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Comparison of 3D Free-Breathing Coronary MR Angiography and 64-MDCT Angiography for Detection of Coronary Stenosis in Patients with High Calcium Scores

Xin Liu¹, Xihai Zhao², Jie Huang³, Christopher J. Francois¹, David Tuite¹, Xiaoming Bi⁴, Debiao Li^{1,5}, and James C. Carr¹

¹Department of Radiology, Northwestern University, 448 E Ontario St., Ste. 700, Chicago, IL 60611

²Department of Radiology, PLA General Hospital, Beijing 100853, China

³Department of Preventive Medicine, Northwestern University, Chicago, IL

⁴Siemens Medical Solutions, Chicago, IL

⁵Department of Biomedical Engineering, Northwestern University, Chicago, IL

Abstract

OBJECTIVE—The objective of our study was to compare the diagnostic performance of coronary MR angiography (MRA) and 64-MDCT angiography (MDCTA) for the detection of significant stenosis (≥ 50%) in patients with high calcium scores.

MATERIALS AND METHODS—Eighteen patients (12 men, six women; mean age, 56 y; age range, 38–77 y) who had at least one calcified plaque with a calcium score of > 100 underwent coronary MRA and conventional coronary angiography (CAG) within 2 weeks of MDCTA. Coronary MRA image quality of the calcified segments was assessed by two observers in consensus on a 4-point scale (1 = not visible, 2 = poor, 3 = good, 4 = excellent) using a 10-segment model from the modified American Heart Association classification. Three experienced radiologists, unaware of the results of conventional CAG, independently assessed for the presence of significant stenosis on MDCTA images and the corresponding MRA images. Receiver operating characteristic (ROC) curves were calculated for each reader using conventional CAG as the gold standard.

RESULTS—Thirty-three calcified plaques with a calcium score of > 100 were detected on MDCTA in the 18 patients. The coronary segments with nodal calcification ($n = 17$) showed a higher mean image quality score than the segments with diffuse calcification ($n = 16$) (3.47 ± 0.62 vs 2.94 ± 0.77 , respectively; $p < 0.05$). Of the 33 coronary segments with calcification, 12 significant stenoses were identified on conventional CAG. The sensitivity, specificity, and area under the ROC curve (AUC) for MRA and MDCTA, respectively, were as follows: reader 1, 75%, 81%, 0.82 versus 75%, 48%, 0.68; reader 2, 83%, 71%, 0.82 versus 67%, 52%, 0.63; and reader 3,

83%, 71%, 0.85 versus 83%, 43%, 0.65, respectively. The average AUC of MRA for the three readers was significantly higher than that of MDCTA ($p = 0.030$).

CONCLUSION—Coronary MRA has higher image quality for coronary segments with nodal calcification than for coronary segments with diffuse calcification. Coronary MRA has better diagnostic performance than coronary MDCTA for the detection of significant stenosis in patients with high calcium scores.

Keywords

coronary angiography; coronary arteries; coronary artery disease; coronary artery stenosis; MDCT angiography; MR angiography

Coronary artery disease (CAD) is one of the leading causes of mortality in industrialized countries. Conventional coronary angiography (CAG) remains the gold standard for the detection of CAD. However, conventional CAG is an invasive and expensive procedure with a small risk of serious complications. Furthermore, only one third of these procedures are performed in conjunction with an interventional therapeutic procedure [1]. Therefore, a noninvasive technique for the detection of CAD is highly desirable for patients with a low to intermediate pretest probability of CAD, whereas direct referral for conventional CAG may still be preferred for patients with a high pretest probability.

Over the past decade, coronary MR angiography (MRA) and MDCT angiography (MDCTA) have emerged as possible alternative noninvasive coronary artery imaging techniques [2]. Previous comparative studies have shown that coronary MDCTA has a higher diagnostic accuracy than MRA in the detection of significant coronary artery stenosis [3-5]. Furthermore, coronary CT angiography (CTA) with 64-MDCT has become a routine clinical test because of its high diagnostic accuracy in identifying significant coronary stenosis [6, 7]. However, coronary MDCTA is limited in its assessment of coronary arteries with moderate and severe calcifications [8, 9]. In addition, the results of recent studies by Wang et al. [10] and Ramakrishna et al. [11] showed that approximately 50-70% of all coronary artery plaques are calcified in patients with asymptomatic or suspected CAD. This high prevalence of calcification further hinders coronary MDCTA from replacing invasive angiography in the foreseeable future.

