Introduction

Rupture of intracranial aneurysm is associated with high morbidity and mortality rates, as it is known to be accountable for 80% of all subarachnoid hemorrhages (SAH), causing 25% of all cerebrovascular-related deaths, [1]. Size and shape of unruptured intracranial aneurysms (UIA) are known to be significantly affiliated with rupture rates, hence, high-quality assessment of UIA and its related features displays an important role on potential aneurysm treatment [2–4].

Digital subtraction angiography (DSA) is considered the gold standard for detection of UIA. Nevertheless, due to the application of ionizing radiation and iodinated contrast agent as well as the general risk affiliated to invasive interventional procedures, DSA is associated with a 0.2%–0.5% risk for severe permanent neurological complications [5,6].

Within the past 15 years, 1.5 Tesla magnetic resonance angiography (MRA) has evolved to become an excellent non-invasive diagnostic alternative to DSA, yielding sensitivity rates of 79–97% for the detection of small UIA [7–10]. With the successful introduction of (ultra-) highfield non-enhanced MRA of the intracranial vasculature, recent studies performed at 3 and 7 Tesla reported improved depiction of UIA with sensitivity rates comparable to the gold standard DSA [11–14]. The increase of the magnetic field strength from 1.5 to 3 Tesla, and respectively to 7 Tesla, allowed for a successful transition of the increased signal-to-noise (SNR) and contrast-to-noise ratio (CNR) to improvements in spatial resolution and vessel contrast.

The purpose of this prospective study was to evaluate the image quality and diagnostic ability in the assessment of UIA of 1.5 Tesla TOF MRA in comparison to ultra-high-field TOF MRA and non-enhanced MPRAGE imaging.
Table 1. Basic demographic data and aneurysm size and location.

| aneurysm | subject | sex | age | location | side | 7 Tesla TOF MRA Ø in mm* | 1.5 Tesla TOF MRA Ø in mm* | 7 Tesla MPRAGE Ø in mm* |
|----------|---------|-----|-----|----------|------|--------------------------|---------------------------|-------------------------|
| 1        | 1       | female | 52  | ICA      | left | 8                        | 7.5                       | 7                       |
| 2        | 2       | female | 56  | giant ICA | right | 36.5                     | 34                        | 35.5                    |
| 3        | 3       | female | 69  | ICA      | left  | 16.5                     | 17                        | 18                      |
| 4        | 4       | female | 56  | MCA      | left  | 8.5                      | 8.5                       | 9                       |
| 5        | 5       | male   | 70  | BT       |       | 2.5                      | 2.5                       | 2.5                     |
| 6        | 6       | male   | 45  | PCA      | left  | 18                       | 13.5                      | 16.5                    |
| 7        | 7       | female | 66  | ACA      | right | 1.5                      | 1                        | 1.5                     |
| 8        | 8       | female | 54  | MCA      | right | 4.5                      | 4.5                       | 6                       |
| 9        | 9       | female | 60  | ICA      | right | 17                       | 17                        | 16.5                    |
| 10       | 10      | female | 44  | ACA      | right | 2.5                      | 2.5                       | 2.5                     |
| 11       | 11      | female | 53  | MCA      | right | 8                        | 8                         | 8                       |
| 12       | 12      | male   | 45  | MCA      | left  | 5                        | 5                         | 4.5                     |
| 13       | 13      | female | 49  | MCA      | left  | 6                        | 5.5                       | 5                       |
| 14       | 14      | male   | 38  | PCA      | left  | 4.5                      | 4.5                       | 3.5                     |
| 15       | 15      | male   | 55  | PcomA    | right | 4.5                      | 3.5                       | 2.5                     |
| 16       | 16      | female | 42  | SC       | right | 3.5                      | 2.5                       | 2.5                     |

Table 2. Interobserver accordance (kappa-statistic).

|          | dome | neck | parent vessel | artifacts | vessel-tissue contrast | overall image quality |
|----------|------|------|---------------|-----------|------------------------|-----------------------|
| 7 T TOF MRA | 0.75 | 0.79 | 0.85          | 0.89      | 0.88                   | 0.50                  |
| 1.5 T TOF MRA | 0.39 | 0.80 | 0.73          | 0.71      | 0.84                   | 0.68                  |
| 7 T MPRAGE  | 0.26 | 1.00 | 0.92          | 1.00      | 0.84                   | 1.00                  |

Study Design and Population
This prospective study evaluates the diagnostic ability of 7 Tesla TOF MRA in comparison to 1.5 Tesla TOF MRA and 7 Tesla non-contrast enhanced MPRAGE for delineation of UIA. The study group comprised 16 neurosurgical patients (male n = 5, female n = 11, average age 53.38 years; range 38–70 years). Inclusion criteria were: 1) single or multiple UIA, 2) age 18–80 years, 3) ability to give informed consent and 4) legal internal carotid artery (ICA). middle cerebral artery (MCA). basilar tip (BT). posterior cerebral artery (PCA). anterior cerebral artery (ACA). posterior inferior cerebellar artery (PICA). posterior communicating artery (PcomA). superior cerebellar artery (SC).

