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Time-resolved contrast-enhanced MR angiography: Value of hemodynamic information in the assessment of vascular diseases

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Summary

Background: To assess the quality of images obtained from time-resolved MRA together with the accuracy of this technique in diagnosing vascular diseases and the usefulness of haemodynamic information provided by this method.

Material/Methods: The study group included 120 patients with different vascular pathologies excluding of intracranial vessels. All patients underwent time-resolved MRA on 1.5T unit. Results were correlated with other imaging techniques: DSA (n=36), CTA (n=28), Doppler ultrasound (n=71) and intraoperative findings (n=10). Independently, two radiologists evaluated the MRA studies assessing the quality of the images in a 3 point scale (3 – good, 1 – poor), as well as the presence or absence of haemodynamic information (3 – relevant dynamic information, 2 – irrelevant dynamic information, 1 – lack of dynamic information) for different vascular pathologies.

Results: Mean quality of MRA examinations was 2.94 (reader A and B) and was similar for different pathologies (kappa value =0.757). The mean grading (reader A and B) for the presence of dynamic information was above 2 for the following pathologies: celiac artery branch pseudoaneurysm (3), vascular malformation (3), subclavian steal syndrome (2.5), Leriche's syndrome (2.25), aortic dissection (2.06), renal artery stenosis (2.03); and below 2 for: pelvic arterial occlusive disease (1.75), abdominal aortic aneurysm (1.31), carotid artery stenosis (1.1), thoracic aortic aneurysm (1.0). Kappa value was 0.802. The sensitivity was 95%, specificity 96% and positive predictive value 98%.

Conclusions: Time-resolved MRA provides good quality images and enables reliable diagnosis of vascular pathologies.

Key words: time-resolved magnetic resonance angiography • contrast-enhanced magnetic resonance angiography • digital subtraction angiography

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Background

Despite the fact that digital subtraction angiography (DSA) remains the gold standard for evaluation of vascular pathologies other imaging modalities, such as computed tomography angiography (CTA) and magnetic resonance angiography (MRA) achieve accuracy close to DSA while being less invasive and better tolerated. Of these two minimally invasive techniques, MRA has the potential advantage of combining static, multiplanar evaluation of vascular morphology with a functional assessment of blood flow. While phase contrast (PC) MRA technique allows for measurement of velocity and direction of blood flow, time-resolved MRA (TR-MRA), introduced in clinical studies by Schoenberg et al. in 1999, enables obtaining vascular images in different phases of contrast enhancement providing additional hemodynamic data [1].

Time-resolved MRA is based similarly to single-phase CE MRA, on 3D gradient-echo (GRE) sequence, however due to a shorter acquisition time which allows obtaining multiple phases of contrast enhancement the time-resolved technique enables visualization of passage of contrast material (CM) in vessels and organs. The method also does not require a time delay estimate between the beginning of CM injection and start of acquisition therefore eliminating possible errors and artifacts related to a suboptimal time delay [2]. With the use of TR-MRA there is usually no overlap of contrast enhanced veins over arteries, which decreases the quality of MRA images, especially in the case of renal arteries. Moreover, evaluation of renal, hepatic or pulmonary vessels may be extended and complemented by the assessment of dynamic contrast enhancement of renal, hepatic and lung parenchyma. This in turn facilitates the correlation of the detected vascular pathology with possible parenchymal perfusion abnormalities.

The biggest disadvantage of the time-resolved technique compared to single-phase MRA is worse spatial resolution, a result of shortening the acquisition time. There is a noted decrease in image quality which may result in worse depiction of anatomical details and small vascular pathologies [3]. In some MRA studies optimal spatial resolution appears to be a critical issue, while in other angiographic studies good temporal resolution may be more important and mandatory for correct diagnosis and assessment of the extent of vascular pathology. To our knowledge, until now there was no study comparing the value of time-resolved MRA in different vascular diseases on large group of patients.

The purpose of this study was to evaluate the use of hemodynamic information obtained with the use of time-resolved MRA in different vascular diseases. We made an attempt to identify specific diseases in which hemodynamic information could be useful in depicting vascular pathologies and their extent. Additionally, the quality of TR-MRA images was evaluated, together with its accuracy in comparison with other imaging modalities.

Material and Methods

Between October 1999 and June 2008, 309 examinations were performed using the time-resolved MRA technique. The analysis included 120 patients (78 men, 42 women) aged from 15 to 86 years (mean age – 56) in whom the TR-MRA results were verified by other imaging modalities or during surgery. The following vessels were evaluated: thoracic and/or abdominal aorta (n=53), renal arteries (n=51), aortic arch branches (n=7), pelvic and lower extremity arteries (n=7) and celiac arteries (n=2).

Final diagnosis was based on the results of DSA and Doppler ultrasound (US) in 20 patients, DSA and CTA in 4 patients, DSA alone in 12 patients, CTA and Doppler US in 1 patient, CTA in 23 patients, Doppler US in 50 patients and during surgery in 10 patients. The study group consisted of 120 patients with following vascular diseases: renal artery stenosis (n=51), aortic dissection (n=29), abdominal aortic aneurysm (n=19), thoracic aortic aneurysm (n=5), carotid artery stenosis (n=5), subclavian steal syndrome (n=2), vascular malformation (n=3), celiac artery branch pseudoaneurysm (n=2), Leriche's syndrome (n=2), lower extremity arterial occlusive disease (n=2).

