Literature review

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Evaluation of some literature reviews to determine contrast enhanced magnetic resonance angiography can replace the other imaging modalities for the assessment of carotid artery stenosis

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Introduction

Cardiovascular disease is a serious public health problem and is the leading cause of morbidity and mortality worldwide. Over 70% of these deaths are atherosclerosis related, which is a systemic disease of the vessel wall that occurs in the aorta, carotid, coronary, and peripheral arteries and often causes stroke, myocardial infarction, and sudden death without prior symptoms.[1] Stroke ranks third among all causes of death in Western countries, Of all strokes, 87% are ischemic, and an estimated 20% are caused by carotid atherosclerotic disease.[2] The microscopic alterations of the initial phase of this disease start during childhood, but usually carotid plaques remain asymptomatic until an advanced pathological stage is reached.[3] In the last few years, the degree of carotid artery stenosis was considered the only determinant factor to address patients to treatment , that's no longer the case in the meantime, several factors are considered potentially important markers for future cerebro-vascular events, including plaque composition, presence and state of the fibrous cap (FC), intra-plaque haemorrhage, plaque ulceration and plaque location.[3] All of these factors, therefore, need to be taken into account for a correct diagnostic and preventive approach aimed at risk stratification and treatment planning to reduce the incidence and severity of acute cerebrovascular disease.[4]

Three large multi-centric randomized studies, NASCET (North American Symptomatic Carotid Endarterectomy Trial), ECST (European Carotid Surgery Trial) and ACAS (Asymptomatic Carotid Athero-Sclerosis Group), provided cut-off values stenosis degree indicating possible benefits of carotid endarterectomy (CEA).[3]

The most used methods to quantify the degree of carotid artery stenosis are North American Symptomatic Carotid Endarterectomy Trial (NASCET) and European Carotid Surgery Trial (ECST), both evaluating the degree of stenosis as the percentage reduction in the linear diameter of the artery.[3] In addition, in both NASCET and ECST trials, stenosis degree was determined by conventional angiography, since Computed Tomography Angiography (CTA) and Magnetic Resonance Angiography (MRA) were not available at that time.[3]

Recently, the reference imaging technique in assessing the degree of carotid stenosis was only Digital Subtraction Angiography (DSA). However, it has been claimed that advanced non-invasive imaging modalities including Doppler Ultrasound (DUS), MRA and CTA have progressively replaced the diagnostic role of DSA.[4] This is mainly due to its high cost and greater risk.[5] In addition, these in vivo techniques assist in analysing plaque morphology and its characteristics.[3] This literature review will highlights the performance characteristics of contrast enhanced - MRA compared to other imaging modalities in the diagnosis of carotid artery stenosis.

Diagnostic modalities

Ultra-Sound Echo-Color-Doppler (US-ECD)

US-ECD is globally accepted as the standard imaging modality for first-line diagnosis of atherosclerosis of the carotid artery bifurcation. This high-resolution, non-invasive technique is readily available, rapidly applicable, and can be performed at relatively low cost.[3] Two different approaches may be adopted to quantify the degree of carotid artery stenosis by using US-ECD: morphological and Peak-Systolic-Velocity (PSV) values in the affected region.[3]

Computed Tomography Angiography (CTA)

CT angiography, undertaken with modern spiral CT machines, enables a volumetric acquisition through continuous radiograph source rotation by simultaneous continuous table movement. This method enables rapid examination with little discomfort by peripheral injection of a contrast agent.[6]

Digital subtraction angiography (DSA)

DSA is employed in both diagnostic and interventional purposes. This invasive procedure a puncture is made and specific catheter is used to access the common carotid artery. 2D or 3D high spatial resolution (SR) x-ray images are acquired before and after the injection of iodinated contrast agents (CA). The carotid arteries axis can be performed from different arterial access including femoral, axillary, brachial and radial arteries, based on the arterial anatomy.[3] DSA as used in NASCET and ECST, is still considered to be the most accurate method for assessment of carotid stenosis.[6]