According to Landis the kappa coefficient (k) was rated as follows:
Poor (k < 0.00), Slight (k = 0.00–0.20), Fair (k = 0.21–0.40), Moderate (k = 0.41–0.60), Substantial (k = 0.61–0.80), Almost Perfect (k = 0.81–1.00).
Disagreements were weighted by 1–(i–j)/(k–1)2 where i and j index the rows and columns of the ratings by the two raters and k is the maximum number of possible ratings.

Materials and Methods
Ethics Statement
The study was conducted according to the principles expressed in the Declaration of Helsinki and was approved by the authorized ethical review board of the University Duisburg-Essen. Written informed consent was obtained before each examination.

Table 2. Interobserver accordance (kappa-statistic).
competence. Exclusion criteria were: 1) cardiac pacemakers or any other electronic implants, 2) metallic implants, 3) pregnancy or breast feeding period, 4) claustrophobia and 5) chronic or episodic vertigo. All patients were accordingly examined at a 7 Tesla (Magnetom 7T, Siemens) and a 1.5 Tesla MR scanner system (Espree, Siemens) utilizing dedicated head coils. The following sequences were obtained: (1) 7 Tesla TOF MRA, (2) 1.5 Tesla TOF MRA and (3) 7 Tesla non-contrast enhanced MPRAGE. A total of 20 intracranial aneurysms were detected, with two patients showing multiple aneurysms (2, respectively 4 aneurysms).

Scanners and Coil Systems
Ultra-high-field examinations were acquired on a 7 Tesla whole-body MRI system (Magnetom 7T, Siemens Healthcare, Erlangen, Germany) utilizing a 32-channel Tx/Rx head coil (Nova Medical, Wilmington, USA). The scanner is equipped with a gradient system of 45 mT/m maximum amplitude and a slew rate of 200 mT/m/ms.

Concomitant 1.5 Tesla examinations were acquired on a whole-body MRI system (Espree, Siemens Healthcare) equipped with a 12-channel Rx head coil (Siemens Healthcare, Erlangen, Germany). The scanner is equipped with a gradient system of 33 mT/m maximum amplitude and a slew rate of 200 mT/m/ms.

Examination at 7 Tesla
Prior to the acquisition of the diagnostic sequences B0 shimming was performed using a vendor-provided gradient echo sequence and algorithm based on the work of Schar [15]. For B1 field mapping and local flip angle optimization a vendor provided spin-echo type sequence was used. After a slice selective excitation, two refocusing pulses generate a spin-echo and a stimulated echo, respectively. The algorithm is mainly based on the work of Hoult [16].

TOF MRA sequence at 7 Tesla
The TOF MRA sequence is based on a 3D FLASH sequence with flow compensation and tilt-optimized non-saturated excitation (TONE) across the slab [17]. Datasets were acquired with an excitation flip angle of \( \alpha = 18° \), TE = 4.34 ms, TR = 20 ms, FOV 200 mm \( \times \) 169 mm \( \times \) 46 mm, 112 slices per slab (oversampling 14%), GRAPPA acceleration factor R = 4 (phase direction), partial Fourier 6/8 in both slice and phase directions, matrix of 896 \( \times \) 756 (non-interpolated), and a voxel size of 0.22 \( \times \) 0.22 \( \times \) 0.41 mm\(^3\) in a total acquisition time of 6 min 22 s. The variable-rate selective excitation (VERSE) algorithm \{Conolly, 1988\} was used to reduce SAR contribution of excitation and venous saturation RF pulses \{Schmitter, 2011\}. The flip angle of the saturation RF pulses was additionally reduced (\( \alpha_{SAT} = 35° \) instead of 90° which is normally used) to further ameliorate SAR constraints [17].

MPRAGE sequence at 7 Tesla
MPRAGE imaging was obtained with the following sequence parameters: TR = 2500 ms, TE = 1.54 ms, TI = 1100 ms.