Examinations were performed on two 1.5T units. On the first unit (Philips, Gyroscan) examinations were performed using body coil and 3D GRE sequence with the following parameters: TR – 5 ms, TE – 2 ms, flip angle – 40, matrix – 164×512, number of signal averages (NSA) – 1, acquisition time – 7–12 s, number of acquired phases 2–4 (in case of MRA of renal arteries 12–14 phases were obtained), slice thickness – 3.6–4 mm. On the second unit (Siemens, Avanto) images were obtained with the use of matrix coil system (TIM, total imaging matrix), employing 3D GRE sequence with the following parameters: TR – 2.75 ms, TE – 1.12 ms, flip angle –25, matrix – 294×448, number of signal averages (NSA) – 1, acquisition time – 5 s, number of acquired phases 13, slice thickness – 1 mm.

Examinations of the thoracic and abdominal vessels were performed during breath-hold. In all patients a gadolinium based paramagnetic contrast agent was injected intravenously at a rate of 2–4 ml/s.

From the source images maximum intensity projection (MIP) views were generated. In all cases a minimum of 18 images rotated by 20° at least in one axis, were obtained. An analysis which included source images and MIP reconstructions was performed by two experienced radiologists (A and B) who independently assessed image quality together with the relevance of haemodynamic information for the diagnosis of different vascular pathologies.

Image quality was assessed using criteria introduced by Van Hoe et al. [3] in our own modification. Images were graded according to the following parameters: a) presence or absence of artifacts, b) presence or absence of venous overlap over imaged arteries (all patients were referred for arterial MRA evaluation), c) presence or absence of optimal arterial enhancement. A three grade scale was used for this purpose: 1 – poor quality, 2 – moderate quality, 3 – good quality.

Relevance of hemodynamic information for diagnosis and vessel assessment was evaluated by the same readers. As before a three grade scale was used: 1 – hemodynamic information absent, 2 – irrelevant hemodynamic data (not useful for the diagnosis of disease and/or assessment of its extent), 3 – relevant hemodynamic data (facilitating the diagnosis of disease and/or assessment of its extent). MRA examinations in which no pathology was diagnosed were also graded as 1.

Statistical analysis

1. Mean values for image quality were calculated and the results evaluated for strength of interobserver agreement between two readers with Cohen's kappa coefficient. Cohen's kappa value range between 0 and 1, where 0 is equal to lack of agreement and 1 is equal to complete agreement. Results >0.75 mean very good agreement, 0.4–0.75 mean-good agreement and <0.4 poor agreement.

2. Mean values for hemodynamic data relevance were calculated separately for each vascular pathology.

Table 1. Assessment of the quality of time-resolved MRA images.

	Radiologist A	Radiologist B	Kappa value
Grade 1 (poor quality)	0	0	
Grade 2 (moderate quality)	5 (4.2%)	8 (6.7%)	
Grade 3 (good quality)	115 (95.8%)	112 (93.3%)	
Mean grade	2.96	2.93	0.757

Table 2. Assessment of the relevance of hemodynamic information from TR-MRA studies for diagnosis.

	Radiologist A	Radiologist B	Kappa value
Grade 1 (hemodynamic information absent)	57 (47.5%)	60 (50%)	
Grade 2 (irrelevant hemodynamic information)	16 (13.3%)	16 (13.3%)	
Grade 3 (relevant hemodynamic information)	47 (39.2%)	46 (36.7%)	
Mean grade	1.92	1.87	0.802

Table 3. The evaluation of hemodynamic information in different vascular diseases.

Vascular disease	Number of examinations	Radiologist A (mean grade)	Radiologist B (mean grade)	Radiologist A and B (mean grade)
Vascular malformation	3	3.00	3.00	3.00
Celiac artery branch pseudoaneurysm	2	3.00	3.00	3.00
Subclavian steal syndrome	2	2.50	2.50	2.50
Leriche's syndrome	2	2.00	2.50	2.25
Aortic dissection	29	2.10	2.03	2.06
Renal artery stenosis	51	2.06	2.00	2.03
Lower extremity arterial occlusive disease	2	1.50	2.00	1.75
Abdominal aortic aneurysm	19	1.37	1.26	1.31
Carotid artery stenosis	5	1.20	1.00	1.10
Thoracic aortic aneurysm	5	1.00	1.00	1.00

Subsequently, diseases in which mean value was equal or above 2 were identified as the ones, in which TR-MRA provided significant hemodynamic data. Interobserver agreement using Cohen's kappa coefficient was also calculated for this parameter.

3. Sensitivity, specificity and positive predictive values of TR-MRA for diagnosis of vascular diseases were calculated in correlation with other imaging modalities (DSA, CTA, Doppler US and surgery results).

All calculations and analysis were performed using the SPSS 12.0 for Windows statistical package.