Because MRI does not suffer from beam-hardening artifact caused by high-density calcification, coronary MRA can potentially depict the lumen of calcified coronary arteries. At present, coronary MRA with steadystate free precession (SSFP) is regarded as an increasingly advantageous approach to coronary MRA with its relatively high signal-to-noise ratio and good ability to image the coronary arteries [2, 12, 13]. To our knowledge, there have been no studies assessing the diagnostic capability of coronary MRA with SSFP for the detection of coronary stenosis in patients with high calcium scores. The purpose of this study was to compare the diagnostic performance of coronary MRA and MDCTA in the detection of significant stenosis caused by moderate and severe calcifications using conventional CAG as the gold standard.

Materials and Methods

Patient Population

This study was approved by the institutional review board, and informed consent was obtained from each patient before entry in the study. The study population consisted of outpatients who had undergone coronary MDCTA examination due to atypical angina or nonspecific chest pain from March 2006 to May 2007. Patients were recruited for coronary MRA if they had at least a single coronary calcified plaque with a calcium score of > 100 . Patients were excluded if they had known contraindications to MRI (i.e., claustrophobia, pacemaker, aneurysm clip or intraauricular metallic implant, coronary artery bypass graft, and coronary artery stent).

Thirty-two eligible patients were recruited for the coronary MRA section of the study within 1–3 days after MDCTA examination. Twenty-seven patients (19 men and eight women; mean age, 58 y; age range, 38–79 y) successfully completed the MRA study. MRA studies could not be completed because of failed respiratory gating in three patients and failed ECG gating in two patients. Eighteen of the 27 patients subsequently underwent conventional CAG 3–10 days (mean, 6 days) after the MRA study.

There were no clinical events or medication changes recorded between examinations. Patients who had a heart rate of > 70 beats per minute (bpm) at rest received an oral β -blocker (25–50 mg) or IV metoprolol (5 mg) to decrease their heart rate before both the MDCTA and MRA examinations. The difference in heart rate between the MDCTA and MRA studies was < 5 bpm. Sublingual or IV nitroglycerine (5 mg) was used in both coronary MDCTA and MRA to achieve maximal coronary vasodilation in all patients.

Coronary MDCTA

Coronary MDCTA was performed and calcium scores were obtained using a 64-MDCT scanner (Somatom Sensation Cardiac 64, Siemens Medical Solutions). An initial unenhanced ECG-gated scan was obtained for coronary calcium scoring (collimation, 24×0.6 mm; pitch, 0.2; tube current, 300 mAs; tube voltage, 120 kV; slice thickness, 3 mm; threshold for calcium detection, 130 H; kernel, B30f). After the calcium scoring scan, a bolus of 82 ± 12 mL (mean $\pm$ SD; range, 65–105 mL) of contrast agent (iohexol [Omnipaque, GE Healthcare], 350 mg I/mL) was injected IV at a rate of 5 mL/s, followed by a 50-mL saline chaser bolus. Scanning started automatically as soon as the intensity in the ascending aorta reached a predefined threshold of 100 H. The detector collimation was 32×0.6 mm; tube rotation speed, 330 milliseconds per rotation; pitch, 0.2–0.3; tube voltage, 120 kV; effective tube current, 750–850 mAs; and voxel size, $0.6 \times 0.6 \times 0.75$ mm³. The temporal resolution was variable between 83 and 165 milliseconds according to the heart rate of the patient. Axial images were reconstructed with a B25f kernel and a slice thickness of 0.75 mm (increment, 0.4 mm) at the optimal ECG phases with minimum motion artifacts for each main branch of the coronary arteries.

Coronary MRA

All coronary MRA studies were performed on a 1.5-T scanner (HD TwinSpeed, GE Healthcare; or Magnetom Avanto, Siemens). A dedicated cardiac 8-element phased-array coil and a body 6-element phased-array coil were used in the two scanners, respectively. Eighteen patients were scanned on the GE Healthcare scanner using a volume-targeted method in which the major coronary arteries are imaged separately by several targeted, thin 3D slabs [14]. The other nine patients were scanned on the Siemens scanner using a whole-heart method in which the whole coronary artery tree is covered by a thick 3D slab with one single measurement [15]. All data acquisitions were performed with an ECG-triggered 3D SSFP sequence with T2 preparation during free breathing.

