Recent advances in managing MRI artifacts caused by auditory implants: the effect of Metal Artifact Reduction Sequences.

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Abstract: Objective: The efforts made over the years to improve the implantable auditory devices technology has led to overcome the concerns related to the interaction between their magnetic system and the complex magnetic resonance (MR) environment. Nowadays, an increasing number of devices has become MR compatible. However, when dealing with patients with implantable auditory devices and cerebral MR, the presence of signal void areas and distortion signals limiting the depiction of the intracranial structures still remains an outstanding issue. Among the strategies to improve the quality of MR image (MRI), the application of metal artifact reduction sequences (MARS) in MRI has been proposed. This review provides a critical analysis of the current literature regarding the utilization of the MARS in cerebral MRI performed in presence of auditory implants. **Methods:** Data sources included PubMed, EMBASE, Web of Science and Scopus. The main eligibility criteria were English-language articles investigating the use of MARS in implantable auditory devices recipients. Data was extracted according to PRISMA guidelines. **Results:** Four articles were identified, the oldest one dated January 2019: two studies dealing with cochlear implants (CI) and two dealing with bone conduction implants (BCI). Three out of four paper were ex vivo, whereas the remaining article was a clinical study. **Conclusion and relevance:** To our knowledge, this is the first review on this emerging topic. Encouraging results with the application of MARS have been reported in all the works consulted, although in our opinion these findings present some restriction and need confirmation.

Keywords: MRI, artifact, cochlear implant, bone conduction implant, auditory brainstem implant

Introduction

Until the recent past, one of the main concerns in patients with implantable auditory devices such as cochlear implants (CI) regarded the interaction between the magnetic field of the magnetic resonance imaging (MRI) and implant magnets. Over the years, the improvement of technology has led to the commercialization of an increasing number of "MR-conditional" devices (Miller 2019, Edmonson et al. 2018), thus allowing to overcome complications due to magnetic systems such as a device magnet displacement, demagnetization and patient's discomfort. However, the presence of artifacts caused by the internal magnet and the metal parts of the devices remains an outstanding challenge, as signal void areas and distortion signals influence the depiction of the adjacent anatomical structures. Some strategies have been implemented to mitigate such artifacts: patient head orientation (Wackym et al. 2004), internal magnet removal (Wagner et al. 2015), device positioning (Todt et al. 2015) and MRI algorithms manipulation (Sharon et al. 2016, Majdani et al. 2009, Canzi et al. 2021). Recently, the application of metal artifact reduction sequences (MARS) in MRI has demonstrated to improve the image quality in patients with metallic implants in the orthopaedic field (Khodarahmi et al. 2019). The aim of this study is to review the published evidence regarding the utilization of MARS in cerebral MRI when auditory implants are present.