Magnetic Resonance Angiography (MRA)

Pulse sequences for carotid plaque include black-blood and bright-blood imaging.[2] The two main techniques for the assessment of carotid disease include time-of-flight and contrast-enhanced MRA.[6] Time-of-flight MRA is a gradient-recalled echo sequences, acquired perpendicularly to the longitudinal axis of the vessels with extremely short TR. The difference in spin saturation between the stationary tissues (completely suppressed) and moving protons in blood (un-saturated) creates the so-called "in flow-enhancement" that produces the angiographic effect used for TOF imaging. to achieve the maximum contrast in signal intensity between blood and background tissue and to avoid venous enhancement, additional saturation pulses can be applied. In addition, 2D or 3D k-space sampling is used in order to increase the spatial resolution.[3] The negative points of TOF are it is time consuming technique as it takes from 10 to 15 min, which may increases susceptibility to artefacts due to motion and swallowing, and susceptibility to turbulent flow and dephasing artefacts, which tend to produce flow voids in regions of tight stenosis.[6]

Contrast-enhanced MRA with T1-weighted 3D Gradient-Echo sequences is based on the introducing of Gadolinium-chelate contrast agents intravenously, which shorten the T1 relaxation time of blood. This results in a significant difference in signal intensity between flowing blood and stationary tissue at heavily T1-weighted arterial phase imaging, leading to the high signal intensity of blood on post-Gd T1-weighted sequences.[3] It depends on the amount of contrast agent concentrated within the vascular bed during acquisition, therefore, imaging should be ideally performed at the peak of vascular enhancement. Unlike TOF imaging, signal of vessels in CE-MRA is less flow sensitive. A further relevant benefits of CE-MRA is that the usual loss of signal-to-noise ratio (SNR) from rapid scanning with most MR pulse sequences can be compensated by injecting the same dose of contrast agent faster over a shorter scan duration.[3]

Literature evidence

In the year of 2016, Netuka et al carried out a study on patients with ICA stenosis for CEA to compare the performance of different diagnostic modalities using histological specimens. The study includes stenosis groups of <50%, 50 to 69% and >70% stenosis degree. Stenosis measurements were all based on both ECST and NASCET methodology. These measurements were done by two independent radiologists for each imaging modality, except for the DUS in which the measurements were performed by an experienced vascular sonographer. Only the high quality specimens were included in the analysis. CTA was performed in 152 patients, DSA in 138 patients, MRA in 107 patients and DUS in 88 patients. CE-MRA scans were performed using 1.5 T MRI scanner before and after introducing Gd based contrast agent injection.

The strongest correlation between preoperative tools and histological findings was observed for CTA. Based on ECST, CTA underestimated histological measurement by 2.4%, DSA underestimated the histological measurement by 7 % and MRA overestimated the histological measurement by 2.6 %. By using NASCET, CTA underestimation is 11.9 %, DSA underestimation is 12.2 %, MRA underestimation is 0.6 % (NASCET) and DUS overestimated the stenosis by 1.8 %. It was concluded that CTA yield the best accuracy in detection of carotid stenosis. In addition, MRA was precise in detection moderate stenosis but slightly underestimated mild stenosis and overestimated high grade stenosis. Although it was claimed that it is impossible to let all patients go through all four investigations, it would be more accurate if the cohort was identical. Furthermore, it was not reported the age range of the patient sample as well as the time period between the examinations.

Gough 2011, reviewed a previous meta-analysis that was published in 2006. He was a co-author in this meta-analysis. It included 41 studies between 1980 and 2004 of a total of 2541 symptomatic patients comparing non-invasive imaging with DSA. Stenosis degree was categorized following NASCET method,[7] stated that only prospective studies of 20 or more participants were included in the original meta-analysis, a median of 45 patients per study. Six studies did not report patients' ages, while the average age in the rest was mostly in the 60s. In addition, two or three reviewers (a neuro-radiologist or radiologist, and a statistician) blinded to the DSA results independently assessed the papers with specific criteria. It was concluded that direct comparisons of test accuracy between non-invasive techniques were impossible because some studies had unequal sample size for each technique.