Results

Assessment of the quality of time-resolved MRA images

Of the performed 120 TR-MRA studies the quality of only 5 (4.2%) studies was graded as moderate (2 points) by radiologist A. The remaining 115 (95.8%) studies were graded as good (3). Radiologist B assessed the quality of 8 (6.7%) studies as moderate (2) and 112 (93.3%) as good (3). None of the examinations were graded as poor (1) by either radiologist. Kappa value for the assessment of the quality of TR-MRA examinations was 0.757 showing a very good interobserver agreement (Table 1). No significant difference in the quality of TR-MRA studies was noted for the different anatomic regions.

Relevence of obtained hemodynamic data

In the assessment of radiologist A sixteen (13.3%) of TR-MRA studies provided irrelevant hemodynamic data and 47 (39.2%) of them provided relevant hemodynamic information. Radiologist B graded 16 (13.3%) TR-MRA studies as containing irrelevant hemodynamic information with 44 (36.7%) studies determined relevant. Mean grades for the presence of hemodynamic data, according to radiologist A and radiologist B, were consequently 1.92 and 1.87. Kappa value was 0.802, reflecting very good interobserver agreement (Table 2).

Mean values were calculated for all analyzed vascular diseases. Pathologies, in which time-resolved MRA provided valuable hemodynamic information (mean grade >2) were selected (Table 3). TR-MRA provided relevant hemodynamic data in the following vascular pathologies: vascular malformation (mean grading – 3 points), celiac artery branch

pseudoaneurysm (3), subclavian steal syndrome (2.5), Leriche's syndrome (2.25), aortic dissection (2.06) and renal artery stenosis (2.03). Assessment of the following diseases returned a mean grading point threshold below 2: lower extremity arterial occlusive disease (mean – 1.75 points), abdominal aortic aneurysm (1.31), carotid artery stenosis (1.1) and thoracic aortic aneurysm (1.0).

Assessment of sensitivity and specificity of time-resolved MRA

Among all TR-MRA examinations, there were 98 true positive results, 48 true negative, 2 false positive (right renal artery stenosis and left subclavian artery stenosis) and 5 false negative (4 renal artery stenoses <50%, 1 dissection of post-traumatic thoracic aortic aneurysm). Time-resolved MRA for the diagnosis of vascular pathologies demonstrated a sensitivity of 95% with a specificity of 96% a positive predictive value of 98% and an accuracy of 95%.

Discussion

The most important advantages of time-resolved MRA are short acquisition time, high-temporal resolution, reduction of motion artifacts and the ability to selectively visualize arteries and veins without the necessity of a time delay estimate between contrast material injection and scanning. This is achieved with the expense of spatial resolution, which is decreased compared to single-phase CE MRA and as a result could affect assessment of small vessels and depiction of some vascular pathologies. On the other hand time-resolved MRA delivers additional hemodynamic data which is comparable to that acquired with DSA. This may be helpful in establishing an accurate diagnosis, as well as in the assessment of the extent of depicted vascular abnormality which may facilitate proper management. Additionally technique of TR-MRA enables, due to short acquisition time, visualization of arterial inflow without venous contamination. This can be especially valuable in anatomical areas where venous return is fast (neck, pulmonary and renal vessels) and in regions where enhancement of the vessel is asymmetric due to dissection, stenosis or occlusion [4,5].

In the performed study two independent readers made quality assessments. The majority of TR-MRA examinations were considered good with only few examinations graded as moderate. There were no poor quality studies in the opinion of either radiologist with a very high interobserver agreement (kappa 0.757). Moreover, there was no difference in the quality of TR-MRA images between various anatomic regions. The most common factors responsible for decrease of image quality were motion artifacts and partial venous overlap over arteries, which, most probably, would also diminish the quality of the single-phase MRA images, at least in the similar degree.

Patients suspected of having renal artery stenosis (RAS) constituted the largest group in our study. RAS in young patients is most commonly caused by fibromuscular dysplasia while atherosclerosis is the leading cause in elderly patients. The most common presentation of RAS is renovascular hypertension, which untreated, may progress to renal insufficiency. According to literature TR-MRA sensitivity for diagnosis of significant RAS (>50%) approaches 100% with a specificity from 98 to 100% [6]. In our material the sensitivity was lower (92%) whereas the specificity was similar to that reported in literature (98%). The decrease in sensitivity in our material may have been a result of including stenoses <50% in our analysis.

We did not perform a statistical analysis of the degree of renal artery stenosis. MR angiography is known to overestimate stenosis by approximately 26% compared to DSA [7]. Furthermore, the spatial resolution of time-resolved MRA is lower than in the single-phase technique which may further decrease the sensitivity of this method in the detection of mild and insignificant stenosis. The method is also significantly inferior in evaluating intrarenal vessels. According to Volk et al. visualization of segmental renal arteries is possible in only 61.3% of patients [7]. Acquisition of renal MRA data in the coronal plane is another possible source of incorrect assessment of antero-posterior stenoses of the renal arteries [8]. On the other hand the dynamic information provided by the high temporal resolution of this technique may compensate the disadvantages related to TR-MRA's lower spatial resolution. State-of-the-art sequences with short acquisition times allow visual assessment of blood inflow into the studied vessel in subsequent phases of the TR-MRA examination. These also include the evaluation of increased flow distally to the stenosis, which indirectly confirms a significant stenosis [6].