Respiratory gating was performed using two spin-echo signals that were located parallel to the z -axis and intersected at the dome of the right hemidiaphragm. The width of the respiratory gating window was 6 mm. Volume-targeted coronary MRA was performed with a 3D slab of 16–20 slices of 2 mm thickness to cover one to two coronary arteries. Two or three slabs were acquired to cover the entire coronary artery tree. The scanning parameters were as follows: TR/TE, 4.9/2.4; flip angle, 65°; readout bandwidth, 125 kHz; field of view, 280 mm; matrix, 256 × 256; and voxel size, 1.1 × 1.1 × 2.0 mm³.

Whole-heart coronary MRA was performed with a 3D slab of 44 transverse slices (sync-interpolated into 88 slices of 1.3 mm thickness) to cover the whole volume of the heart. The imaging parameters were as follows: 3.7/1.7; flip angle, 90°; readout bandwidth, 870 Hz per pixel; lines per heartbeat, 25–33; and voxel size, 0.9 × 0.9 × 1.3 mm³.

Conventional CAG

Selective conventional CAG was performed with a standard Judkins technique. The images were interpreted by a cardiologist who was unaware of the results of coronary MDCTA and MRA. The severity of coronary artery stenosis was expressed as the percentage reduction in the luminal diameter determined using the quantitative coronary analysis method. An 50% reduction in luminal diameter was considered significant stenosis.

Image Analysis

All coronary MDCTA data were transferred to a computer workstation (Leonardo, Siemens) for postprocessing. Maximum-intensity-projection (MIP), curved multiplanar reformation (MPR), and volume-rendering (VR) images were generated and used to evaluate the coronary arteries.

The coronary artery calcium scores were measured for each calcified plaque using a dedicated software program (Calcium Scoring, Leonardo, Siemens). Calcium scores were calculated according to the method of Agatston et al. [16]. A coronary calcification is usually classified as minimal (calcium score of 1–10), mild (11–100), moderate (101–400), or severe (> 400) according to the total Agatston calcium score in the whole coronary artery system [17]. Because the small size of a calcification does not affect the interpretation of coronary MDCTA, only a single calcified plaque with a calcium score of > 100 and a diffuse coronary calcification were included in the analysis. Calcified plaques were further

characterized as having either a nodal or diffuse pattern. Diffuse coronary artery calcification was defined as a single arterial segment with more than three calcified plaques resulting in a combined calcium score of > 100 [18]. If diffuse calcifications extended to more than two segments, each segment was considered a separate calcified plaque.

All coronary MRA images were transferred to a computer workstation (ADW 4.3, GE Healthcare; or Leonardo, Siemens) for postprocessing. MIP and curved MPR images were reviewed for image analysis. VR images were not used for analysis of the MRA images.

Coronary MRA image quality was assessed for each of the segments with calcified plaque by two observers in consensus on a 4-point scale: 1, not visible; 2, poor (severe motion artifacts or poor fat saturation); 3, good (good vessel delineation with minor artifacts); 4, excellent (excellent vessel delineation with no artifacts). An image quality score of 1 or 2 was classified as a nonassessable segment. The coronary arteries were divided into 10 segments, according to a modified American Heart Association classification [19], as follows: proximal, middle, and distal right coronary artery (RCA); left main (LM) artery; proximal, middle, and distal left anterior descending (LAD) artery; and proximal, middle, and distal left circumflex artery (LCX). For an intention-to-diagnose analysis [20], all coronary segments were included in the image analysis even if a vessel or a segment was not assessable.

Three radiologists experienced in cardiac image analysis as part of their daily clinical practice for at least 3 years reviewed coronary MDCTA and MRA images independently and separately. They were not involved in performing the examinations and were unaware of the results of conventional CAG and of other clinical information. Coronary MDCTA and MRA images were reviewed in random order and 2 weeks apart. Each reader assessed the severity of coronary stenosis to be $\geq 50\%$ or $< 50\%$ at the site of each calcification on MDCTA and corresponding site on MRA. The analysis of significant coronary stenosis was performed visually by the three readers on the image workstations. To estimate the likelihood that a significant stenosis was present, the readers used a 5-point confidence scale: 5, definitely positive; 4, probably positive; 3, possibly positive; 2, probably negative; 1, definitely negative.

