3.0 TESLA CONTRAST-ENHANCED MR ANGIOGRAPHY OF CAROTID ARTERY STENTS: IN VITRO MEASUREMENTS AS COMPARED WITH 1.5 TESLA

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SUMMARY

Background and Purpose: To assess the appearance of carotid artery stents at 3.0Tesla contrast enhanced magnetic resonance angiography (CE-MRA) as compared with 1.5Tesla.

Methods: 19 stents (GUIDANT Acculink, GUIDANT Dynalink, BOSTON SCIENTIFIC SMART Neuroform, GUIDANT Omnilink, EV3 Protege, BOSTON SCIENTIFIC Carotid Wallstent, ABBOTT Xact) of different materials (nitinol, stainless steal, cobalt alloy) and different sizes (4.0mm-10.0mm) were investigated regarding their appearance on CE-MRA at 3.0Tesla and at 1.5 Tesla. For each stent artificial lumen narrowing (ALN) was calculated based on a pixel-by-pixel profile of the contrast-to-noise-ratio giving an objective indicator for the size of the evaluable stent diameter.

Results: Only in two stents (Omnilink 7.0mm, Omnilink 10.0mm) was ALN higher at 3.0Tesla relative to 1.5Tesla. In all other stents ALN at 3.0Tesla was the same or even lower as compared with 1.5Tesla. In contrast to the ferromagnetic stents where ALN was typically higher than 85%, in most of the nitinol stents (Acculink, Dynalink, Neuroform, Protege) ALN was below 35%. In the Xact stents ALN was generally 100% at 1.5Tesla and ranged between 31.8% and 100% at 3.0Tesla.

Conclusion: CE-MRA after carotid artery stenting is considerably impaired by ALN both at 1.5Tesla and at 3.0Tesla. Nevertheless, CE-MRA is well suited for the examination of carotid artery stents made of nitinol at both field strengths. Stent manufacturers should be aware of potential artifacts caused by their stents during noninvasive diagnostic methods such as CE-MRA.

Key words: Magnetic Resonance Angiography, Stenting, Artifacts, Carotid Artery.

RéSUMÉ

Étude in vitro des stents carotides en ARM injectée à 3 Tesla et à 1.5 Tesla

Objectif : Évaluer l’aspect des stents carotides en ARM injectée à 3 et 1.5 Tesla.

Méthodes : L’aspect de 19 stents (Acculink-Guidant, Dynalink-Guidant, Neuroform-Boston Scientific, Omnilink-Guidant, Protege EV3, Carotid wallstent-Boston Scientific, Xact Abbott) de matériaux et dimensions (4,0 mm à 10,0 mm) différentes a été étudié en ARM injectée à 3,0 et 1,5 Tesla. Pour chaque stent, le rétrécissement artificiel de la lumière (RAL) a été mesuré à partir d’une comparaison de rapports contraste sur bruit du signal résiduel.

Résultats : Dans deux cas seulement (Omnilink 7,0 mm et Omnilink 10,0 mm) le RAL était plus important à 3 Tesla. Dans tous les autres cas, le RAL était le même. Contrairement aux stents ferromagnétiques où le RAL était supérieur à 85 %, dans la plupart des stents en nitinol, (Acculink, Dynalink, Neuroform, Protege) ALN était inférieur à 35 %. Dans les stents Xact, le RAL était en général de 100 % à 1,5 Tesla et variant de 31,8 % à 100 % à 3Tesla.

Conclusion : L’ARM injectée après stenting carotide est considérablement altérée par un RAL aussi bien à 1,5 qu’à 3 Tesla. Néanmoins, l’ARM injectée est une méthode adaptée aux stents en nitinol quelque soit le champ. Les industriels doivent être avertis des potentiels artefacts causés par leurs stents lors des examens d’imagerie non invasive telle que l’ARM injectée.

Mots-clés : angiographie par résonance magnétique, stenting, artefacts, artère carotide.

INTRODUCTION

Stent protected angioplasty of the extracranial carotid artery (SPAC) has become a widespread used method for stroke prevention as an alternative to endarterectomy. The total number of SPAC procedures that was performed worldwide was about 12,000 until 2003 [1]. Especially when postinterventional doppler ultrasound examination is not unequivocal, contrast enhanced magnetic resonance angiography (CE-MRA) may help to decide whether residual or restenoses are evident or not. The aim of our study was to compare the appearance of carotid artery stents on CE-MRA at 3.0 Tesla with the appearance at 1.5 Tesla.