Another important advantage of time-resolved MRA is the possibility of comparative evaluation of renal perfusion and function. The technique, described as MR renography, requires evaluation of additional phases or renal contrast enhancement. These may be obtained with the use of the same TR-MRA sequence (Figure 1), allowing qualitative or semi-quantitative analysis of renal enhancement with good contrast and spatial resolution. Paramagnetic gadolinium chelates used for MRA have very similar kinetics to ^{99m}Tc-DTPA used in nuclear medicine, and are almost completely excreted (98%) in the glomerular filtrate. Renal enhancement may be depicted with the use of time curves of the whole organ as in traditional renography or due to the higher spatial resolution of mMR, using separate enhancement curves for the renal cortex, medulla and pyelocalyceal system. MR renography also enables better detection of segmental renal perfusion abnormalities, as compared to traditional renography [9,10].

Comparative analysis of renal perfusion and enhancement was an important evaluation aspect for the hemodynamic significance of renal artery stenosis. Delayed and/or lower enhancement of the cortex and medulla, as well as, delayed excretion of contrast material, compared to the contra lateral kidney, were considered a hemodynamic predictor of significant stenosis. Interpretation problems arose when bilateral perfusion abnormalities were present as reference standard could not be established. In such cases, enhancement curves were compared to other renal studies with the results subjectively evaluated by both readers.

The mean grading of hemodynamic information provided by TR-MRA in patients suspected of RAS was slightly

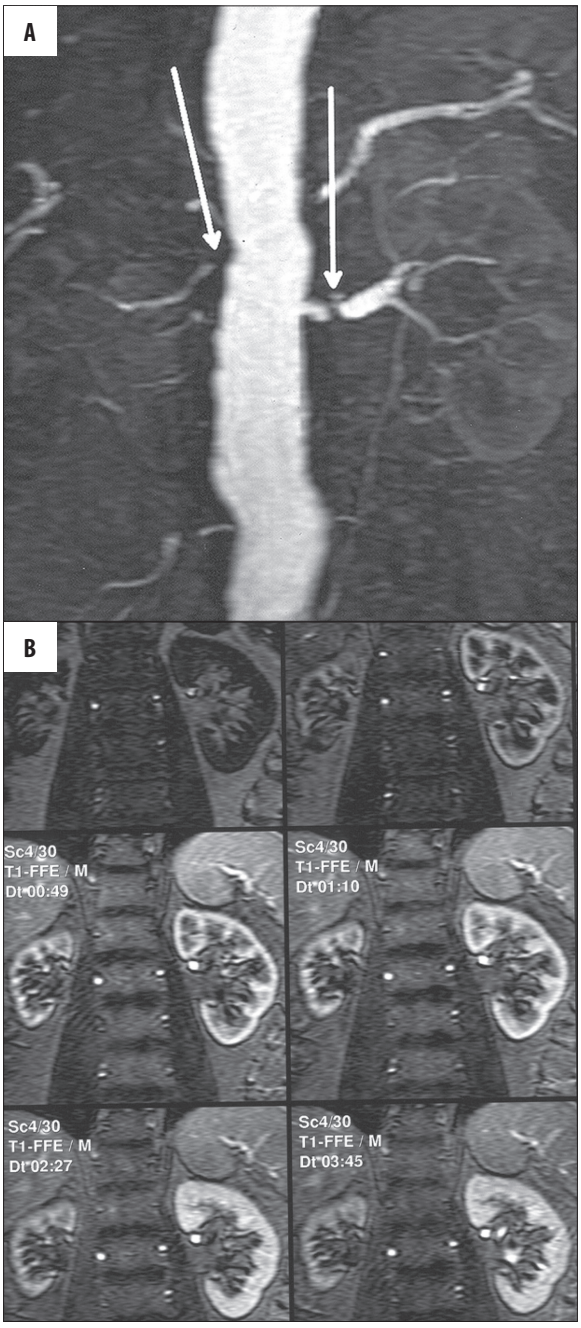

Figure 1. MIP reformation from arterial phase (**A**) demonstrates significant stenoses of the proximal right and left renal arteries and narrowing of the whole right renal artery. On source 3D GRE images from different phases of contrast enhancement (**B**) the right kidney is smaller than the left, with narrow parenchyma and lack of significant enhancement of renal medulla and pyelocalyceal system. Normal contrast enhancement of the left kidney. The quality of mMRA examination assessed as very good and hemodynamic data as relevant.

above the threshold of 2 (2.06). This indicates that time-resolved techniques may be useful in selected patients with RAS, although the correlation of hemodynamic data with the significance of renal artery stenosis warrants further investigation.