Statistical Analysis

To compare the diagnostic performance of coronary MRA and MDCTA, receiver operating characteristic (ROC) curves were generated for each of the two techniques. The overall diagnostic accuracy of each imaging technique for each reader was evaluated by calculating the area under the ROC curve (AUC) [21]. An AUC value of > 0.80 was considered to have good diagnostic accuracy [22]. The difference between the imaging techniques in terms of the AUC for each reader and the mean AUC across the three readers was analyzed using the bootstrap method (1,000 replicates), which accounts for potential intrasubject correlation [23]. For each reader, the number of significant stenoses correctly judged to be probably positive (confidence level of 4) or definitely positive (confidence level of 5) was considered the number of correctly diagnosed significant stenoses. The sensitivity and specificity of each imaging technique were estimated and compared between the two imaging techniques with the McNemar test [24].

To assess interobserver agreement in image interpretation for coronary MDCTA and MRA for the three independent readers, kappa statistics were calculated between any two readers and among the three readers for each technique. The significance of the difference between the kappa values of the two techniques was tested using the bootstrap method.

All statistical analyses were performed using statistical software (SAS version 9.1, SAS Institute; and R-2.2.0, R Development Core Team). For all tests, except when indicated otherwise, a *p* value of 0.05 indicated a statistically significant difference.

Results

Thirty-three calcified plaques with a calcium score of > 100 (calcium score: mean $\pm$ SD, 257 ± 65 ; range, 101–813) were detected on MDCTA in the 18 patients. The calcifications were located in the LM artery ($n = 4$), proximal and middle LAD artery ($n = 19$), proximal LCX ($n = 2$), and RCA ($n = 8$). Of the 33 coronary calcifications, 17 were presented as nodal pattern and the remaining 16 were presented as diffuse pattern (Fig. 1).

Of the 33 calcified coronary segments on coronary MRA, six had an image quality score of 2, 14 had an image quality score of 3, and 13 had an image quality score of 4. For the six non-assessable segments that had an image quality score of 2, five were due to severe diffuse calcifications (calcium score > 400) and one was due to significant motion artifacts. The mean image quality score of the segments with nodal calcification was higher than that of the segments with diffuse calcification (3.47 ± 0.62 vs 2.94 ± 0.77 , respectively; $p < 0.05$).

Of the 33 calcified coronary segments, 12 showed significant stenoses at corresponding sites of calcification on conventional CAG. For the 12 lesions with significant stenosis identified on conventional CAG, four were caused by diffuse calcification, six were caused by mixed calcified plaque (Fig. 2), and two were caused by nodal calcification located at the bifurcation of the LAD artery and a diagonal branch (Fig. 3).

For the 33 segments with readings from conventional CAG, the calculated AUC values for each reader for coronary MDCTA and MRA are given in Table 1, along with the sensitivity and specificity for each technique from the three readers. The AUC values of MRA were > 0.80 for all readers. The average AUC value for the three readers for coronary MRA was significantly greater than that for MDCTA (0.831 vs 0.651 , respectively; $p = 0.030$). The sensitivity values for MRA were similar to those of MDCTA among the three readers ($p > 0.3$). However, the average specificity value for coronary MRA was significantly higher than that for coronary MDCTA (0.746 vs 0.476 , respectively; $p = 0.002$).

The interobserver agreement in image interpretation among the three independent readers is summarized in Table 2. The agreement between any two readers for coronary MRA was moderate ($0.3 < \kappa < 0.5$), whereas the agreement for coronary MDCTA was poor between readers 1 and 2 and 1 and 3 ($\kappa < 0.1$) and moderate between readers 2 and 3 ($\kappa = 0.38$). The kappa value that measures the agreement between readers 1 and 2 was significantly higher in MRA than in MDCTA ($\kappa = 0.45$ vs 0.01 , respectively; $p = 0.007$). In addition, the overall

kappa statistic that measures the agreement among the three readers was significantly higher for coronary MRA than for coronary MDCTA ($\kappa = 0.39$ vs 0.15 , respectively; $p = 0.014$).

