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FULL PAPER

Non-contrast MR angiography using three-dimensional balanced steady-state free-precession imaging for evaluation of stenosis in the celiac trunk and superior mesenteric artery: a preliminary comparative study with computed tomography angiography

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Objective: Although non-contrast MR angiography (NC-MRA) is well established for the evaluation of renal artery stenosis, its usefulness in the evaluation of other abdominal aortic branches remains to be studied. This study aimed at evaluating the image quality and diagnostic accuracy of NC-MRA using a three-dimensional balanced steady-state free-precession sequence in identifying stenosis in the celiac trunk (CTR) and superior mesenteric artery (SMA) as compared with CT angiography (CTA) as the reference standard.

Methods: 41 patients underwent both NC-MRA and CTA of the abdominal aorta. Two radiologists analyzed the quality of the images (diagnostic vs non-diagnostic) and the performance (accuracy, sensitivity and specificity) of NC-MRA for the identification of arterial stenosis. Kappa tests were used to determine the interobserver agreement and the intermethod agreement between NC-MRA and CTA.

Results: NC-MRA provided diagnostic quality images of the CTR and SMA in 87.8% and 90.2% of cases, respectively, with high interobserver agreement (kappa 0.95 and 0.80, respectively). For stenosis assessment, NC-MRA had a sensitivity of 100%, a positive-predictive value of 50% and a negative-predictive value of 100% for both segments, with accuracies of 88.8% for the CTR and 94.5% for the SMA.

Conclusion: NC-MRA is an accurate method for detecting stenosis in the CTR and SMA.

Advances in knowledge: Data from this study suggest that MR angiography with balanced steady-state free-precession sequence is a viable non-contrast alternative for stenosis evaluation of these branches in patients for whom a contrast-enhanced examination is contraindicated.

INTRODUCTION

CT angiography (CTA) has been replacing digital angiography for the diagnosis of abdominal arterial diseases. Compared with digital angiography, CTA is less invasive, widely available and provides a detailed, concomitant evaluation of the solid abdominal viscera and bowel loops.¹ In recent years, MR angiography (MRA) has been used as an alternative to CTA in the study of vascular diseases, primarily because MRA does not use ionizing radiation or iodinated contrast medium (CM).² Despite these advantages, MRA has lower spatial resolution and requires more time to perform than CTA; these drawbacks have rendered MRA the second-choice diagnostic

method for evaluating the visceral branches of the abdominal aorta.^{3,4} Moreover, concerns have arisen regarding the risk of developing irreversible nephrogenic systemic fibrosis in patients with renal disease undergoing a paramagnetic CM injection⁵ and, more recently, about gadolinium deposition in the basal ganglia and globus pallidus after repeated administration of gadolinium chelates.⁶ These concerns have rendered MRA even less attractive; however, concomitantly, interest has increased in MRA methods that do not use intravenous (i.v.) CM [non-contrast MRA (NC-MRA)]. A NC-MRA study can reduce the risks and costs of this diagnostic method.^{7–9}

Recently, NC-MRA using a balanced steady-state free-precession (bSSFP) sequence has been advocated to evaluate atherosclerotic renal arteries stenosis.¹⁰ The bSSFP sequence is acquired in three-dimensions, with a hybrid T_2/T_1 weighting, which suppresses signals from fat, stationary tissues and venous flow. This sequence has allowed acquisition of high-quality images, improved the reproducibility of the method, and increased the degree of diagnostic confidence.^{11–15}

Despite several studies that showed the usefulness of NC-MRA for evaluating renal arteries, just a small number of studies have investigated the role of this new method in evaluating the other visceral abdominal aortic branches. These few studies have focused primarily on the hepatic artery and portal vein.^{8,16–18}

Recently, the American College of Radiology suggested that NC-MRA can be used as an alternative and complementary diagnostic method for the evaluation of the celiac trunk (CTR) and the superior mesenteric artery (SMA) in patients who exhibit contraindications to iodine- and gadolinium-based contrast agents.¹ Lately, the utility of this NC-MRA sequence was also considered in the evaluation of patients with suspected chronic mesenteric ischaemia.¹⁹ However, to our knowledge, there have been no studies in which the value of NC-MRA has been demonstrated in the assessment of diseases that affect these vascular segments. Therefore, the purpose of this study was to establish the accuracy of NC-MRA with a bSSFP sequence for detecting stenosis in the CTR and SMA, adopting CTA as the reference method.