| Table 3. Ratings for dome, neck and parent vessel delineation (mean ratings from both readers). |
|---|---|---|---|---|---|---|---|
| aneurysm | 7 Tesla | 1.5 Tesla | 7 Tesla | 7 Tesla | 1.5 Tesla | 7 Tesla | 7 Tesla |
| | TOF MRA | TOF MRA | MPRAGE | TOF MRA | TOF MRA | MPRAGE | TOF MRA | TOF MRA | MPRAGE |
| dome | dome | dome | neck | neck | neck | parent vessel | parent vessel | parent vessel |
| 1 | 5 | 4 | 5 | 4 | 5 | 4 | 5 | 5 |
| 2 | 4.5 | 3 | 3.5 | 5 | 4 | 2 | 5 | 4 | 3.5 |
| 3 | 4 | 3 | 5 | 4.5 | 4 | 4 | 4 | 5 | 4 |
| 4 | 5 | 4 | 5 | 5 | 5 | 5 | 5 | 4.5 | 5 |
| 5 | 4.5 | 3.5 | 4.5 | 5 | 4 | 5 | 5 | 4.5 | 5 |
| 6 | 5 | 4 | 5 | 5 | 4 | 4 | 5 | 4 | 5 |
| 7 | 5 | 3.5 | 5 | 5 | 3 | 5 | 5 | 3 | 5 |
| 8 | 4 | 4 | 4.5 | 4.5 | 3.5 | 5 | 4 | 3 | 5 |
| 9 | 4 | 4.5 | 4 | 4 | 3.5 | 5 | 4 | 4 | 5 |
| 10 | 4.5 | 4.5 | 4 | 4.5 | 5 | 5 | 4.5 | 5 | 5 |
| 11 | 5 | 4 | 4.5 | 5 | 4.5 | 5 | 4.5 | 4 | 5 |
| 12 | 3 | 4 | 5 | 4 | 3 | 5 | 4 | 4 | 5 |
| 13 | 4 | 4 | 5 | 3 | 4 | 4 | 3 | 4 | 3 |
| 14 | 5 | 4 | 5 | 5 | 3.5 | 5 | 5 | 4 | 5 |
| 15 | 5 | 3.5 | 5 | 5 | 4 | 5 | 5 | 3.5 | 5 |
| 16 | 5 | 4.5 | 5 | 4 | 3 | 3 | 5 | 4 | 3 |
| 17 | 5 | 4.5 | 5 | 5 | 3 | 5 | 4 | 3 | 5 |
| 18 | 4 | 4 | 5 | 4 | 3 | 3 | 4 | 3.5 | 5 |
| 19 | 3.5 | 3 | 5 | 4 | 4 | 5 | 4 | 3.5 | 5 |
| 20 | 5 | 3.5 | 5 | 4 | 3 | 5 | 5 | 4 | 5 |
| mean | 4.5 | 3.9 | 4.8 | 4.5 | 3.8 | 4.8 | 4.4 | 3.9 | 4.8 |

5 = excellent. 4 = good. 3 = moderate. 2 = poor. and 1 = non-diagnostic vessel delineation.
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TA = 6 min 13 s, GRAPPA acceleration factor R = 2, excitation flip angle $\alpha = 7^\circ$, adiabatic WURST pulse for magnetization preparation [18], bandwidth = 570 Hz/px, 256 slices per slab (slice oversampling 75%), matrix 384x336 (non-interpolated), FOV = 270x236 mm$^2$, voxel size 0.7x0.7x0.7 mm$^3$.

**TOF MRA sequence at 1.5 Tesla**

The TOF MRA sequence was based on a clinically used standard 3D gradient echo sequence. Datasets were acquired with an excitation flip angle of $\alpha = 25^\circ$, TE = 7 ms, TR = 26 ms, matrix 512x448 (interpolated), FOV 180 mm x 157 mm, 3 slabs with 44 slices per slab (oversampling 18.2%) and a voxel size of 0.35x0.35x0.7 mm$^3$ in a total acquisition time of 4 min 3 s.

**Image Evaluation**

Image evaluation was performed separately and independently by two experienced radiologists on standard post-processing Picture Archiving and Communication system (PACS) workstations (Centricity RIS 4.0i, GE Healthcare, USA). Both radiologists were blinded to image acquisition methods and intracranial pathologies. Visual evaluation was performed using 3D image reconstructions; all measurements were performed on 2D multiplanar reconstructions of the 3D datasets. The total number of aneurysms, the maximal diameter as well as the diameter of neck and dome of each aneurysm were assessed. For qualitative analysis the following features were evaluated, utilizing a five-point scale (5 = excellent, 4 = good, 3 = moderate, 2 = poor, and 1 = non-diagnostic vessel delineation):

1. Delineation of aneurysm dome
2. Delineation of aneurysm neck
3. Delineation of parent vessel
4. Presence of artifacts
5. Vessel tissue contrast
6. Overall image quality.

**Vessel-tissue contrast ratio (VTCR)**

\[ \text{VTCR} = \frac{\text{Signal}_{\text{MCA}} - \text{Signal}_{\text{GM}}}{\text{Signal}_{\text{MCA}} + \text{Signal}_{\text{GM}}} \]

of the middle cerebral artery (MCA) was assessed in correlation to surrounding gray matter (GM) for 7 Tesla MPRAGE sequences, 7 Tesla TOF sequences and for 1.5 Tesla TOF sequences. Therefore, regions of interest (ROI) were placed in the largest diameter of the proximal left M1 segments ($\text{Signal}_{\text{MCA}}$) and adjacent gray matter ($\text{Signal}_{\text{GM}}$). The average diameter for the ROI of the vessel was 3–5 mm; the ROI for brain parenchyma amounted to approximately 10 mm.

Interobserver accordance for ordinal scale variables were rated using the kappa coefficient [19] ($k$) according to Landis [20] as follows: Poor ($k < 0.00$), Slight ($k = 0.00–0.20$), Fair ($k = 0.21–0.40$), Moderate ($k = 0.41–0.60$), Substantial ($k = 0.61–0.80$), Almost Perfect ($k = 0.81–1.00$). Interobserver accordance for ratio scale variables were rated using Lin’s [21,22] concordance correlation coefficient.