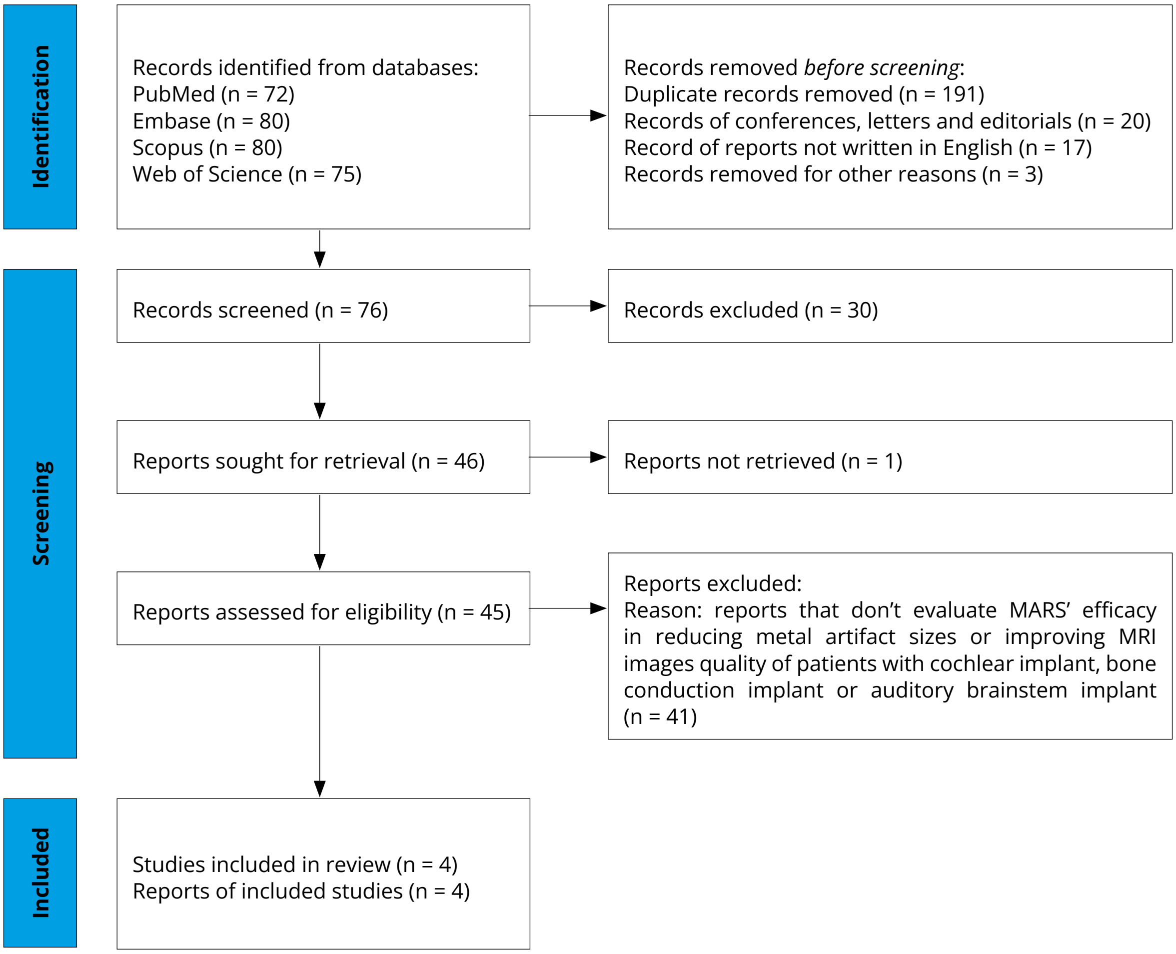
Methods

This review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Guidelines (Page et al. 2021). The literature search was performed using four databases: PubMed, EMBASE, Web of Science and Scopus. The key words "MRI", "artifact", "bone conduction implant", "cochlear implant" and "auditory brainstem implant" were combined. The authors collected articles published before and in August 2021. Results were limited to English language. There were no restrictions regarding the age group of the patients taken into account for the study. Editorials, letters to editors and proceedings of academic conferences were excluded. Duplicate results were filtered and removed. Reference lists were cross-checked for additional relevant studies. The search aim was to include papers that met the following criterion: studies evaluating the benefits of a metal artifact reduction technique in MRI in terms of artifacts reduction, image quality or diagnostic usefulness in presence of auditory implants.

Results

A PRISMA flow chart illustrating both the search figures and the included studies is schematically presented in Figure 1.

Figure 1. Identification of studies via databases



PRISMA 2020 based flow-diagram showing review search

We identified 307 records. However, after excluding duplicate findings, articles written in languages other than English, editorials, letters to editors, proceedings of academic conferences and records with unavailable data, 76 studies were considered. A preliminary selection was made on the basis of titles and abstracts: 46 papers were evaluated in their full text version, of which 41 did not met the inclusion criterion. Four articles were included in the review and were further analysed: two publications dealing with CI (Amin et al. 2021, Canzi et al. 2021) and the remaining two dealing with bone conduction implants (BCI) (Utrilla et al. 2021, Wimmer et al. 2019). Amin and colleagues proposed a clinical study on 8 CI recipients, whereas the other investigations were conducted on head specimens (Amin et al. 2021). Among the ex-vivo studies, Wimmer and colleagues included in their article a case report (Wimmer et al. 2019). The details of the materials employed in each study are outlined in Table 1. The authors of each paper propose qualitative and quantitative assessments regarding the quality of images through different analyses. Wimmer and colleagues conducted an exclusively qualitative evaluation (Wimmer et al. 2019). The methods and outcomes of each research are reported in Table 2.