METHODS AND MATERIALS

This prospective clinical study was conducted in a single centre. It was approved by the ethics board committee, and all patients gave informed consent prior to the examination.

All patients were referred by their physicians to the Department of Diagnostic Imaging at our institution and were submitted to an enhanced CTA of the aorta. We included consecutive patients with normal renal function. After the CTA study, all patients underwent a complementary NC-MRA examination in a 1.5-T MRI scanner. In most cases, both examinations have been performed on the same day, but when this was not possible (e.g., due to patients' requests, MRI scanner schedule availability etc.), the maximum interval between the two modalities was 1 month.

In order to avoid hindsight, contextual and observation biases,^{20–22} these consecutive patients were selected for the CTA study from a wide range of clinical indications of the standard clinical practice (in whom a vascular stenosis was not necessarily being expected), such as need to evaluate aortic aneurysms, high blood pressure, potential renal and liver donation, suspected chronic mesenteric ischaemia, renal asymmetry or a renal nodule detected in a previous ultrasound examination. Participants were excluded when they were unsuitable for MRI scanning due to standard contraindications (e.g., a pacemaker or ferrous implants), phobias or a history of adverse reaction to iodinated CM.

The final sample included 41 patients (27 males and 14 females) with a mean age of 62 years (range: 26–87 years).

MR angiography technique

All NC-MRA examinations were performed with a 1.5-T whole-body superconducting magnet (Signa HDxt®; General Electric, Milwaukee, WI) with a phased-array surface coil. Parallel imaging techniques were employed with an acceleration factor of two. After performance of a localizer sequence, which consisted of three imaging stacks oriented in the transverse, sagittal and coronal planes, a coronal two-dimensional steady-state free-precession sequence was performed for localization of the origin of the CTR and SMA. Next, axial free-breathing fat-saturated sequence was performed (bSSFP), using a respiratory trigger and acquiring images during the expiration phase. This sequence was characterized by the following parameters: repetition time ms/echo time ms, 4.5/2.3; inversion pulse time (TI), 1200 ms; flip angle, 90°; field of view, 36 × 40 cm; matrix, 256 × 256; and spatial resolution, 1.6 mm. The total time required for acquisition of MRA images was of 4.36 min.

CT angiography technique

CTA was performed on a 64-row multidetector CT scanner (LightSpeed VCT®; General Electric, Milwaukee, WI) using 120 kVp. The milliamperage selection was based on automatic current tube modulation at a noise index of 12; the gantry rotation time was 500 ms; the detector collimation and table feed were 0.6 and 20.6 mm/rotation, respectively. Patients received an i.v. injection of water-soluble, non-ionic, iodinated CM at a dose of 1.5 ml kg⁻¹ with an automatic power injector (Stellant®; Medrad, Pittsburgh, PA) at an injection rate of 5.5 ml s⁻¹. Next, an i.v. injection of 40 ml of saline was administered.¹⁰ Automatic triggering (Smart Prep®, General Electric, Milwaukee, WI) was used to begin image acquisition that was performed during inspiration. The radiation dose in these examinations ranged from 2.4 to 13.8 mSv (as a function of abdominal circumference and the use of radiation dose modulation), with a mean of 8.6 mSv.

Imaging evaluation

Two certified abdominal radiologists (PPC, with 12 years of experience, and TJP, with 9 years of experience) reviewed the anonymized imaging data separately, and both were blinded to the patients' clinical data, also to avoid the aforementioned biases. The image analysis began with an evaluation of the NC-MRA examinations. To reduce a potential memory effect, the CTA images were evaluated in random order, after an interval of 21 days, and these results (settled as the reference standard) were reached by consensus.