### Table 4. Combined readings of both raters for dome and neck diameter in mm and dome/neck ratio (DNR) for all aneurysms.

| Subject | 7 Tesla MPRAGE | 7 Tesla MPRAGE | 7 Tesla MPRAGE | 7 Tesla TOF MRA | 7 Tesla TOF MRA | 1.5 Tesla TOF MRA | 1.5 Tesla TOF MRA | 1.5 Tesla TOF MRA |
|---------|----------------|----------------|----------------|----------------|----------------|-----------------|----------------|------------------|
|         | dome | neck | DNR | dome | neck | DNR | dome | neck | DNR |
| 1       | 6.5  | 3    | 2.167 | 7    | 3    | 2.333 | 6    | 3    | 2 |
| 2       | 35   | 11   | 3.182 | 34   | 11   | 3.091 | 34   | 10.5 | 3.238 |
| 3       | 10   | 4    | 2.5   | 10   | 3    | 3.333 | 9.5  | 3    | 3.167 |
| 4       | 8    | 2    | 4     | 8    | 3    | 2.667 | 8.5  | 3    | 2.833 |
| 5       | 2.5  | 2    | 1.25  | 2.5  | 2    | 1.25  | 2.5  | 2    | 1.25 |
| 6       | 6.5  | 2    | 3.25  | 6.5  | 2.5  | 2.6   | 6.5  | 2    | 3.25 |
| 7       | 15   | 2    | 7.5   | 15   | 2    | 7.5   | 13.5 | 2    | 6.75 |
| 8       | 1.5  | 1    | 1.5   | 1.5  | 1    | 1.5   | 1    | 1    | 1 |
| 9       | 4    | 2    | 2     | 4    | 2    | 2     | 3    | 2.5  | 1.2 |
| 10      | 5    | 2    | 2.5   | 5    | 2    | 2.5   | 5    | 2    | 2.5 |
| 11      | 10.5 | 3    | 3.5   | 10   | 3    | 3.333 | 10   | 3    | 3.333 |
| 12      | 4    | 2    | 2     | 4    | 1    | 4     | 4    | 2    | 2 |
| 13      | 16.5 | 4.5  | 3.667 | 17   | 5    | 3.4   | 17   | 5.5  | 3.091 |
| 14      | 2.5  | 2    | 1.25  | 2.5  | 2    | 1.25  | 2.5  | 2    | 1.25 |
| 15      | 8    | 2    | 4     | 8    | 2    | 4     | 8    | 2    | 4 |
| 16      | 4.5  | 2    | 2.25  | 4    | 1.5  | 2.667 | 4    | 2    | 2 |
| 17      | 4    | 2    | 2     | 4    | 2    | 2     | 4    | 2    | 2 |
| 18      | 3    | 1    | 3     | 3    | 1    | 3     | 3    | 2    | 1.5 |
| 19      | 2.5  | 1    | 2.5   | 3    | 1    | 3     | 3    | 1    | 3 |
| 20      | 2.5  | 2    | 1.25  | 3    | 2    | 1.5   | 2.5  | 2    | 1.25 |

**mean**

| 2.763* | 2.846** | 2.531*** |

*standard error = 0.318, 95% confidence interval [2.098–3.428].
**standard error = 0.307, 95% confidence interval [2.203–3.489].
***standard error = 0.299, 95% confidence interval [1.906–3.156].
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coefficient. For intermethod comparison the Wilcoxon signed rank test was applied. Differences of continuous scaled variables were tested by Student's t-test.

Statistical analysis was carried out with the STATA software package (Stata/SE 12.1 for Mac (64-bit Intel), StataCorp, 4905 Lakeway Drive, College Station, Texas 77845 USA).

### Results

All 1.5 Tesla and 7 Tesla scans were performed successfully without any relevant side effects. Both readers identified twenty intracranial aneurysms in 1.5 Tesla and 7 Tesla TOF MRA and 7 Tesla MPRAGE imaging. Fourteen of the twenty intracranial aneurysms were located in the anterior circulation: middle cerebral artery (n = 7), anterior cerebral artery (n = 2), internal carotid artery (n = 4) and posterior communicating artery (n = 1). Six aneurysms were detected in the posterior circulation: basilar tip (n = 2), posterior cerebral artery (n = 2), posterior inferior cerebellar artery (n = 1) and superior cerebellar artery (n = 1). Two patients had multiple intracranial aneurysms (2, respectively 4 aneurysms). Ten of twenty identified aneurysms were defined as small (3–5 mm), five as medium-sized (6–10 mm), three as large (11–25 mm) and one was rated a giant cerebral aneurysm (>35 mm). The mean aneurysm size was 8.65 mm (Standard Error (SE) 1.823) for the 7 Tesla TOF MRA reading, 8.075 mm (SE 1.708) for the 1.5 Tesla TOF MRA reading and 8 mm (SE 1.826) for the 7 Tesla MPRAGE reading. Interobserver agreement measured by Lin's concordance correlation coefficient was substantial for 7 Tesla TOF MRA readings (rc = 0.963) and 1.5 Tesla TOF MRA readings (rc = 0.951) and moderate for 7 Tesla MPRAGE readings (rc = 0.922). Table 1 shows an overview on basic demographic data and aneurysm size and location.