As shown in table 1,[5] emphasized the following: Compared to DSA, the sensitivity and specificity for noninvasive imaging of a 70-99% carotid artery stenosis are DUS: 0.89 and 0.84; TOF-MRA: 0.88 and 0.84; CE-MRA: 0.94 and 0.93; and CTA: 0.77 and 0.95, respectively. Therefore, for 70–99% stenosis group, CE-MRA has the highest sensitivity while CTA is more specific. However, these techniques were less reliable in the assessment of 50-69% carotid stenosis since there were less data available for comparison. Finally, DUS provides the optimum screening tool due to its sensitivity and specificity, availability and low cost. A further investigation with CE-MRA is most reliable when CEA appears indicated.

Table 1 Meta-analysis of sensitivity and specificity for 70–99% and 50–69% stenosis groups in non-invasive imaging techniques. Adapted from (Wardlaw et al., 2006)

	DUS	CTA	TOF-MRA	CE-MRA
70–99% stenosis				
Sensitivity	0·89	0·77	0·88	0·94
Specificity	0·84	0·95	0·84	0·93
50–69% stenosis				
Sensitivity	0·36	0·67	0·37	0·77
Specificity	0·91	0·79	0·91	0·97

In (2012), Anzidei et al, conducted a comparative study between imaging modalities using a DSA as the reference standard on a total of 170, age range 62-90 years, 108 men and 62 women. All patients had history of cerebrovascular problems and carotid artery stenosis calculated sonographically according to NASCET criteria as >70% or 30-50%. Supsequently, they underwent combined evaluation with first-pass (FP) and steady-state (SS) CE-MRA and CTA. Finally, these patients sent for DSA, 73 DSA was performed during CEA while 97 DSA during stenting. The four examination techniques were achieved within a period of two weeks. Linear regression measurement according to the NASCET criteria was followed to calculate and compare the degree of stenosis: I (1-29%) mild, II (30-49%) and III (50-69%) moderate, IV (70-99%) severe and V occlusion. Two blinded independent radiologists with 15 and 10 years of experience in vascular radiology assessed the MRA and CTA scans, while the DSA examinations were assessed by a third radiologist with several years of experience in the same field. The latter was unaware of the findings of the other scans.

With regards to MRA scans, they were done in 1.5 Tesla MR system. The FP-MRA was taken after the injection of Gd contrast agent with sequence parameters TR 3.5ms, TE 1.2ms, FA 30°, TA 14s,

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thickness 0.7mm, matrix 384x384 and IPAT x2. Four minutes after the injection, the higher SR SS-MRA scans were acquired with TR 7.5ms, TE 2.3ms, FA 30°, TA 325s, thickness 0.7mm, matrix 512x512 and IPAT x2, facilitating iso-tropic voxel size. FP-MRAs produce optimal image quality of 224 (66%) carotids, adequate of 76 (22%) carotids and suboptimal of 36 (12%) due to either motion artefacts or incorrect timing. Image quality in SS-MRA was optimal in 284 (84%) vessels and adequate in 52 (16%).

In this study, two MRA cases were excluded as a result of low diagnostic quality related to motion artefacts. Therefore, 336 carotid bifurcations were clinically evaluated. Accuracy, sensitivity and specificity of the imaging modalities for detecting stenosis are presented in table 2. The analysis of stenosis degree shows no statistically significant difference between CTA and MRA. The authors concluded that CTA is the most accurate scan in studying carotid stenosis with a slightly improved accuracy compared to SS & FP-MRA, 97%, 95% & 92% respectively, and greater performance than DUS 97% & 76 respectively . In addition, SS-MRA scans have enhanced the evaluation of stenosis relative to FP-MRA.