METHODS

We examined a total of 19 stents which were deployed in silicon tubes (neoLab GmbH, Heidelberg, Germany) with different diameters (4.0 mm to 10.0 mm) (table I). The stented tubes were positioned in a plastic bowl filled with saline solution at 37 °C to ensure complete expansion of the stents. Digital photographs and x-ray images (biplanar angiographic system, Philips Integris, Best, the
Nederlands; tube voltage =80kV; tube current =1.5mAs; diameter of the x-ray image amplifier =17cm; focus-film-distance =90cm) were taken of the stented tubes (figure 1). According to other groups [2] before MR examination the tubes were filled with a 2.00 mmol/L gadopentetate dimeglumine in saline solution: 1 L of saline solution was mixed with 4ml of gadopentetate dimeglumine (0.5 mol/L; Magnevist; Schering, Berlin, Germany). CE-MRA was performed both at 1.5 Tesla (SYMPHONY 1.5 Tesla Siemens Medical Solutions, Forchheim, Germany) and at 3.0 Tesla (TRIO 3.0 Tesla, Siemens Medical Solutions, Forchheim, Germany). The stented tubes were placed parallel to the z-axis of the MR scanners; scanning plane was generally perpendicular to the z-axis of the scanners. The calculation of the diameter (\(D_{x\text{ray}}\)) was performed by the use of the medical imaging software OSIRIS® (www.expasy.org/UIN/html1/projects/osiris/DownloadOsiris.html). The profile of the contrast-to-noise ratio (CNR) of the lumen of each stented tube segment and of the stent-free tube segments were calculated semiautomatically in three consecutive slices within the middle third of the stent along the x- and the y-axis by a pixel-by-pixel analysis using the medical imaging software OSIRIS® as

\[\text{CNR} = \left(\frac{\text{SI}_{\text{Pix}} - \text{SI}_{\text{saline}}}{\text{SD}_{\text{Air}}}\right)\]  

where \(\text{SI}_{\text{Pix}}\) is the signal intensity of each pixel along the x- or y-axis, \(\text{SI}_{\text{saline}}\) is the signal intensity of the saline solution surrounding the stented tubes, and \(\text{SD}_{\text{Air}}\) is the standard deviation of the signal of the air outside the phantom

<table>
<thead>
<tr>
<th>Stent/Tube name</th>
<th>Acronym in this Paper</th>
<th>Manufacturer</th>
<th>Material</th>
<th>Nominal stent diameter/length (mm)</th>
<th>Tube diameter (mm)</th>
<th>(D_{x\text{ray}}) (mm)</th>
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<tr>
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<td>Nitinol</td>
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Note. – na indicates data not available; SS, stainless steel; mc, multicellular; ST, strut thickness; SW, strut width, SFA, stent free area; shca, semihelical coil array; * tapered stent.
From these 6 measurements we calculated the mean profile of the CNR perpendicular to the tube wall (figures 2 and 3). For reliable depiction of vessels in maximum intensity projection reconstructions, the CNR of the vessel lumen must be at least two SDs more than the CNR of the background tissue [3], that was saline in our study. Thus, based on the CNR profile, we counted the number of pixels with CNR-values of at least two standard deviations more than the CNR of the saline solution for each stent (\(N_{\text{pix/stent}}\)) and for each tube (\(N_{\text{pix/tube}}\)) giving an objective parameter for reliable depiction of the lumen [3]. For comparison between the stents we calculated the apparent lumen narrowing (ALN) of each stent and tube as 
\[
\text{ALN} = \left( \frac{D_{\text{xray}} - N_{\text{pix/stent}}}{D_{\text{xray}}} \right) \times 100\%, \quad \text{and} \quad \text{ALN} = \left( \frac{D_{\text{xray}} - N_{\text{pix/tube}}}{D_{\text{xray}}} \right) \times 100\%.
\]

RESULTS

Objective evaluation

CNR within in the stent-free tubes and in the nitinol stents was up to twofold higher at 3.0Tesla than at 1.5Tesla. This phenomenon was less pronounced...
in tubes and stents with small (4-5mm) diameters but was highly pronounced in tubes and stents with larger (8-10mm) diameters.

Nitinol stents

At both field strengths ALN was 0% for the Neuroform stent, and 33.4% for the Protege stent. At 1.5Tesla ALN ranged between 17.2% (DY8) and 23.9% (AC4) in the Acculink and Dynalink stents, and was 100% for all Xact stents. At 3.0Tesla ALN ranged between 17.0% (DY7) and 23.9% (AC4) in the Acculink and Dynalink stents, was 100% for both X 6-8 and X7, 37.7% for X8 and 31.8% for X8-10 (figure 4).

Stainless steel and cobalt alloy stents

At both field strengths ALN was 100% for OM5 (stainless steel) and OM6 (stainless steel) and the carotid wallstents (cobalt alloy). At 1.5Tesla ALN was 87.7% for OM7, 100% for OM8, 90.4% for OM9 and 46.6% for OM10. At 3.0Tesla ALN was 100% for OM7, 88.7% for OM8, 61.7% for OM9, and 55.5% for OM10 (figure 4).