### Dome, neck and parent vessel

Mean score values of both readers' for delineation of the aneurysm dome were 4.5 (excellent) (SE 0.136) for 7 Tesla TOF MRA, 3.9 (good) (SE 0.109) for 1.5 Tesla TOF MRA and 4.8 (excellent) (SE 0.092) for 7 Tesla MPRAGE imaging. Wilcoxon matched-pairs two-sided signed-ranks test showed significant differences between 7 Tesla TOF MRA and 1.5 Tesla TOF MRA (p = 0.0042) ratings as well as between 7 Tesla MPRAGE and 1.5 Tesla TOF MRA (p = 0.0005) ratings. There were no significant differences between 7 Tesla TOF MRA and 7 Tesla MPRAGE (p = 0.1797) ratings.

The delineation of the aneurysm neck was rated 4.5 (excellent) (SE 0.126) in 7 Tesla TOF MRA, 3.8 (good) (SE 0.136) in 1.5 Tesla TOF MRA and 4.8 (excellent) (SE 0.156) in 7 Tesla MPRAGE MRI. Wilcoxon matched-pairs two-sided signed-ranks test showed significant differences between 7 Tesla TOF MRA and 1.5 Tesla TOF MRA (p = 0.0042) ratings as well as between 7 Tesla MPRAGE and 1.5 Tesla TOF MRA (p = 0.0005) ratings. There were no significant differences between 7 Tesla TOF MRA and 7 Tesla MPRAGE (p = 0.0063) ratings.

| aneurysm | 7 Tesla TOF MRA | 1.5 Tesla TOF MRA | 7 Tesla MPRAGE | 7 Tesla TOF MRA | 1.5 Tesla TOF MRA | 7 Tesla MPRAGE | 7 Tesla TOF MRA | 1.5 Tesla TOF MRA | 7 Tesla MPRAGE |
|---------|----------------|------------------|---------------|----------------|------------------|---------------|----------------|------------------|---------------|
| artifacts | 4.5 | 5 | 5 | 5 | 3.5 | 5 | 4 | 4.5 | 4.5 |
| VTC | 4.5 | 5 | 5 | 4 | 4.5 | 5 | 5 | 4.5 | 4.5 |
| image quality | 4.5 | 5 | 5 | 4 | 4.5 | 5 | 5 | 4.5 | 4.5 |

Table 5. Ratings for artifacts, vessel-tissue contrast (VTC) and overall image quality (mean ratings from both readers).

| mean | 4.3 | 4.4 | 5.0 | 4.4 | 4.2 | 4.9 | 4.3 | 4.3 | 5.0 |

5 = excellent. 4 = good. 3 = moderate. 2 = poor. and 1 = non-diagnostic vessel delineation.

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Quantitative measurements for dome and neck diameter showed larger dome/neck ratio for 7 Tesla MPRAGE (p = 0.0597) and 7 Tesla TOF MRA (p = 0.0305) compared to 1.5 Tesla TOF MRA. There was no significant difference between dome/neck ratio in 7 Tesla MPRAGE and 7 Tesla TOF MRA (p = 0.5816).

In accordance with the delineation of the aneurysm dome and neck, 7 Tesla MRA also offered best assessment of the parent vessel 4.8 (excellent) (SE 0.128). TOF MRA yielded good assessment of the parent vessel at both field strengths (1.5 Tesla vessel 4.8 (excellent) (SE 0.128). TOF MRA yielded good assessment in all three MRI sequences are shown in Figures 1 and 2.

Table 6 shows mean ratings for delineation of dome, neck and parent vessel of both readers. Table 4 lists the combined readings of both raters for dome and neck diameter in mm and calculated dome/neck ratio for all aneurysms.

Examples for aneurysm dome, neck and parent vessel delineation in all three MRI sequences are shown in Figures 1 and 2.

**Table 6. Combined readings of both raters for signal intensities of left middle cerebral artery, adjacent gray matter and calculated vessel-tissue contrast ratio for all subjects.**

| Subject | 7T MPRAGE | 7T TOF MRA | VTCR | 1.5 T TOF MRA | 1.5T GM | 1.5T GM | 1.5T TOF VTCR |
|---------|-----------|-----------|------|--------------|--------|--------|--------------|
| 1       | 1032      | 263       | 0.594| 908          | 145    | 0.725  | 486          | 132          |
| 2       | 1071      | 282       | 0.583| 1063         | 192    | 0.694  | 581          | 142          |
| 3       | 543       | 135       | 0.602| 881          | 216    | 0.606  | 409          | 89           |
| 4       | 897       | 204       | 0.629| 897          | 157    | 0.702  | 408          | 106          |
| 5       | 773       | 141       | 0.691| 785          | 185    | 0.619  | 438          | 128          |
| 6       | 844       | 179       | 0.650| 864          | 176    | 0.662  | 519          | 139          |
| 7       | 1014      | 205       | 0.664| 951          | 193    | 0.663  | 532          | 143          |
| 8       | 913       | 188       | 0.658| 1088         | 154    | 0.752  | 485          | 121          |
| 9       | 851       | 141       | 0.716| 851          | 176    | 0.657  | 426          | 94           |
| 10      | 998       | 152       | 0.736| 912          | 198    | 0.643  | 508          | 105          |
| 11      | 846       | 174       | 0.659| 865          | 202    | 0.621  | 470          | 113          |
| 12      | 909       | 240       | 0.582| 921          | 193    | 0.654  | 520          | 133          |
| 13      | 858       | 219       | 0.593| 818          | 175    | 0.648  | 534          | 149          |
| 14      | 792       | 165       | 0.655| 944          | 209    | 0.637  | 411          | 92           |
| 15      | 831       | 141       | 0.710| 902          | 196    | 0.643  | 540          | 127          |
| 16      | 926       | 186       | 0.665| 843          | 184    | 0.642  | 494          | 108          |