Table 2 Accuracy, sensitivity and specificity of the imaging modalities for detecting stenosis. Adapted from: (Anzidei et al., 2011)

	Accuracy (%)	Sensitivity (%)	Specificity (%)
DUS	76	67	87
FP-MRA	92	88	95
SS-MRA	95	93	97
CTA	97	95	98

A recent study has been published on a total of 21 patients, 15 men and six women, with known calcified stenosis of carotid artery, 11 patients were symptomatic while 10 were asymptomatic. The age range of these patients was 54-82 years.[8] Korn et al investigated the performance of CE-MRA compared to Dual-Energy (DE-CTA) in grading of carotid artery stenosis with extensive calcification. DSA was the gold standard technique. A 1.5 MR system was selected to scan patients in this study. Two independent radiologist evaluated the stenosis according to NASCET criteria, with a gap at least four weeks between different techniques to avoid a recall bias. Average grades of stenosis were 80.7 in DSA, 81.4 in CE-MRA and 80.0 in DE-CTA. DSA showed 99% stenosis grade in six out of 21 patients. Five of these cases were identified as pseudo-occlusions in CE-MRA, whereas four were identified as occlusions in DE-CTA. This study concludes that in comparison with DSA, DE-CTA had a slightly better performance in measuring the severity of stenosis than CE-MRA. Furthermore, DE--CTA is preferred in case of sever calcification.

The downside if this study is the small number of patients, which could influence the accuracy of the final result. Moreover, it was not specified the time period between different imaging techniques[9] sought to assess the correlation of 3D TOF-MRA and CE-MRA for carotid artery stenosis evaluation at 3T MR system. It comprised 23 patients, five women and 18 men, age range 45 to 78 years, with internal carotid artery stenosis detected with DUS. 15 patients were asymptomatic. MR scans were assessed independently by two board-certified radiologists with eight and four years of MRI experience, respectively. A four-week time period between evaluation sessions of both MRAs techniques was followed, while the readers wear blinded for other clinical information or other diagnostic imaging. Stenosis grading was based on a five-point scale: 0 = normal; 1 = mild stenosis, < 50%; 2 = moderate, 50–69%; 3 = severe, > 70% but < full occlusion; 4 = occlusion. CE-MRA detected stenosis in 24 (52%) out of 46 carotids evaluated, while TOF-MRA showed stenosis in 27 (59%). The authors conclude that 3D TOF-MRA should not replace CE-MRA of the carotid arteries at 3T MRI, as it significantly overestimates stenosis, unless Gadolinium is contraindicated. Limitations in this study include are: as DSA reference technique was not performed, the sensitivity and specificity of both CE-MRA and TOF-MRA were not able to identify, and the small cohort size may invalidate the final findings.

Discussion

(4) have proved the high levels of accuracy, sensitivity and specificity for both CTA and CE-MRA in stenosis group >70% or 30--50%. The high resolution SS-MRA was more accurate, specific and sensitive than FP-MRA, with almost no difference compared to CTA. This result may highlight the importance of introducing delayed phase imaging in MRI of carotids. However, CTA is more accurate comparing to FP-MRA owing to its higher SR, 97% and 92% respectively (Anzidei et al., 2011). For 70-99% carotid artery stenosis, Gough (2011) has shown that CE-MRA and DUS have a higher sensitivity than CTA, 0.94; 0.89 and 0.77 respectively. However, the latter has a slightly better specificity than CE-MRA, 0.95 and0.93 respectively. In this meta-analysis revision, it has been validated that CE-MRA is more sensitive while CTA is more specific for 70-99% stenosis group. For 50-69% group, there were no sufficient data for possible (Gough, 2011).

In other study that is conducted by Netuka et al (2016), CTA presents the highest accuracy in stenosis groups <50%, 50-69% and >70%, while CE-MRA shows overestimation or underestimations. Histological specimens were used for comparison purposes which may affect the validity of the final results. This is because several studies have reported that plaques before and after laboratory processing show minor and uniform shrinkage (Netuka et al., 2016).