Dedicated workstations were used to evaluate the original images in the axial plane (Advantage® Workstation; General Electric, Milwaukee, WI). The readers were allowed to generate additional multiplanar reconstructions and multiple intensity projections, when necessary.

Parameters evaluated

Image quality

The quality of the images generated by the NC-MRA examinations was evaluated subjectively and independently. Images

Figure 1. Non-contrast MR angiography image quality. (a) An image classified as “diagnostic”, and (b) an image classified as “non-diagnostic”. Note the difference in image quality and, in particular, the visualization of the celiac trunk (large arrows) and superior mesenteric artery (small arrows). (a, b) Reformatted in the sagittal plane.

were evaluated at the CTR, common hepatic artery (CHA; extra-hepatic segment), left gastric artery (LGA; ascending segment before reaching the lesser curvature of the stomach), splenic artery (SA; up to approximately 3.0 cm after its emergence) and the SMA (proximal portion before the emergence of vascular branches). The image quality was graded according to the following scale, based on the methodology adopted from a previous study:¹³ A, excellent (high signal in the arterial lumen, high degree of diagnostic reliability); B, good (good signal strength in the arterial lumen, adequate for diagnosis); C, moderate (barely visible signal intensity in the arterial lumen, less than adequate for diagnosis); and D, “non-diagnostic” (no visible signal intensity in the arterial lumen, inadequate for diagnosis). The results were grouped into “diagnostic” (grades A and B) and non-diagnostic (grades C and D) categories for data analysis^{23–25} (Figure 1).

Vessel lumen caliber

To evaluate similarities between NC-MRA and CTA in measurements of the vessel lumen caliber, one observer (PPC) used the multiplanar reconstruction technique in NC-MRA images considered diagnostic to measure the “true axial” diameter of the vessels within 5–10 mm distal from its origin. The same technique was used to measure the same segments in the CTA studies.²⁶

Significant stenosis

One reader (PPC) visually graded each CTR and SMA stenosis, based on the degree of occlusion, as follows: none/mild ($\leq 50\%$); moderate ($>50\%$ and $<75\%$); and severe ($\geq 75\%$). Moderate and severe stenoses, *i.e.* those that caused $>50\%$ occlusion, were considered significant.²⁷ In some cases, stenosis was caused by the impression of the median arcuate ligament, characterized by focal narrowing of the proximal celiac artery. This finding can be more pronounced in end expiration and presents a characteristic hooked appearance.²⁸ In these cases, stenosis was included in a subgroup called “significant stenosis/arcuate ligament”.

Statistical analyses

The kappa test was used to determine the interobserver agreement in evaluating the quality of the images generated by NC-MRA, and to determine the intermethod agreement between NC-MRA and CTA modalities. A κ -value <0.4 indicated low agreement; values between 0.41 and 0.60 indicated moderate agreement; values between 0.61 and 0.80 indicated substantial agreement; and values >0.80 indicated nearly perfect agreement. The intraclass correlation index (r) was used for intermethod comparisons of vessel calibers in the diagnostic groups ($r < 0.4$ = weak agreement, r between 0.41

Figure 2. Examples of non-contrast MR angiography that exhibited “diagnostic” quality in all segments evaluated. (a) The left gastric artery (curved arrow); the image was multiplanar reformatted in the sagittal plane; (b) the common hepatic artery (large arrow) and splenic artery (small arrow); image is shown in the coronal plane.

Table 1. Distributions of “diagnostic” and “non-diagnostic” image qualities in non-contrast MR angiography examinations of arterial segments ($n = 41$ patients)

Segment	Diagnostic, n (%)	Non-diagnostic, n (%)
CTR	36 (87.8)	5 (12.2)
LGA	18 (43.9)	23 (56.1)
CHA	21 (51.2)	20 (48.8)
SA	21 (51.2)	20 (48.8)
SMA	37 (90.2)	4 (9.8)

CHA, common hepatic artery; CTR, celiac trunk; LGA, left gastric artery; SA, splenic artery; SMA, superior mesenteric artery.