Indications for MRA of the thoracic and abdominal aorta often include previously diagnosed aneurysm or dissection. Common etiologies of these diseases include atherosclerosis and hypertension and less frequently trauma or congenital arterial wall anomalies (ie. Marfan's syndrome). In our study group 29 patients presented with aortic dissection and 24 with aortic aneurysm. From the first group the majority of patients were diagnosed with chronic type B aortic dissection. MRA was performed either for follow-up or for evaluation before planed stent-graft implantation. Only 5 patients had acute dissection (2 weeks or less from onset of symptoms) while one patient was referred for assessment of possible leak after stent-graft implantation. One patient had post-traumatic aneurysm with a resulting aortic dissection.

With the use of time-resolved MR angiography and with a sufficient blood velocity difference between the false and true channel it is possible to achieve separate enhancement of dissected channels (Figure 2). This enables accurate visualization of visceral artery ostia (true versus false channel) and additional reentry points between channels. The shorter the acquisition time of the TR-MRA phase, the smaller the velocity difference is required for visualization of separate channel enhancements in subsequent study phases. The state-of-the-art MR scanners with very short acquisition times enable selective visualization of both channels even with subtle differences in blood velocity [11].

In single-phase MRA, acquisition is often synchronized with contrast-enhancement of true channel. In cases with a high blood velocity difference, this may cause suboptimal depiction of the false channel together with vessels originating from false lumen. On the other hand, if the acquisition takes place during optimal enhancement of the false channel, the visualization of the true channel could be compromised.

In acute dissections (5 patients in our study group), short examination times are essential, therefore CT angiography is still considered to be the primary diagnostic modality for these lesions. However, Vogt et al., who examined 10 patients with acute dissection, showed that time-resolved MRA may also be viable alternative in this group of patients [12]. In three of ten patients this method provided additional information compared to static MRA and had impact on therapy planning. The state-of-the art MR equipment allows significant reduction in acquisition times leading to a decrease in the total examination time down to a few minutes and therefore enabling rapid diagnosis in patients with acute aortic dissections. In chronic dissections, for follow-up or out-patients referred for procedure planning, the perspectives of time-resolved MRA are even more promising. However, the number of publications addressing the use of time-resolved MRA in aortic dissection is limited and further studies with larger groups of patients are necessary. In our material the mean grading of hemodynamic information provided by TR-MRA was slightly above the threshold of 2, suggesting that this technique may be useful in these patients.

In the majority of 24 patients with aortic aneurysms time-resolved MRA technique did not provide additional,