In general, the advantages of high resolution images and the estimation of blood flow dynamics obtained by DSA are undeniable. However, DSA has several disadvantage, such as, it is invasive, labour intensive, time intensive, expensive, and requires a period of bed rest. Moreover, it requires skilled operators and is usually done in specialist neurovascular centres, therefore, it is much less readily available, particularly compared with alternative non-invasive tests, and this can delay definitive management.Regardless of the improvement in catheter technology and expertise, other major concern with DSA is that it may cause neurological complications.[6]

The major advantages of CTA lie in its availability, rapidity, relatively low cost, ability to measure absolute tissue density, high spatial and contrast resolution images and ability to identify and quantify calcifications with great accuracy.[2] From the axial source images, post-processing that uses multi-planar reformats, maximum intensity projections, or three-dimensional volume-rendering algorithms can be undertaken to produce angiographic images similar to those produced from DSA and to enable stenosis measurements in accordance with NASCET or ECST criteria.[6] However, there are some drawbacks of CT angiography, such as ionisation radiation dose and artefacts caused by plaque calcium. Extensive plaque calcification, particularly when circumferential, can obscure a clear image of the lumen of the diseased carotid artery and thus affect exact assessment of the extent of stenosis.[6]

As reported by Anzidei et al (2012) in their study, there were nine cases of mild adverse reaction to CTA iodinated CA, whereas two patients suffered moderate to severe reactions. Following the DSA procedure, there were 11 cases of complications and eight patients suffered moderate to severe reactions to iodinated CA. however, there

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were no complications following the CE-MRA. This makes MRA more preferable in some cases particularly those who have allergy to iodinated CA.

With refers to DUS technique, it has many advantageous that have been approved in several published studies. It is as CTA and CE-MRA does not require surgical intervention to assess the stenosis. In addition to its low cost and portability, it provides information about the location and extension of carotid stenosis. Moreover, a general background related to blood flow dynamics, plaque structure and vessel-wall can be obtained using DUS.[2,6] In spite of the all of these benefits, DUS scan is high operator dependent as the movement of US probe, selecting of Doppler angles and cross-checking with color flow ultrasound are different from one US radiographer to another. Additionally, it is more susceptible to artefacts from calcified plaques and difficult in distinguishing a subtotal from total occlusion.[6] This technique, also, does not provide a 3D visualization of the vascular anatomy and surrounding structures, which makes the use of CTA or MRA crucial.[4]

Beside the fact that patients are not exposed to ionizing radiation in MRI, the main advantage of MRA is its capability in capturing blood vessels in a format identical to DSA without surgical intervention. Post-processing format can generate multiple projections of the carotid arteries such as MIP that facilitate stenosis detection. Comparing to TOF-MRA, CE-MRA is relatively independent of flow dynamics and artefacts associated with saturation effects are ultimately reduced. This is because of the usage of Gadolinium-based CA that enhances the contrast between the intravascular lumen and background tissue, resulting in a lumen less sensitive to dephasing effect, as previously mentioned.[6] 3D TOF-MRA results in significantly higher stenosis grades at 3T MR scanners.[9] Furthermore,[6] have stated that CE-MRA covers a large FOV from the aortic arch to the circle of Willis in less than 60 seconds. Conversely, 3D TOF-MRA offers restricted FOVs in order to reduce the scan time, causing stenosis to be missed.[9] Although some patients may be inappropriately referred for surgery due to inaccurate results obtained using TOF-MRA, it remains a useful option in some cases. These case, who are contraindicated to Gd based CA, including patients with renal impairment or pregnant patients.[6]