Discussion

We completed this pilot study to evaluate the diagnostic capability of coronary MRA for the detection of significant stenosis in patients with high coronary calcium scores. On the basis of the ROC analysis for coronary CTA and MRA, the results of this study initially show that coronary MRA has better diagnostic performance than coronary CTA for the detection of significant stenosis in coronary artery segments with moderate to severe calcified plaque. With the additional advantages of patients receiving no ionizing radiation or IV contrast material, coronary MRA has the potential to become the primary imaging technique for the assessment of the coronary arteries.

In this study, coronary MRA showed a limitation for visualizing the coronary lumen in segments with severe diffuse calcification. This limitation is mainly caused by the limited spatial resolution of coronary MRA. In addition, the severe luminal narrowing and reduced blood flow within diffuse calcified arteries [25] may also impair the signal-to-noise ratio of the calcified segments on coronary MRA. However, coronary MRA showed a good capability for the assessment of coronary arteries affected by a nodal pattern of calcification.

On the basis of ROC analysis, this study revealed that all readers achieved an AUC value of > 0.80 for coronary MRA, indicating good diagnostic performance of MRA in the detection of significant stenosis in patients with high calcium scores. In this study, although six of 33 calcified segments were nonassessable on coronary MRA, all readers had an AUC value of > 0.80 because the nonassessable segments were mainly affected by severe diffuse calcification, which is commonly associated with significant coronary stenosis. The AUC values of MRA were greater than those of MDCTA for all readers. In addition, the average AUC value for MRA was statistically significantly greater than that for MDCTA among the three readers (0.831 vs 0.651 , respectively; $p = 0.030$).

The sensitivity values of coronary MRA and MDCTA were similar across the three readers ($p > 0.05$). This result is different from previous comparative studies that showed coronary MDCTA had a higher sensitivity than MRA [1-4]. The possible reason for our results may be related to the use of a site-by-site design in our study. The site-by-site comparison between coronary MDCTA and MRA may make coronary MRA more sensitive for the detection of significant stenosis in the corresponding site of calcification. This may also explain the higher AUC value (mean AUC = 0.831) of coronary MRA in this study than in previous studies [26]. The average specificity value for coronary MRA was greater than that for MDCTA (0.746 vs 0.476 , respectively; $p < 0.05$), which is consistent with the results from previous studies [2-4]. Coronary MDCTA is prone to allow overestimation of the severity of coronary stenosis due to the beam-hardening artifacts from calcification. Previous studies have also shown that severe coronary calcification may reduce the specificity of coronary MDCTA for the detection of significant stenoses in patients with high calcium scores [8, 27-30].

Regarding the interobserver agreement in image interpretation, coronary MRA showed moderate interobserver agreement among all readers. For coronary MDCTA, only readers 2 and 3 had moderate agreement, and the agreement was poor between readers 1 and 2 and between readers 1 and 3. Consequently, the overall kappa among all readers in the interpretation of MDCTA was only 0.15. However, the overall kappa value among the three readers was significantly higher for coronary MRA than for MDCTA ($p = 0.014$). This result indicates that coronary MRA allows more reliable image interpretation for evaluating significant coronary stenosis with moderate to severe calcification than MDCTA.

There were several limitations to this study. First, the study population in this preliminary study was small, and a multicenter study is necessary to further support the diagnostic value of coronary MRA for the detection of significant coronary stenosis with moderate and severe calcifications. Second, although an SSFP sequence was used in all studies, the available 3D coverage and spatial resolution of the pulse sequence from the two scanners were different. The impact of such a difference on image interpretation was out of the scope of this study and thus was not compared. Third, the design of site-by-site comparison between coronary MDCTA and MRA may have allowed a bias toward higher sensitivity with coronary MRA. Fourth, due to limited spatial resolution, coronary MRA does not allow the detection of stenoses in distal segments and side branches; thus, only calcifications located in the proximal and middle segments were assessed in our study.

In conclusion, coronary MRA has higher image quality for coronary segments with nodal calcification than that for coronary segments with diffuse calcification. Coronary MRA has better diagnostic performance than coronary MDCTA for the detection of significant stenosis in patients with high calcium scores.

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Fig. 1.

77-year-old man with stable angina.