Classification of image quality: the diagnostic images were graded as A and B, and the non-diagnostic images were graded as C and D.

and $0.75 =$ satisfactory agreement and $r > 0.75 =$ excellent agreement).²⁹

We also calculated the accuracy, sensitivity, specificity, positive-predictive value (PPV) and negative-predictive value (NPV) of NC-MRA for detecting significant stenoses in the CTR and SMA, using CTA results as the reference standard. All statistical analyses were performed by using a commercially available software (SPSS®; IBM Corp., New York, NY; formerly SPSS Inc., Chicago, IL).

RESULTS

Image quality

The image quality of the NC-MRA sequence was considered diagnostic in 87.8% of CTR analyses (36/41), 90.2% of SMA analyses (37/41), 43.9% of LGA analyses (18/41) and 51.2% of CHA and SA analyses (21/41) (Figure 2, Table 1).

Interobserver agreement in evaluating the quality of non-contrast MR angiography examinations

Good or excellent interobserver agreement ($k = 0.70$ – 0.95) was achieved in all the arterial segments examined (CTR 0.95; LGA 0.77; CHA 0.93; SA 0.70; and SMA 0.80).

Comparison of non-contrast MR angiography and CT angiography methods

High intermethod agreement between NC-MRA and CTA was observed in the image quality evaluations of the CTR and SMA,

with kappa = 0.76 for both. A lower agreement was observed in the branches of the CTR (kappa = 0.38–0.61; Table 2).

An excellent intraclass correlation index was observed between the NC-MRA and CTA methods in the analysis of vessel caliber measurements of the SMA. Satisfactory intermethod agreement was observed for the CTR and CHA, and an agreement was nearly satisfactory for the LGA and SA (Table 2).

Comparisons of diagnoses of significant stenosis in the CTR and SMA and relation to the presence of calcified atherosclerotic plaques

We identified 21 patients with calcified atherosclerotic plaques in the 36 CTRs analyzed (58.3%). CTA identified four significant stenoses in CTRs, all of them demonstrating calcified plaques. NC-MRA identified eight significant stenoses in CTRs (three characterized by the impression of the median arcuate ligament), meaning that in 37.5% of studies, NC-MRA overestimated a stenosis caused by the impression of the median arcuate ligament. The CTA and NC-MRA examinations provided equivalent diagnoses of the presence or absence of a significant stenosis in the CTR for 32 of 36 images (88.8%) that achieved diagnostic quality (graded as A or B quality; Figure 3), with kappa = 0.60 and a confidence interval (CI) = 0.30–0.91 (Table 2). In conclusion, CTR stenosis was overestimated in four NC-MRA studies (Figure 4), three of them associated with impression of the median arcuate ligament and one associated with calcified plaques.

Table 2. Comparison between non-contrast MR angiography and CT angiography methods for image quality (intermethod agreement ratio and kappa value), caliber measurement (intraclass correlation index) and significant stenosis detection (kappa value and confidence interval) in different arterial segments

Segment	Intermethod agreement ratio (%)	Kappa	Intraclass correlation index (r)	Kappa/confidence interval
CTR	87.8	0.76	0.71	0.60/0.30–0.91
LGA	43.9	−0.12	0.38	Not measured
CHA	51.2	0.0	0.61	Not measured
SA	51.2	0.02	0.38	Not measured
SMA	90.2	0.76	0.79	0.78/0.43–1.00

CHA, common hepatic artery; CTR, celiac trunk; LGA, left gastric artery; SA, splenic artery; SMA, superior mesenteric artery.

Figure 3. Intermethod agreement in evaluations of the celiac trunk (large arrows) and superior mesenteric artery (small arrows). Both branches were considered to have “no significant stenosis” in (a) non-contrast MR angiography and (b) CT angiography images; both were multiplanar reformatted in the sagittal plane.