From other perspective, MRI is more susceptible to motion artefacts related to patient movement due to relatively long scan time, resulting in low image quality. Secondary, it has a limited role in obese patients or patients with non-MR-compatible implants.[4] The SR of CE-MRA is two to three times lower than that of DSA or CTA. This is mainly as a consequence of using a large FOV with relatively reduced matrix in order to maintain accurate timing of pure arterial phase before intravenous.[6] However, this issue continues to improve with new state-of-art MR scanners which offer high field strengths and parallel imaging techniques, facilitating high temporal resolution. Additionally, the introduction of blood-pool CA that stay in blood circulation for longer time contributes to improve the SR.[4]

In order to improve the diagnostic accuracy in either CE-MRA or CTA and avoid pseudo-occlusion appearances, a strong contrast enhancement should be obtained at the position of maximum stenosis. Additionally, partial volume effects associated with large voxel sizes and low SR lead to overestimation of sever stenosis.[8]

Although there were a plenty of research that compare different imaging modalities in assessing carotid artery stenosis, there was much controversy on whether non-invasive imaging techniques could replace DSA. Some researchers argued that if these modalities show misclassification of stenosis resulting in incorrect patient selection for surgery, they are not safer than DSA. However, the fact that many of the available studies might not be qualified enough due to poor design, improper data analysis and insufficient cohort size invalidates this argument.[6]

overall, in clinical practice, DSA technique has become limited to severe multiple vessels disease or when the image quality of non-invasive procedure is low.[3] Thus, it seems logical to initially screen patients with DUS, then refer patients with identified significant stenosis to either CTA or CE-MRA to confirm the diagnosis.[5] DUS combined with CTA or MRA are now useful in determining the degree, location and extent of carotid narrowing.[10]

CA-MRA

To produce a high quality CE-MRA scan that optimize the visualization and detection of carotid stenosis, there has to be a balance between high temporal resolution, signal to noise ratio (SNR), contrast to noise ratio (CNR) and SR. The primary concern when acquiring CE-MRA is the time limit to capture pure arterial enhancement before the starting of jugular filling that obscures arterial anatomy and pathology. This require rapid acquisition time (14-18 s) while maintaining high SR.[3] The usual loss of SNR from fast scanning can be compensated by injecting the contrast bolus over a shorter scan duration. The enhancement of carotid arteries in the correct time provides high CNR between the enhanced vessels and their background. The proper selection of k-space filling techniques is crucial for CE-MRA to compromise between the needs for SR and temporal resolution.[3] Centric or elliptic-centric k-space filling are the ideal types for that purpose. In these forms of k-space fillings, the center of k-space where it contributes most to image contrast is filled first and timed to correspond to the peak arterial enhancement;[11] Elster, 2018). High magnetic fields also is an important factor which is produce high MR signal that can be exploited to minimize the sequence time or improving the SR. Moreover, with high gradient amplitude and short gradient rise time, thin slices and minimum echo time (TE) can be obtained (Elster, 2018). The selected TE in CE-MRA has to be as short as possible to reduce dephasing and T2 effect. Dedicated phased-array coils should be used because they contain multiple small coils with multiple receivers whose individual signals are combined to create one image with improved SNR and high coverage in a shorter scan time. These coils support parallel imaging techniques which are employed to reduce scan time or increase SR, but at the expense of SNR because it fills multiple lines of k-space per repetition time (TR).[11]

MRA Protocol

Localizer: three planes of sagittal, axial and coronal, it covers the right and left common carotid arteries from the aortic arch to top of skull.

Coronal T1 3D Pre-contrast

Pre-contrast Mask sequence-3D spoiled gradient**,** to produce T1-weighted image, and acquired to enable post-processing subtraction which increase CNR between enhanced vessels and background tissue.[3] large FOV of 325 x 294 mm, and small flip angle excitation pulse of 25° with short TR 3.09 ms are set up to reduce scan time and saturate the signal from stationary tissue to maximise T1 contrast.[11] The steady state in this sequence is maintained and the residual transverse magnetization from previous TR is de-phased/spoiled using RF spoiler pulse, in order to minimise T2 contrast. As a result, only transverse magnetisation from the previous excitation is used, maximising T1 contrast.[11] Furthermore, the selection of short TE 1.12 ms is essential to reduce dephasing and T2/T2* effects.[3] A High bandwidth (BW)