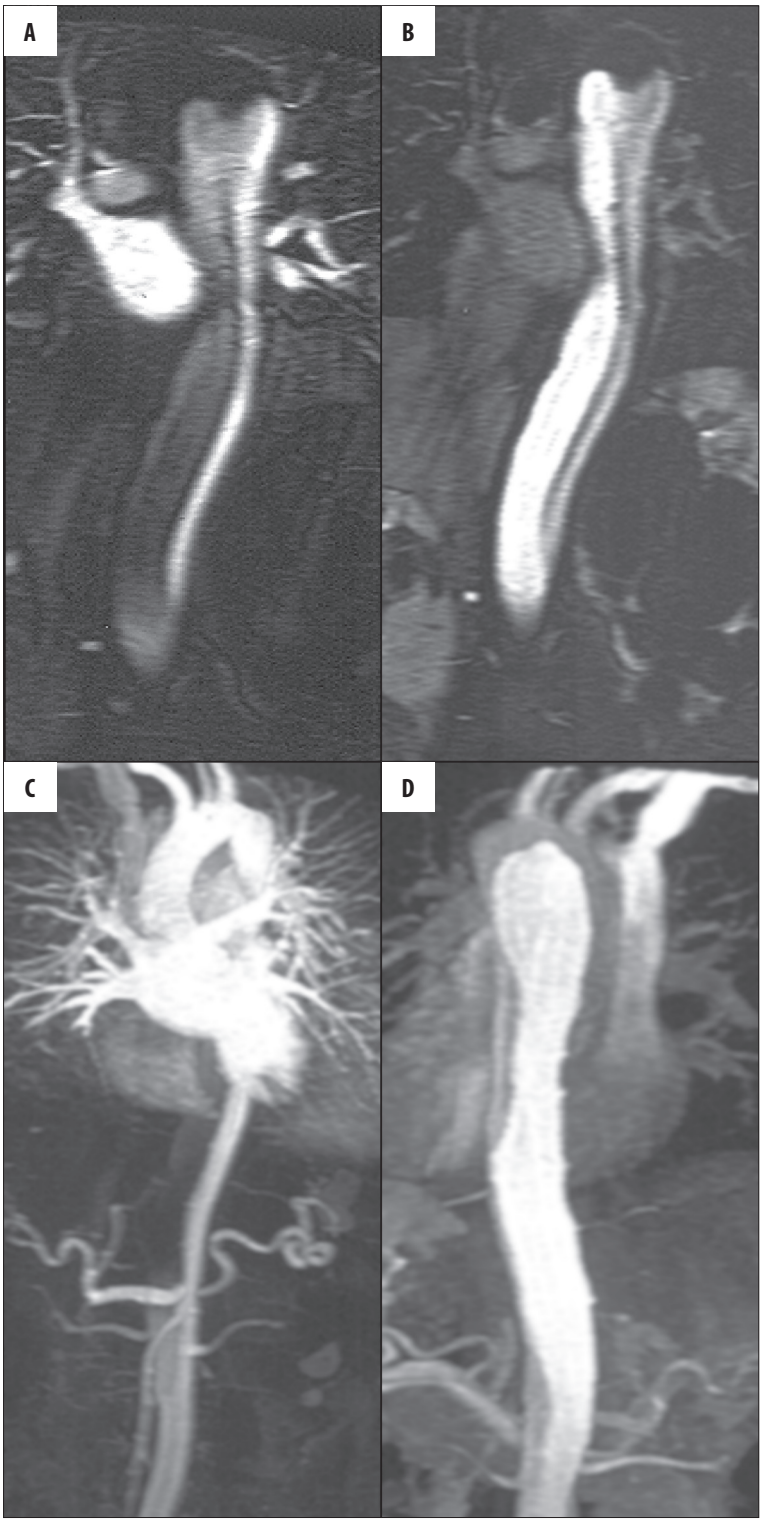

Figure 2. Thoracic and abdominal aortic dissection type Stanford B. Time-resolved MRA - source images: early (**A**) and subsequent (**B**) phases; MIP reformations: early (**C**) and subsequent (**D**) phases. In the early phase (**A** and **C**) true channel of dissected aorta and arteries originating from this channel are demonstrated. Distal communication between true and false channels, just below the level of renal arteries, and the origin of the right renal artery from the false lumen, is also noted. During subsequent phase (**B** and **D**) the enhancement of the false lumen is more pronounced than of the true lumen. The quality of this examination was assessed as very good and hemodynamic data as relevant.

important hemodynamic information in the readers opinion (mean grading – 1.31 for abdominal aorta and 1.0 for thoracic aorta) (Figure 3). The exceptions were patients with large abdominal aneurysms which slowly enhanced with contrast material. In these cases, detailed visualization of different segments of the aortic aneurysm was possible with the visualization of subsequent phases of contrast enhancement of aorta on time-resolved MRA images. Our experiences are not different to observations made by other authors, based on larger groups of patients [5,13].

The presented material included 7 cases with stenosis or occlusion of carotid or subclavian arteries. Stenoses of carotid arteries are not related to any significant hemodynamic effect, beside turbulent flow and change in blood

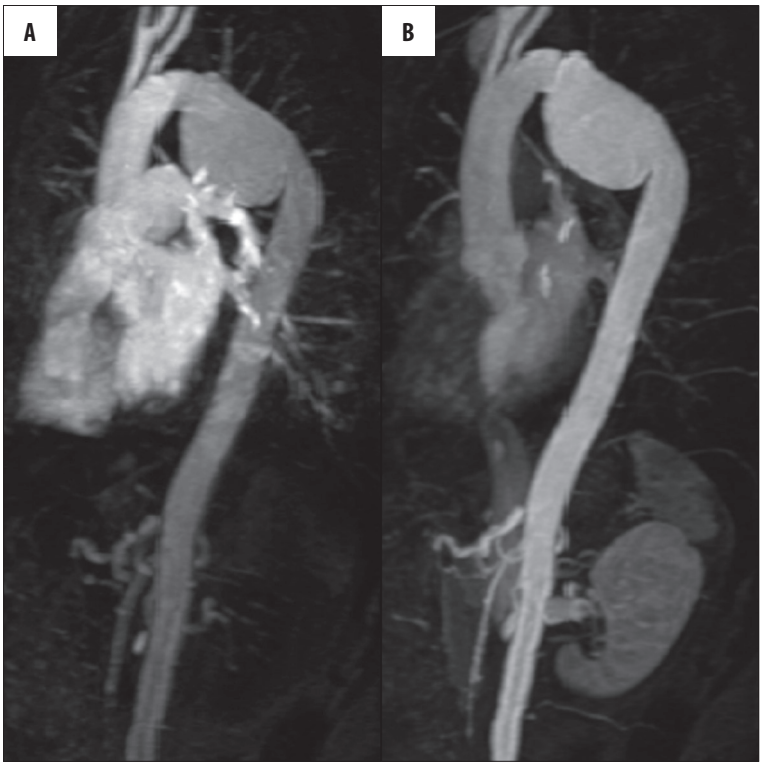

Figure 3. Post-traumatic aneurysm of thoracic aorta located at aortic isthmus. Time-resolved MRA (MIP reformations): early (**A**) and subsequent (**B**) phases. The quality of mMRA examination assessed as very good; absent hemodynamic information.