We identified 14 patients with calcified atherosclerotic plaques in the 37 SMAs analyzed (37.8%). CTA identified four significant stenoses in SMAs, all of them demonstrating calcified plaques. NC-MRA identified six significant stenoses in SMAs. The CTAs and NC-MRAs provided equivalent diagnoses of the presence or absence of significant stenoses in 35 of the 37 (94.5%) evaluable SMA studies ($\kappa = 0.78$; $CI = 0.43-1.00$; Table 2). In conclusion, SMA stenosis was overestimated in two NC-MRA studies (Figure 5), both of them positive for the presence of calcified plaques.

Accuracy in the diagnosis of significant stenosis in the celiac trunk and superior mesenteric artery NC-MRA showed 100% sensitivity and 87.5% specificity in the detection of significant stenosis in the CTR, with 50% PPV, 100% NPV and 88.8% accuracy. NC-MRA had 100% sensitivity, 94.2% specificity, 50% PPV, 100% NPV and 94.5% accuracy in the detection of significant stenosis in the SMA. The low PPV values were due to NC-MRA overestimations of the degree of stenosis in both segments evaluated. Conversely, in no case did NC-MRA fail to reveal some stenosis of the CTR or SMA, which resulted in high sensitivity and NPV values.

Figure 4. Intermethod disagreement in evaluations of the celiac trunk (CTR). (a) The non-contrast MR angiography (sagittal plane) shows a region (arrow) classified as “significant stenosis” in the CTR; (b) the CT angiography (sagittal plane) shows the same region (arrow) classified as “no significant stenosis” in the CTR. The methods were in agreement in the evaluations of the superior mesenteric artery, which was classified as normal (no significant stenosis).

Figure 5. Intramethod disagreement in evaluating superior mesenteric artery stenosis (small arrows). (a) The non-contrast MR angiography (NC-MRA) indicates a “significant stenosis” and (b) the CT angiography indicates “no significant stenosis”. Also, note the anatomical variation characterized by the right hepatic artery (large arrows) which emerges separately from the celiac artery and the different angle of the celiac artery caused by the impression of the median arcuate ligament in the NC-MRA study.

DISCUSSION

To our knowledge, this is the first study to compare image quality and accuracy of the bSSFP sequence to CTA in the evaluation of the CTR, CTR branches and SMA. Our preliminary results demonstrated high-quality images in the majority of the cases (almost 90%), with good accuracy for the detection of CTR and SMA stenosis of NC-MRA studies, which may contribute to establish this method as an alternative to CTA for detecting significant stenosis of these vessels.

With the development of high-spatial-resolution contrast-enhanced MRA sequences, this method became an alternative tool for diagnosing aortic branch stenosis with the primary advantage of not exposing patients to ionizing radiation.^{30,31} However, gadolinium-based contrast agents (particularly their linear compounds, such as gadodiamide, gadopentetate dimeglumine and gadoversetamide) are known risk factors in nephrogenic systemic fibrosis among patients with chronic renal disease.⁵ Given these risks, NC-MRA could be a more appealing option than contrast-enhanced MRA in particular clinical settings.^{13,14}

In a recent study, NC-MRA with bSSFP sequence was compared with contrast-enhanced MRA for evaluating the renal arteries in terms of image quality and stenosis detection in the proximal portions of the CTR and SMA.³² These authors showed excellent results in sensitivity, specificity, NPV and accuracy in the CTR (100%, 97%, 100% and 98%, respectively) and in the SMA (100% for all measures). However, the reference standard that they used (contrast-enhanced MRA) had limited effectiveness; consequently, those outstanding results may have been influenced by that drawback. A more robust, consistent gold standard method, such as CTA, may provide more reliable and accurate assessments, as we have obtained in our study.