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value 480 Hz/Px is used to enable minimum TE (Elster, 2018). This would increase the noise, but high signal from contrast enhancement will compensate the signal appearance of blood vessels since there is no interest in visualising background tissue. Additionally, relatively small voxel size 1.0x0.8x0.8 mm with relatively fine matrix size 384 x 303 mm reduce intra-voxel dephasing while improve the SR.[11] The high SR is important in visualisation of small vessels and detection of stenosis. GRAPPA technique with 2 iPAT acceleration factor is set up to help reducing scan time.

Flouro-triggering window

It is 2D coronal continuous images through the aortic arch and the carotid arteries, with ultra-high temporal resolution displayed in a real time manner to show the arrival of the contrast bolus.

Coronal T1 3D Post-contrast (CE-MRA-3D spoiled gradient)

Once the CA has arrived in the aortic arch and the origin of carotid arteries, this sequence is acquired using the same gradient parameters. This sequence followed centric reordering to fill the centre of k-space at the peak arterial enhancement to maximise the intra- arterial signal while avoid the signal from jugular vein.[11]

Injection methods for CE-MRA

Although hand injection is possible, bolus injection provides more accurate detection and timing of the peak arterial phase before the venous contamination.[11] However, it requires a skilled MR radiographer, so the arterial phase not to be missed.

Maximum Intensity Projection (MIP) Technique

MIP rendering technique is used to filter the image by selecting the pixels with maximum signal (brightness), creating a MR angiogram (Elster, 2018). Although it is helpful in rapidly locating the stenosis, 3D source images should be reviewed with MIP to increase specificity. This is because small vessels and vessel stenosis seen in 3D original images could be missed on MIP, leading to overestimation.[12]

Image analysis

Image 1 (Pre-contrast Mask sequence-3D spoiled gradient)

The noisy image reflecting mottled appearance due to low SNR as short TR, TE and low flip angle are selected. This is because the application of short TR with partial flip angle does not permit for sufficient longitudinal magnetisation. As a result, the flowing blood, which have long T1 time, appears hypo-intense on this T1W image. The fat appears hyper-intense compared to blood due to its short T1 time. The mask phase does not provide sufficient diagnostic information, but acquired to enable post-processing subtraction which increase CNR between enhanced vessels and background (Figure 1).[3]

Image 2 (CE-MRA-3D spoiled gradient)

The hyper-intense appearance of the carotid arteries and aortic arch relative to the background soft tissue and fat after injecting contrast agent, as the CA shortens T1 time of blood. The signal intensity between stationary tissues and the enhanced blood is distinguished at this image (Figure 2).

Image 3 (Subtracted Image)

A post-processed subtracted image of the carotid arteries and aortic arch. this mask image is subtracted from the post-contrast enhancement image. It can be seen that this technique provides the maximum contrast to noise ratio (CNR) between the enhanced left, right carotid arteries and aortic arch and their backgrounds, as the noise from background is eliminated.[11] As a result, the aortic arch and common carotid arteries have the highest signal intensity (Figure 3).

Image 4 (MIP)

The aortic arch, subclavian arteries, common carotid arteries, internal carotid artery, vertebral arteries and circle of Willis appear hyper-intense relative to background soft tissue (Figure 4).

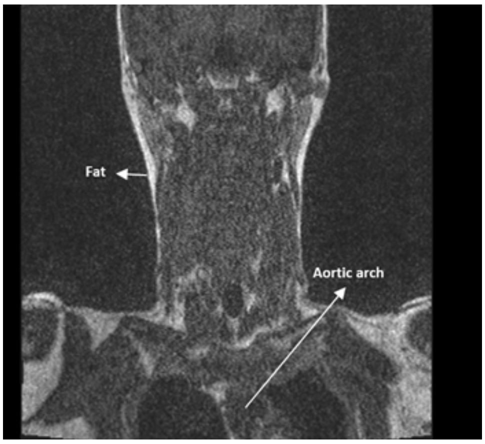

Figure 1 Pre-contrast Mask sequence-3D spoiled gradient. Adapted from: (private MRI clinic, 2018).