A, Diffuse calcification (*arrow* and *arrowheads*) was detected in right coronary artery (RCA) on MDCT angiography maximum-intensity-projection (MIP) image. AO = aorta.

B and **C**, MR angiography MIP image (**B**) shows moderate stenosis (*arrow*, **B**) and conventional coronary angiography image (**C**) confirms moderate stenosis (*arrow*, **C**) in corresponding segment where heavy diffuse calcification can be seen in **A** (*arrow* in **A**). **B** and **C** show no significant stenosis (*arrowheads*) in corresponding segments where nodal calcifications are located in **A**.

Fig. 2.

60-year-old woman with stable angina.

A, Calcification in left main (LM) artery (*arrowhead*) and mixed plaque in proximal left anterior descending (LAD) artery (*arrow*) are visible on MDCT angiography maximum-intensity-projection (MIP) image. Cross-sectional image shown as inset in top left corner shows noncalcified components (*arrow* and *arrowhead*, inset) within plaque. AO = aorta.

B, MR angiography (MRA) MIP image shows significant stenosis in proximal LAD artery (*arrow*), but normal LM artery (*arrowhead*). AO = aorta.

C, MRA findings shown in **B** are consistent with findings on conventional coronary angiography image (**C**): Arrow points to significant stenosis in proximal LAD artery and arrowhead points to normal LM artery.

Fig. 3.

68-year-old woman with unstable angina.

A, Two mixed plaques (*arrowheads*) and calcification (*arrow*) in left anterior descending (LAD) artery are visible on MDCT angiography maximum-intensity-projection (MIP) image. AO = aorta.

B, MR angiography MIP image shows significant stenoses (*arrowheads*) at sites of two mixed plaques shown in **A** and mild stenosis (*arrow*) at site of calcification shown in **A**. AO = aorta.

68-year-old woman with unstable angina.

C, Conventional coronary angiography image shows severe stenosis in proximal (*left arrowhead*) and distal (*arrow*) plaques but does not show significant stenosis in middle plaque (*right arrowhead*).

TABLE 1
Comparison of Coronary MR Angiography (MRA) and CT Angiography (CTA) in the
Detection of Significant Stenosis with Moderate to Severe Calcification: Sensitivity,
Specificity, and Area Under the Receiver Operating Characteristic Curve (AUC)

Performance Measure	Value (95% CI)		<i>p</i>
	MRA	CTA	
Reader 1			
Sensitivity	0.750 (0.602–0.898)	0.750 (0.602–0.898)	1.000
Specificity	0.810 (0.676–0.944)	0.476 (0.306–0.647)	0.020
AUC	0.823 (0.658–0.957)	0.675 (0.486–0.854)	0.147
Reader 2			
Sensitivity	0.833 (0.706–0.960)	0.667 (0.506–0.828)	0.317
Specificity	0.714 (0.560–0.868)	0.524 (0.353–0.694)	0.206
AUC	0.819 (0.649–0.945)	0.631 (0.424–0.830)	0.076
Reader 3			
Sensitivity	0.833 (0.706–0.960)	0.833 (0.706–0.960)	1.000
Specificity	0.714 (0.560–0.868)	0.429 (0.260–0.597)	0.058
AUC	0.849 (0.706–0.952)	0.649 (0.470–0.831)	0.082
Overall			
Sensitivity	0.806 (0.671–0.941)	0.750 (0.602–0.898)	0.564
Specificity	0.746 (0.598–0.895)	0.476 (0.306–0.647)	0.002
AUC	0.831 (0.726–0.914)	0.651 (0.509–0.792)	0.030

Note—Sensitivity and specificity values specified at a confidence level of 4 (range, 1 = lowest confidence to 5 = highest confidence for significant stenosis diagnosis).

TABLE 2
Interobserver Agreement in Image Interpretation Using MR Angiography (MRA) and
CT Angiography (CTA)

Readers	κ (95% CI)		<i>p</i>
	MRA	CTA	
1 versus 2	0.45 (0.090.67)	0.01 (−0.17 to 0.21)	0.007
2 versus 3	0.41 (0.210.62)	0.38 (0.090.59)	0.852
1 versus 3	0.34 (0.110.54)	0.07 (−0.14 to 0.26)	0.092
Overall	0.39 (0.180.60)	0.15 (0.08 to 0.43)	0.014