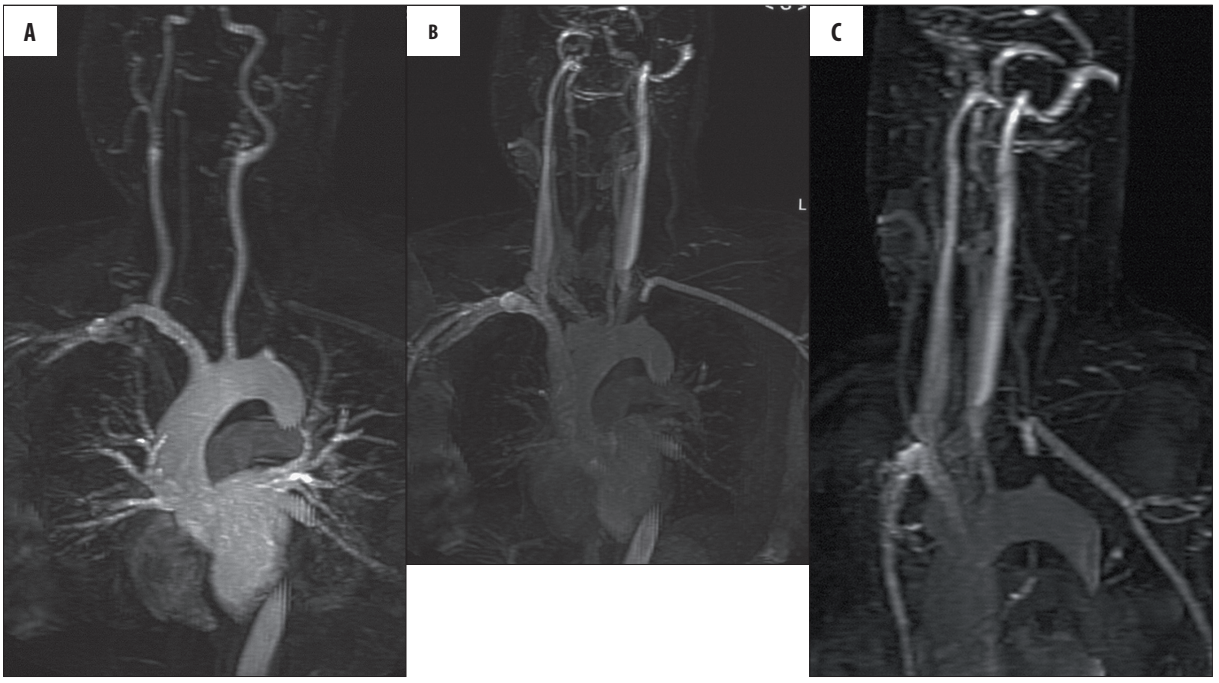

Figure 4. Steal syndrome. Time-resolved MRA – MIP reformations: early phase (**A**), subsequent phase (**B** and **C**). Occlusion of the proximal left subclavian artery is well demonstrated in the early (arterial) phase of the examination. During subsequent phase distal aspect of the left subclavian artery is depicted. The quality of mMRA study was assessed as very good and hemodynamic data as relevant.

velocity. On the other hand, severe stenosis or occlusion of the proximal subclavian artery results in a reverse flow in the carotid artery, leading to the subclavian steal syndrome, where blood to the upper extremity is supplied through the vertebral and carotid artery via the circle of Willis. In our material there were two patients with confirmed subclavian steal syndrome, 5 with carotid artery stenosis and one with false positive diagnosis of stenosis of the proximal subclavian artery.

In patients with steal syndrome, the hemodynamic information had high significance (mean grade – 2.5) in the opinion of both readers (Figure 4). In both cases, time-resolved techniques enabled visualization of the proximal, to the

occlusion site, aspect of subclavian artery in the early phase and filling of a distal subclavian artery from reversed flow in carotid artery, in subsequent phases. This allowed the length of occluded segment to be assessed, as well as facilitated the selection of optimal therapeutic procedure (angioplasty vs. stent placement vs. vascular surgery). In cases suitable for percutaneous intervention, the data provides useful information enabling optimal pre-procedure planning (balloon or stent suitable for detected abnormality). To our knowledge, there are no previous reports regarding the use of time-resolved MRA in patients with subclavian steal syndrome. Despite small number of patients in our material, we presume that this technique may become useful for the evaluation of steal syndrome, providing not only morphological information but also enabling assessment of important hemodynamic parameters related to blood flow in the carotid and subclavian arteries.

Contrary to steal syndrome, in patients presenting with carotid artery occlusive disease, TR-MRA did not provide significant hemodynamic information (mean grade – 1.1). In these patients, high spatial resolution appears to be paramount, enabling precise evaluation of the stenosis grade which, according to North American Symptomatic Carotid Endarterectomy Trial (NASCET), facilitates decision upon optimal medical treatment. Single phase MRA with longer acquisition time and highest possible resolution, still seems to be the optimal diagnostic modality for assessment of this pathology. The only possible, although not crucial, advantage of time-resolved MRA is its short acquisition time, which allows for selective visualization of cervical arteries without venous contamination. In the neck region, as compared to the lower extremities, there is no collateral vasculature, which could develop into a vascular network providing blood supply to arteries distal to the occlusion site. Moreover, differences in blood velocity due to stenosis are not significant and single-phase MRA provides a sufficient time window (usually 20–30 s.) for the visualization of all cervical arteries [14].

