.0–94.2)         | NA    | 78.2   | 91.7   | 86     | 244    | 24     | 22     |
| GadaCAD1               | Reader 3         | 376         | 108    | 268    | 78.7 (69.8–86.0)         | 90.7 (86.5–93.9)         | NA    | 77.3   | 91.4   | 85     | 243    | 25     | 23     |
| GadaCAD2               | Reader 4         | 388         | 105    | 283    | 77.1 (67.9–84.8)         | 82.0 (77.0–86.3)         | NA    | 61.4   | 90.6   | 81     | 232    | 51     | 24     |
| GadaCAD2               | Reader 5         | 388         | 105    | 283    | 71.4 (61.8–79.8)         | 87.3 (82.8–90.9)         | NA    | 67.6   | 89.1   | 75     | 247    | 36     | 30     |
| GadaCAD2               | Reader 6         | 388         | 105    | 283    | 76.2 (66.9–84.0)         | 86.9 (82.4–90.6)         | NA    | 68.4   | 90.8   | 80     | 246    | 37     | 25     |

AUC = area under the curve; CI = confidence interval; FN = false negative; FP = false positive; NPV = negative predictive value; PPV = positive predictive value; TN = true negative; TP = true positive; other abbreviations as in Table 3.

### DISCUSSION

The GadaCAD1 and GadaCAD2 studies were pivotal, phase 3 clinical trials that led to FDA approval of gadobutrol-enhanced CMR to assess stress and rest myocardial perfusion and LGE in adult patients with known or suspected CAD. The GadaCAD studies had high diagnostic accuracy for detection of CAD. The results were consistent at the individual reader level, the clinical trial level, and at the meta-analysis level.
combining the 2 trials. First-pass perfusion and LGE CMR with gadobutrol (0.1 mmol/kg dose, divided into 2 separate and equal injections) is now indicated in the United States to assess stress and rest myocardial perfusion and myocardial infarction in adult patients with known or suspected CAD.

The results of GadaCAD1 and GadaCAD2 are in accord with meta-analyses of CMR stress perfusion (3), are comparable to the large CE-MARC study (5), and are a slightly better than the MR IMPACT clinical trials (6,7). In the European Society of Cardiovascular Radiology MRCT registry, stress perfusion represents ~25% of CMR scans performed and had few moderate or severe adverse events (16). Stress perfusion CMR risk stratifies patients with stable angina in the multicenter SPINS (Stress CMR Perfusion Imaging in the United States) study (17), a negative CMR has low long-term cardiac events (18), and stress perfusion CMR has low spending on subsequent ischemia testing (19), a finding also applicable to European economics (20).

A prior clinical trial aimed at getting approval for a different GBCA to image MI (21) did not make it through U.S. regulatory processes. Although the MR IMPACT I and II clinical trials (6,7) brought approval in several European countries, these studies did not succeed in the FDA regulatory process, which appeared to have focused on a 50% QCA stenosis, a factor that may have contributed to low apparent sensitivity as explained in subsequent paragraphs. As a multivendor study, MR IMPACT II had a more complicated trial design compared with the single-vendor GadaCAD studies, but had superior diagnostic accuracy compared with SPECT (8).
Arai et al. has important clinical implications (17, 22). Multiple (4) extended this concept to managing patients based on physiological significance of the stenosis by FFR (25–29). The MR INFORM study (4) extended this concept to managing patients based on stress perfusion CMR. MR INFORM was an unblinded, international, multicenter, prospective, randomized, clinical-effectiveness trial. CMR was noninferior to invasive FFR with respect to major adverse cardiac events. Because the CMR strategy had significantly fewer coronary revascularization procedures than invasive FFR, the CMR strategy has potential to reduce costs.