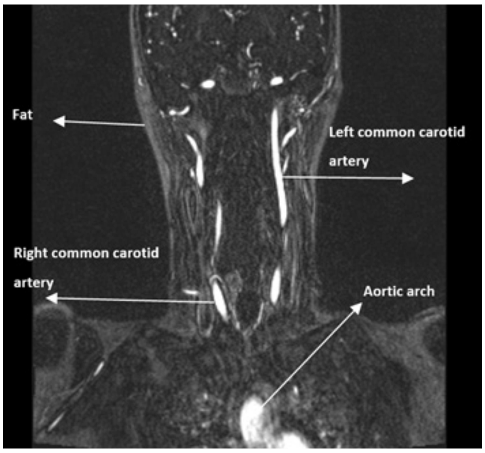

Figure 2 CE-MRA-3D spoiled gradient. Adapted from: (private MRI clinic, 2018).

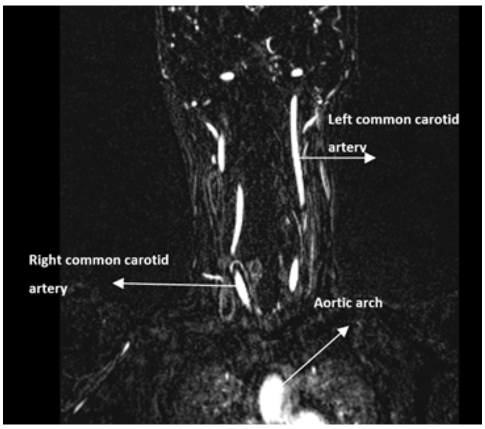

Figure 3 Subtracted image. Adapted from: (private MRI clinic, 2018).

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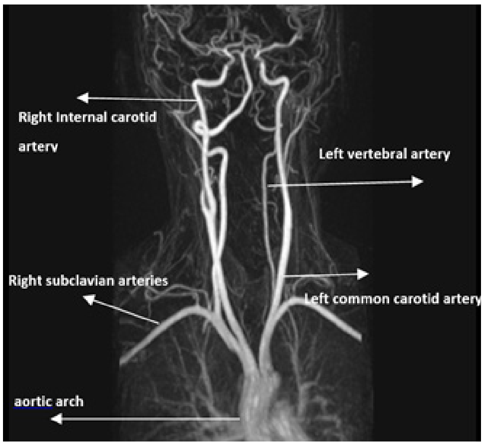

Figure 4 MIP. Adapted from (private MRI clinic).

Conclusion

In conclusion, non-invasive imaging techniques are less accurate when lesser degrees of carotid stenosis are indicated. It is evident that a new gold standard method is required for carotid stenosis imaging. A combined of two imaging modalities would be more efficient and practical in order to diagnosis of stenosis, hence confirm the correct patient selection for surgery. Moreover, each imaging modality has its own pros and cons, makes it difficult to rely on only one technique. DUS generally considered reliable method can be used as an ideal first-line investigation. Either CE- MRA or CTA can be used as second-level of investigation following DUS when significant stenosis degree is suspected. CE-MRA is now achieved with high temporal and spatial resolution since the development of new MR technologies such as phased-array coils, high gradient and magnet strengths and parallel imaging techniques. These assist in overcoming motion-related artefacts, long scan time and improve the SR to avoid overestimation of stenosis. The lack of ionizing radiation and minimal CA's side effects are a considerable advantage for using CE-MRA instead of CTA unless patients are contraindicated to MRI. Finally, more investigations are required to standardize diagnostic imaging pathway used in the assessment of carotid artery stenosis.

Acknowledgments

None.

Conflicts of interest

Authors declare that there is no conflict of interest.

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