Our results showed that NC-MRA provided satisfactory image quality when compared with CTA. Most images were considered as having diagnostic quality, mainly for the evaluation for CTA

and SMA. On the contrary, the method seems limited for the assessment of CTA branches such as LGA, CHA and SA, probably due to their smaller caliber. On the other hand, it is important to emphasize that the interobserver agreement for evaluation of the proximal segments of the main branches was high (kappa: 0.70–0.95). The image quality of the CTR branches can be improved by optimizing the bSSFP sequence with greater spatial resolution and higher magnetic fields (*e.g.* 3.0 T), as it has been suggested elsewhere.¹¹

This study showed that NC-MRA could detect significant stenoses in the CTR and SMA with high accuracy. However, we observed a trend towards overestimations of stenosis; NC-MRA images had a 50% PPV for both segments. Several studies have reported similar results in measuring the accuracy of NC-MRA for detecting stenoses in other abdominal aortic branches, such as the renal arteries.^{12,14–16} The overestimation of stenosis using NC-MRA images has been attributed to a reduction in flow velocity in post-stenotic vascular segments.³³ A similar mechanism may occur in stenotic CTR and SMA segments, which could explain our results. Moreover, we observed, in some cases, a stenosis overestimation related to compression of the CTR by the median arcuate ligament. In the present study, this compression may have occurred because the NC-MRA images were obtained during expiration and the CTA studies were performed during inspiration. Indeed, several studies have shown that the expiration phase commonly exacerbates the physiological compression of the CTR by the arcuate ligament, a fact that may explain the difference in our results. Otherwise, in this same situation, if the focal narrowing of the CTR was observed during inspiratory CTA, it may have represented a clinically significant stenosis, since the transient compression seen only during expiration in some patients would not be manifested at inspiratory CT, as demonstrated before in the literature.^{34,35} In that way, knowing that proximal CTR compression may be seen in asymptomatic patients, this fact should always be remembered to avoid overdiagnosis of this entity.²⁸ This situation can also be

avoided by achieving NC-MRA with the “breath-hold” technique, which is currently commercially available.¹⁴ However, despite the stenosis overestimation, our results indicated that NC-MRA with the bSSFP sequence did not fail to detect any significant stenosis in the CTR and SMA, compared with CTA.

There were some intrinsic limiting characteristics of the bSSFP sequence that we used. First, the field of view restriction was pre-set at 120–140 mm, which prevented the inclusion of distal segments of the CTR and SMA branches in our analyses. Moreover, a reduction in the signal-to-noise ratio occurred within the limits of the areas studied. This reduction degraded the quality of the images of vascular segments in those areas. This limitation was also observed by Shimada et al¹⁷ in a study on hepatic arteries with NC-MRA. Another specific limitation of the bSSFP sequence used in the present study was the fixed inversion pulse time (TI = 1200 ms). It is well known that often it is necessary to increase the TI in patients with slow blood flow to identify the distal arterial branches.^{10,36} Recent technical developments have made it possible.³⁶ We also found that the image quality was degraded in patients with irregular breathing, as other authors have mentioned.¹³ The effects of this technical drawback may be minimized by implementing novel NC-MRA sequences; for instance, an acquisition during “guided breathing” (patients are guided to maintain a regular breathing rhythm with an audible command) or using the breath-hold technique can improve the image quality.^{9,37}

In addition to these technical limitations, which may be expected in a recently developed technology, our study had a few other limitations. First, we included a relatively small number of individuals in the study. Also, the sample predominantly comprised individuals with only a few significant stenoses in the CTR and SMA. The low incidence of stenoses, considered rare in the general population,³⁸ may explain the profile of the samples studied. Moreover, although we have not employed a wide range of observers with different levels of expertise, in order to address possible biases related to observer experience, we assessed kappa statistics, intraclass correlation index and CI values for the most important parameters aimed in this study, which are acceptable ways of addressing this limitation in a preliminary study.³⁹ Finally, we also consider as a limitation of our study the fact that the distal arterial segments of the vessels were not included in our analysis.

Despite these limitations, the results from our study demonstrated that NC-MRA had a high sensitivity and provided image quality comparable to that of CTA in evaluations of stenosis in the CTR and proximal segments of the SMA. This finding suggested that NC-MRA may be an effective preliminary approach for imaging vasculature in patients with contraindications to contrast materials, haemodynamic stability and a clinical suspicion of significant stenosis in the CTR or SMA.

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