The large number of intermediate-severity stenoses between 50% and <70% may have contributed to the relatively low sensitivity for a ≥50% QCA stenosis in the GadaCAD studies. It is widely accepted that most 50% to <70% stenoses are not functionally significant (30). In a post hoc analysis of the GadaCAD data, the proportion of intermediate coronary stenoses that led to abnormal CMR scans was comparable to the fraction of intermediate-severity stenoses in the FAME (Fractional Flow Reserve Versus Angiography for Multivessel Evaluation) and DEFERR (Deferral of percutaneous coronary intervention) studies that caused abnormal invasive FFR (30, 31).

Although stress perfusion CMR has generally used 50% to 100% higher GBCA doses (32) than other indications, the GadaCAD studies have proven that single-dose gadobutrol (0.1 mmol/kg) is sufficient to evaluate CAD (32). A dose ranging study concluded that 0.1 mmol/kg of gadopentetate dimeglumine was as efficacious as higher doses (33). For the GadaCAD studies, the gadobutrol dose was based on the results of a phase 2 clinical trial (Myocardial Perfusion MRI; NCT01490294) that did not reveal benefit of increasing the dose to 0.2 mmol/kg, but did show benefit compared with a dose of 0.05 mmol/kg. The published data does not support a dose-related tendency for higher sensitivity for stress-perfusion CMR at 0.2 mmol/kg (5, 6, 34–38) versus 0.15 mmol/kg (7, 39–41) and versus 0.1 mmol/kg (42–45) total doses of GBCA. The Supplemental Materials describe methods aimed at obtaining diagnostic quality images with the dose of contrast used.

The study did not recommend or exclude aminophylline to reverse the vasodilators. Aminophylline is not generally needed for adenosine stress due to the short half-life, but could be considered to get closer to “rest” perfusion after regadenoson to improve distinction of artifacts from perfusion defects. LGE imaging is considered the most accurate way to detect MI and improves interpretation of stress perfusion CMR (46).

**STUDY LIMITATIONS.** A QCA reference to define CAD is imperfect but practical for large-scale recruitment. However, the 70% stenosis threshold is widely used.
to infer the presence of hemodynamic significance of the obstruction. Although FFR might have been a more ideal reference standard, only about 3% of subjects in the GadaCAD studies had FFR performed clinically in a post-study survey (unpublished data, A. Arai, March 2019). In the United States, invasive FFR utilization remains relatively low despite clinical trial evidence (27–29).

The GadaCAD trials did not test a higher dose of gadobutrol or different specific GBCA so the results should not be extrapolated beyond what was studied. The GadaCAD trials were not designed to differentiate diagnostic accuracy of different image acquisition sequences or magnetic field strength. The studies allowed use of adenosine or regadenoson as a vasodilator due to divergent geographic preferences or regulatory approval status. The study did not randomize adenosine and regadenoson and, thus, was not designed to compare these agents.

Despite methods aimed to obtain identical slices for stress and rest perfusion, matching was not always perfect (Figure 2), but LGE images can also be used to help interpret stress perfusion images (46).

CONCLUSIONS

Gadobutrol-enhanced CMR has high diagnostic accuracy for detecting CAD and is now FDA approved at a dose of 0.1 mmol/kg to assess myocardial perfusion and LGE in adults with known or suspected CAD.

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PERSPECTIVES

COMPETENCY IN PATIENT CARE AND PROCEDURAL SKILLS: Stress perfusion CMR imaging with gadobutrol can be utilized to assess left ventricular function, stress and rest perfusion, and the transmural extent of MI in adults with known or suspected CAD. Adverse and side effects of stress perfusion CMR are dominated by those of the vasodilator agent.

TRANSLATIONAL OUTLOOK: Additional prospective studies are needed to compare the sensitivity, specificity, predictive value, advantages, and limitations of gadobutrol-enhanced CMR for assessment of CAD in specifically defined subpopulations.

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**KEY WORDS** coronary artery disease, CMR, gadobutrol, myocardial infarction, myocardial perfusion

**APPENDIX** For an expanded Methods section, supplemental tables, and videos, please see the online version of this paper.