DISCUSSION

SPAC is an increasingly used method for the treatment of carotid artery stenoses [1]. Furthermore, there is a trend to higher field strengths in clinical MR imaging. Currently, the highest MR field strength used for routine examinations in patients is 3.0Tesla. Therefore knowledge of the MR angiographic appearance of carotid artery stents becomes more and more important not only at 1.5Tesla but also at 3.0Tesla. When metallic stents are imaged by MR two kinds of artifacts may occur. Susceptibility artifacts result from local inhomogeneities of the
magnetic field due to the metallic stent struts [4]. Beside the field strength of the MR scanner they depend on the magnetic susceptibility of the stent relative to the surrounding tissue and the blood within the vessel, on the orientation of the stent relative to the static magnetic field, and on the MR sequence parameters [4, 5]. Radiofrequency artifacts are the result of a lower deposition of HF energy into lumen of the stented vessel segment because it is shielded by the mesh of the stent (Faraday cage effect) [6]. Generally, susceptibility artifacts are stronger at 3.0Tesla than at 1.5Tesla, whereas CNR is generally higher at 3.0Tesla than at 1.5Tesla. Susceptibility artifacts are the main reason for signal loss inside and outside stents made of stainless steel or cobalt alloy. Therefore, vessel lumina of ferromagnetic stents are less well visualized by MRI than lumina of stents made of nitinol, where only slight ferromagnetic effects occur. From a theoretical point of view the influence of the higher CNR at 3.0Tesla rises with growing stent diameters because susceptibility artifacts are locally restricted. In nitinol stents, however, the visualization of the stented vessel segment is reduced mainly by radiofrequency artifacts. Radiofrequency artifacts can be reduced by variation of the flip angle of the radiofrequency impulse [7-9].

In the majority of the stents that we have examined ALN at 3.0Tesla was the same (AC4, AC5, DY6, DY8, NEU4, OM5, OM6, PRO, WAL7, WAL9, X6/8, X7) or even lower (DY7, OM8, OM9, X8, X8/10) as compared with 1.5Tesla. In our opinion, in the stents where ALN was lower at 3.0Tesla than at 1.5Tesla artifacts at 3.0Tesla were overcompensated by the higher CNR relative to 1.5Tesla. Therefore, in these stents a higher count of pixels with CNR values of at least two SDs more than the CNR of the background tissue (saline solution) was evident. Only in two stents (OM7, OM10) was ALN higher at 3.0Tesla relative to 1.5Tesla. In contrast to the ferromagnetic stents (OMNILINK, Carotid Wallstent) where ALN was at least 46.6% (OM10 at 1.5Tesla) and typically even higher than 85% (OM5, OM6, OM7, OM8, WAL7, WAL9) most of the nitinol stents (AKKULINK, DYNALINK, PROTEGE, Neuroform) revealed ALN values below 35%. Instant restenoses of more than 50% should therefore be detectable in these stents at both field strengths. The nitinol stents X7, X8 and X8/10, however, revealed ALN values of up to 100% in our study. To our opinion this might be due to the tightly braided meshes of the Xact-stents leading to strong radiofrequency artifacts with homogenous signal decrease within the stent.

To our knowledge, from all the stents we have examined in vitro only the Acculink and the Dynalink stents and the neuroform stent, which is approved for the treatment of wide-necked cerebral aneurysms, have been proven to be safe at 3.0Tesla also for human use [10, 11]. The carotid wallstent has been proven to be safe only at 1.5Tesla [12]. About the other stents we have studied (Omnilink, Protege, Xact) we have found no information about MR safety at 1.5 or 3.0 Tesla in the medical literature.

Our study was performed in vitro; therefore it has several limitations: First, the absence of flow and pulsatility in our phantom study may reduce the comparability to an in vivo situation. On the other hand, CE-MRA depends on the T1-shortening effects of gadopentetate dimeglumine and is insensitive to flow and motion [13]. Therefore, our model is sufficient to obtain comparable results of the interstent visibility. The concentration of gadopentetate dimeglumine chosen in the phantom (2.00 mmol/L) cannot simulate all CE-MRA situations, but it is close to that used in an in vivo investigation [14]. Secondly, we did not evaluate how the visibility of a vessel containing a stent is influenced by the background signal intensity in different tissues. Thirdly, the stented tubes were placed parallel, and the scanning plane was generally perpendicular to the z-axis of the scanners. In oblique scan orientations and in vessels with curved shape or irregular

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FIG. 4. – ALN of the stents at 1.5Tesla (black bar) and at 3.0Tesla (grey bar). Note: ALN was zero for NEU4.

FIG. 4. – Rétrécissement apparent de la lumière à 1,5 T (barre noire) et à 3 T (barre grise).
walls, artificial lumen narrowing might be even more pronounced than it was observed in our study. Fourthly, despite being an objective criterion for the comparison of the different stents, ALN is an arbitrary parameter that does not exactly reflect the dimensions of the evaluable diameter of the stents. Fifthly, as other groups, we used silicone tubes for the simulation of the vessel wall [9]. Silicon itself induces artificial lumen narrowing to a moderate degree. All these limitations preclude that our results can be transferred directly to imaging in humans.

CONCLUSION

Our study shows that it is necessary to know about artificial lumen narrowing and artifacts in stented vessels examined using CE-MRA. In the majority of the stents that we have examined artificial lumen narrowing at 3.0 Tesla was the same or even lower than at 1.5 Tesla. Our data might influence selection criteria for CE-MRA in patients who were treated with SPAC. Stent manufacturers should be aware of the potential artifacts caused by these devices during noninvasive diagnostic examinations such as MR angiography.

REFERENCES