mean *0.649* **0.660*** ***0.604***

Vessel-tissue contrast ratio \( \frac{\text{VTCR}}{\text{Signal}_\text{MCA} - \text{Signal}_\text{GM}} \) of the middle cerebral artery (MCA) were assessed in correlation to surrounding gray matter (GM) for 7 Tesla (T) magnetization prepared rapid acquisition gradient echo (MPRAGE) sequences, 7T time-of-flight (TOF) sequences and for 1.5T TOF sequences. Therefore, regions of interest (ROI) were defined in the largest diameter of the proximal left M1 segments (Signal\text{MCA}) and adjacent gray matter (Signal\text{GM}). The average diameter for the ROI of the vessel was 3–5 mm; the ROI for brain parenchyma amounted to approximately 1 cm.

*standard error = 0.012, 95% confidence interval [0.623 – 0.675].
**standard error = 0.010, 95% confidence interval [0.639 – 0.681].
***standard error = 0.008, 95% confidence interval [0.587 – 0.622].

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Quantitative measurements for dome and neck diameter showed larger dome/neck ratio for 7 Tesla MPRAGE (p = 0.0597) and 7 Tesla TOF MRA (p = 0.0305) compared to 1.5 Tesla TOF MRA. There was no significant difference between dome/neck ratio in 7 Tesla MPRAGE and 7 Tesla TOF MRA (p = 0.5816).

In accordance with the delineation of the aneurysm dome and neck, 7 Tesla MRA also offered best assessment of the parent vessel 4.8 (excellent) (SE 0.128). TOF MRA yielded good assessment of the parent vessel at both field strengths (1.5 Tesla TOF MRA mean: 4.4 (SE 0.125); 7 Tesla TOF MRA mean: 3.9 (SE 0.146).

Wilcoxon matched-pairs two-sided signed-ranks test showed significant differences between 7 Tesla MPRAGE and 7 Tesla TOF MRA (p = 0.0002) ratings and between 7 Tesla MPRAGE and 1.5 Tesla TOF MRA (p = 0.0005) ratings. No significant differences were detected between 7 Tesla TOF MRA and 1.5 Tesla TOF MRA (p = 0.3438) ratings. Figure 3 shows examples of pulsation artifacts for 1.5 Tesla and 7 Tesla MRA sequences.

**Artifacts, vessel-tissue contrast and overall image quality**

Seven Tesla MPRAGE imaging was the sequence to be least impaired by artifacts (excellent) with mean value of 4.9 (SE 0.000). 7 Tesla and 1.5 Tesla TOF MRA showed equivalent artifact impairment (good) with mean values of 4.3 (SE 0.147) for 7 Tesla and mean 4.4 (SE 0.124) for 1.5 Tesla imaging.

Wilcoxon matched-pairs two-sided signed-ranks test showed significant differences between 7 Tesla MPRAGE and 7 Tesla TOF MRA (p = 0.0002) ratings and between 7 Tesla MPRAGE and 1.5 Tesla TOF MRA (p = 0.0005) ratings. No significant differences were detected between 7 Tesla TOF MRA and 1.5 Tesla TOF MRA (p = 0.3438) ratings. Figure 3 shows examples of pulsation artifacts for 1.5 Tesla and 7 Tesla MRA sequences.

Vessel-tissue contrast was rated equally good for TOF MRA at both field strengths, with mean values of 4.4 (good) (SE 0.146) for 7 Tesla and 4.2 (good) (SE 0.122) for 1.5 Tesla MRI. MPRAGE imaging provided highest vessel-tissue contrast with excellent mean values of 4.9 (SE 0.088). Wilcoxon matched-pairs two-sided signed-ranks test showed significant differences between 7 Tesla MPRAGE and 7 Tesla TOF MRA (p = 0.0063) ratings and between 7 Tesla MPRAGE and 1.5 Tesla TOF MRA (p = 0.0001) ratings. There were no significant differences detected between 7 Tesla TOF MRA and 1.5 Tesla TOF MRA (p = 0.5811) ratings.