Our material included relatively small number of TR-MRA examinations of the arteries of the pelvis and lower extremities (2 cases of Leriche's syndrome, 2 cases of occlusive disease of the lower extremities, 3 vascular malformations of lower extremity) preventing a thorough assessment of this technique in these areas. In Leriche's syndrome, time-resolved MRA allowed for visualization of the level of aortic occlusion and accurately showed collaterals supplying the distal arteries. In both readers' opinions, the time-resolved technique provided additional data on the extent of the disease as well as provided significant hemodynamic information about pelvic arterial blood flow (direction of flow in collateral vessels, approximate assessment of blood velocity) in both patients which facilitated treatment. In single-phase MRA, acquisition of data is usually synchronized with the highest concentration of contrast material in aorta. Therefore, assessment of collateral vessels, which may enhance in later phases, may be suboptimal or even impossible. Similar, static images are obtained in CT angiography. Nowadays, with the multi-detector CT units with short acquisition times, it is possible to obtain time-resolved CTA images. However, due to patient's exposition to multiple radiation doses, such studies are not performed in routine practice.

Despite only three patients with vascular malformation in our material, it appears that time-resolved technique may play an important role in evaluation of these lesions and become a non-invasive alternative for subtraction angiography [15]. The majority of malformations consist of vessels which can be easily visualized with MR angiography. In these vascular pathologies good spatial resolution appears to be less important than good temporal resolution, which allows visualization of inflow of contrast-enhanced blood into vascular malformation, nidus and draining veins. In three cases from our material, there was a high level of agreement between time-resolved MRA and DSA. Analysis of MRA images facilitated preoperative assessment of malformation and was helpful in the planning of an intravascular procedure.

Previously used, non-contrast enhanced MR techniques, such as heavily T2-weighted sequences or contrast-enhanced single-phase MRA, despite relatively good morphological assessment of vascular malformation, were often not able to discriminate between different types of anomaly (ie. venous, arterio-venous or hemangioma). Time-resolved MRA techniques, together with the analysis of multiple phases of vascular enhancement could facilitate more accurate determination of malformation type. Ziyeh et al., who investigated the use of time-resolved MRA with temporal resolution of 1.5 seconds, in intra- and extra-cranial vascular malformations at 3T, obtained good agreement between time-resolved MR and conventional angiography [16]. The advantage of TR-MRA, as compared to DSA and Doppler US, is a shorter acquisition time. The additional advantage of TR-MRA in comparison to DSA is lower cost and less invasiveness. The obvious disadvantage of TR-MRA is the non-selective visualization of the imaged vessels.

One of the limitations of this study is lack of evaluation of some anatomic regions such as head and lungs, or limited number of patients with certain vascular diseases (i.e. lower extremity arterial occlusive disease). Data available from recent years indicates that TR MRA technique may be useful in patients with lower extremities ischemia, especially in those having asymmetric arterial occlusions, which may result in different time of arrival of contrast material to each extremity [17,18]. In preoperative assessment of patients with lower extremity ischemia, identification of segmental artery branches below knee is paramount to planning vascular surgery. In the study of Thornton et al., TR-MRA technique with spatial resolution of $1.1\times1.1\times1.5$ mm provided better depiction of dorsal pedis and posterior tibial artery than 2D Time-of-FLIGHT (TOF) MRA [17]. Also Zhang et al. demonstrated that TR MRA is accurate technique for evaluating infrapopliteal vascular disease. They studied 52 patients with calf and pedal arterial disease, using 2D TR MRA and X-ray DSA and achieved higher interobserver agreement for TR MRA than for DSA [18].

Technique of TR MRA can be also of some benefit in patients with vascular diseases of the chest. Ersoy et al., who evaluated efficiency and reproducibility of TR 3D MR angiography in the diagnosis of pulmonary embolism, concluded that this technique provides confident diagnosis of emboli from the main pulmonary artery through segmental branches and can be incorporated as screening examination

of patients with contraindication to the use of iodinated contrast material [19]. The technique of TR pulmonary MR angiography may be useful not only in depicting morphologic abnormalities in pulmonary vasculature, but also in evaluation of the passage of the bolus through the cardiopulmonary circulation or even in semi-quantitative assessment of lung perfusion [20].

Conclusions

In summary, developments of 3D MRA sequences allowed obtaining of multiple phases of contrast-enhanced vessels, enabling the use of this technique in various anatomic regions and in different vascular diseases. Radiologists planning MRA examinations of a patient with particular vascular pathology should take into consideration possible advantages and disadvantages of both contrast enhanced techniques: high-resolution single phase MRA and time-resolved MRA with lower spatial resolution. To our knowledge, this paper is the first attempt to assess and compare the usefulness of time-resolved MRA in different vascular territories and different pathologies. Despite limited number of patients with some vascular diseases (carotid artery stenosis, steal syndrome, Lerich'e syndrome, vascular malformation, occlusive disease of the lower extremities) we were able to identify several pathologies, in which the hemodynamic information obtained with the use of TR-MRA provided additional, important data facilitating diagnosis. They also enabled a thorough assessment of disease extent and severity, resulting in better treatment planning in some cases. Although these results require further confirmation on larger population of patients, they suggest that time-resolved MRA may be valuable technique in the evaluation of patients with the following vascular diseases: visceral artery pseudoaneurysms, arterio-venous malformations, subclavian steal syndrome, Leriche's syndrome, aortic dissection and renal artery stenosis.

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