Quantitative measurements of signal intensities showed significantly higher vessel-tissue contrast for 7 Tesla MPRAGE (p = 0.0018) and 7 Tesla TOF MRA (p = 0.0014) compared to 1.5 Tesla TOF MRA. No difference between vessel-tissue contrast
could be detected in 7 Tesla MPRAGE and 7 Tesla TOF MRA (p = 0.5337).

Overall image quality was rated equivalently good (4.3) for 7 Tesla (SE 0.105) and 1.5 Tesla (SE 0.117) TOF MRA and excellent (5.0) (SE 0.025) for 7 Tesla MPRAGE imaging. Wilcoxon matched-pairs two-sided signed-ranks test showed significant differences between 7 Tesla MPRAGE and 7 Tesla TOF MRA (p = 0.0000) ratings and between 7 Tesla MPRAGE and 1.5 Tesla TOF MRA (p = 0.0001) ratings. There were no significant differences detected between 7 Tesla TOF MRA and 1.5 Tesla TOF MRA (p = 0.6250) ratings.

Interobserver accordance was almost perfect (kappa coefficient) for most readings with slightly lower accordance (substantial) for artifact and overall image quality assessment in 1.5 Tesla TOF MRA Details are shown in Table 2.

Table 5 shows mean ratings for artifact delineation, vessel-tissue contrast and overall image quality. Table 6 lists the combined readings of both raters for signal intensities of left middle cerebral artery, adjacent gray matter and calculated vessel-tissue contrast ratio for all subjects.

Discussion

With DSA remaining to be the gold standard, 1.5 Tesla TOF MRA has evolved to become a reliable and equivalent non-invasive technique for detection and follow-up of UIA larger than 3 mm [1,23–27]. The increase in SNR and CNR affiliated to the increase in magnetic field strength has been shown to result in superior vessel (disease) assessment at 3 Tesla compared to 1.5 Tesla [26]. With further increase of the field strength to 7 Tesla, the combination of the associated increase in SNR (up to 4–5 fold higher than at 1.5 Tesla) and longer T1 relaxation times [28] are known to offer an improved vessel-tissue contrast based on more efficient background tissue suppression [29]. Studies in healthy volunteers at 7 Tesla have shown superior vessel delineation compared to 1.5 Tesla [30,31]. Furthermore, patient studies demonstrated the high diagnostic ability and superiority of 7 Tesla non-enhanced TOF MRA for evaluation of intracranial vasculature and aneurysm detection compared to DSA and/or 1.5 Tesla TOF MRA [13,32].

Initial studies of 7 Tesla non-enhanced T1w brain imaging revealed an incidental finding, by means of a homogeneously

![Figure 1. Seventy years old male patient (subject 5) suffering from basilar tip aneurysm. White arrows are marking the aneurysm neck, black arrows are marking the aneurysm dome.](image)
hyperintense signal of arterial vasculature. This incidental finding bears a strong diagnostic potential for non-enhanced high-quality vessel imaging at 7 Tesla, as demonstrated in numerous studies [18,32–36]. In a study presented at the ISMRM 2010, Grinstead et al. analyzed the primary source of the hyperintense vessel signal. Their investigations showed an association of the high vessel signal to the lack of body RF transmit coils at 7 Tesla, resulting in the utilization of head coils for transmit and receive. Hence, non-selective infrared pulses effectively become slab-selective infrared-pulses. Furthermore a combination of steady state and inflow effects seems to be accountable.

To investigate the diagnostic ability of T1w non-enhanced 7 Tesla MRI, Maderwald et al. [32] published an intra-individual comparison trial of 7 Tesla TOF MRA, VIBE imaging (three-dimensional volume interpolated breath hold examination) and MPRAGE imaging of the intracranial vasculature in 25 subjects. Their results demonstrated the superiority of MPRAGE imaging in the assessment of non-enhanced vasculature, providing high-quality delineation of all vessel segments and least impairment due to pulsation artifacts near the carotid bifurcation in TOF MRA scans. The artifacts in 1.5 Tesla (a) and 7 Tesla (b) TOF MRA scans make vessel depiction more difficult (M1: middle cerebral artery (M1 segment); A1: anterior cerebral artery (A1 segment)).

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Figure 2. Forty-five years old male patient (subject 6) with partially thrombosed left sided fusiform posterior cerebral artery aneurysm. White arrows are marking the aneurysm neck, black arrows are marking the aneurysm dome. p1: posterior cerebral artery (p1 segment). a: Volume rendering of the 7 Tesla TOF MRA illustrating the three dimensional structure of the aneurysm (ba: basilar artery; sc: superior cerebellar artery; p2: posterior cerebral artery (p2 segment); ab: aneurysm body); b: transverse plane of the 7 Tesla TOF MRA depicting the parent vessel and part of the aneurysm body; c: Excellent delineation of parent vessel and part of the aneurysm body in 7 Tesla MPRAGE scan; d: Moderate depiction of parent vessel and aneurysm body in 1.5 Tesla TOF MRA.

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Figure 3. Pulsation artifacts near the carotid bifurcation in TOF MRA scans. The artifacts in 1.5 Tesla (a) and 7 Tesla (b) TOF MRA scans make vessel depiction more difficult (M1: middle cerebral artery (M1 segment); A1: anterior cerebral artery (A1 segment)).

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to intraluminal signal variations. Furthermore, MPRAGE and 
VIBE imaging offered full brain coverage in contrast to TOF 
MRA. Zwanenburg et al. [37] confirmed the high diagnostic 
potential of non-enhanced MPRAGE MRI at 7 Tesla, yielding 
excellent assessment of cerebral perforating arteries and related 
anatomical parenchymatous structures. In another recent study, 
the potential diagnostic benefit of the application of contrast agent 
to 7 Tesla MPRAGE MRI was investigated. The study results 
revealed only minor non-significant improvement based on the 
administration of contrast agent, underlining the high-diagnostic 
potential of non-enhanced 7 Tesla MPRAGE MRI [36].

Based on these previous study results, we decided to include 
non-enhanced MPRAGE imaging to our 7 Tesla protocol and 
compare its diagnostic ability to 7 Tesla and 1.5 Tesla TOF MRA 
regarding the assessment of intracranial aneurysms and their 
related features. Our study results go in line with previous 
publications regarding the superiority of 7 Tesla TOF MRA over 
1.5 Tesla TOF MRA as well as 7 Tesla MPRAGE over 7 Tesla 
and 1.5 Tesla TOF MRA. However, while previous studies mainly 
focused on the evaluation of the overall image quality and overall 
delineation of the aneurysms, our study results deepen the 
assessment of the diagnostic ability based on a dedicated analysis 
of numerous aneurysm features and image quality parameters. 
Due to its high spatial resolution and excellent vessel-to-tissue 
contrast MPRAGE MRI offered best delineation of all assessed 
aneurysm features. It also yielded highest scores in overall image 
quality and least artifact impairment with significant difference to 
TOF MRA at 7 Tesla and 1.5 Tesla. Furthermore, aside from 
excellent vessel delineation, it also offers the potential for 
simultaneous high quality assessment of related anatomical 
parenchymatous structures and full brain coverage. While 7 Tesla 
TOF MRA yielded superior diagnostics of the aneurysm dome 
and neck over 1.5 Tesla, it was slightly inferior in the assessment of 
the parent vessel. This inferiority was mainly due to amplified 
intraluminal signal variations at 7 Tesla, resulting in impaired 
parent vessel delineation.

Clearly, our study is not free of limitations. The study group 
comprised a rather small population of 16 patients with a total of 
20 untreated IA. Nevertheless, to our knowledge this is one of 
the largest neurosurgical patients cohorts suffering from UIA scanned 
at 7 Tesla and 1.5 Tesla MRI, published in literature. Further 
investigations with larger patient cohorts, also including patients 
with clipped or coiled intracranial aneurysms should be the focus 
of future studies. Ultrahighfield imaging in patients with treated 
aneurysms has been a restricted so far, as neither Guglielmi 
detachable coils nor aneurysm clips are certified for 7 Tesla MR 
imaging. Nevertheless, first promising preliminary results on 
implant safety in cerebral 7 Tesla MRI have been recently 
demonstrated [Kraff, 2013#1639] [Noureddine, 2012#1640] [Noured- 
dine, 2013#1641]. Future studies on the diagnostic potential of 7 
Tesla MRI for follow-up of coiled aneurysms would be of high 
scientific and clinical interest with special focus on aneurysm 
recanalization and its precise detection, comparing MRA at 
different magnetic field strengths to DSA.

Furthermore, another limitation is posed by the lack of a 
comparison to the diagnostic gold standard, in terms of digital 
subtraction angiography. However, with MRA offering equivalent 
non-invasive vessel diagnostics to DSA, particularly applied for 
aneurysm monitoring (as in our patient cohort), the main focus of 
this trial was set on a direct comparison of the diagnostic ability of 
different magnetic field strengths. Finally, as known from previous 
studies, 3 Tesla MRA is considered to provide improved vessel 
delineation over 1.5 Tesla. Hence, a comparison of 7 Tesla MRA 
to 3 Tesla MRA instead of 1.5 Tesla imaging would have been 
desirable. Unfortunately, this was not applicable due to availability 
reasons in this clinical setting. Nevertheless, 1.5 Tesla MRI is still 
considered the worldwide clinical standard. Hence, in order to 
investigate the diagnostic ability of 7 Tesla MRA, a comparison to 
the clinical worldwide standard (1.5 Tesla) may be a fair 
comparison after all.

In conclusion, we believe our study demonstrates the superiority 
of 7 Tesla MRA over 1.5 Tesla MRA and underlines the high 
diagnostic potential of 7 Tesla non-enhanced MPRAGE imaging 
for assessment, screening and follow-up of UIA.

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Conceived and designed the experiments: KHW PD CM IES OM NO¨ MEL MF MUS US LU. Wrote the paper: KHW PD CM IES OM NO¨ MEL MF MUS US LU. Analyzed the data: KHW 
PM Teadsale EM, Wardlaw JM, Easton V (2001) What is the most-sensitive 
non-invasive imaging strategy for the diagnosis of intracranial aneurysms? 
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