Table 1. Materials

Authors (year of publication)	MARS	MR scan model (manufacturer)	Imaging study protocol	Auditory device	Sample	Surgical position
Amin et al. (2021)	SEMAC-VAT	1.5 T Somatom Aera (Siemens)	Axial T1w spin echo post-gadolinium	9 CI: 6 Synchrony (Med-El), 1 CI422 (Cochlear), 1 CI24 (Cochlear), 1HiRes Ultra 3D (Advanced Bionics)	8 adult CI recipients (6 diagnosed with Neurofibromatosis type 2, 1 with IgG4 disease, 1 with metastatic malignant melanoma). 7 implanted unilaterally, 1 bilaterally	NA
Canzi et al. (2021)	O-MAR	1.5 T Ingenia (Philips)	Axial T1w and T2 turbo spin echo	2 CI HiRes Ultra 3D (Advanced Bionics)	3 head specimens	With an angle of 135°, at 9 cm from the outer ear canal
Utrilla et al. (2021)	MAVRIC	1.5 T Signa (General Electrics)	Axial T2 fast spin echo	BCI 601, BCI 602	4 head specimens	sinodural placement middle fossa placement middle fossa placement retrosigmoid placement
Wimmer et al. (2019)	SEMAC-VAT-WARP	1.5 T MAGNETOM Avanto (Siemens)	Axial T1w and coronal T2w	BCI 601	2 head specimens (+ 1 adult BCI recipient)	Presigmoid placement

MARS: magnetic artifact reduction sequence; CI: cochlear implant; BCI: bone conduction implant; NA: not assessable

Table 2. Methods and outcomes

Authors (year of publication)	Observers	Evaluated anatomical structure	Methods for qualitative evaluation	Specific qualitative assessment of visibility	Quantitative assessment	Overall evaluation of diagnostic usefulness
Amin et al. (2021)	2 radiologists reaching a consensus	IAC, CPA, cerebellar hemisphere and brainstem	4-points scale (visibility of anatomical structures) 4-points scale (visibility through penumbra)	6 out of 9 cases ↑ ipsilateral IAC/CPA 8 out of 9 cases ↑ ipsilateral cerebellar hemisphere 4 out of 9 cases ↑ brainstem 7 out of 7 cases = contralateral IAC/CPA 7 out of 7 cases = contralateral cerebellar hemisphere 4 out of 5 cases ↑ penumbra visibility	↑ signal void distance from midline ↑ penumbra size	↑
Canzi et al. (2021)	2 neuroradiologists and 1 otoneurosurgeon independently	frontal lobe, parietal lobe, temporal lobe, occipital lobe, hypophysis, IAC, cochlea, semicircular canals, vestibulum, brainstem, anterior lobe of the cerebellum, cerebellar vermis, middle cerebellar peduncle and CPA	4-points scale (visibility of anatomical structures)	/	↓ signal void size	↑
Utrilla et al. (2021)	1 neuroradiologist	IAC and CPA	4-points scale (visibility of anatomical structures)	↑ ipsilateral structures with middle fossa placement of BCI 602	↓ signal void size	↑
Wimmer et al. (2019)	2 neuroradiologists reaching a consensus	frontal lobe, parietal lobe, temporal lobe, occipital lobe, IAC, cerebellum, petrous bone, brainstem and skull base	4-points scale (visibility of anatomical structures)	6 out of 7 cases ↑ ipsilateral structures 7 out of 7 ↑ contralateral structures 2 out of 2 ↑ midline structures	/	↑

IAC: internal auditory canal; CPA: cerebellopontine angle; ↑ improved; ↓ reduced; = unchanged

Qualitative analysis

Amin and colleagues have demonstrated that the application of SEMAC-VAT protocol improved the visibility of the ipsilateral hemisphere. By examining 9 cases, the authors have reported a better visualization of both the ipsilateral internal auditory canal/ cerebellopontine angle (IAC/CPA) and cerebellar hemisphere in respectively 6 and 8 cases (it remained unchanged in the others). As to the brainstem, it was better visualized in 3 cases (the visualization remained unchanged with no or only mild distortion in the others). On the other hand, contralateral structures resulted completely visible with and without the SEMAC-VAT sequence. Moreover, the scoring of the penumbra demonstrated to improve from 2.3±0.5 to 3.0±0.0 when the SEMAC-VAT sequence was employed, excluding the cases with no penumbra without MARS (Amin et al. 2021). Canzi and colleagues have found significantly better quality outcomes with the utilization of O-MAR sequences (Canzi et al. 2021). Utrilla and colleagues have claimed an artifact reduction and a better evaluation for both the brain parenchyma and IAC/CPA through the application of MAVRIC protocol. In particular the authors have reported full visibility of ipsilateral structures by employing MARS when the BCI 602 was implanted via the middle fossa approach, whereas the ipsilateral side remained obscured by signal loss in all the other cases (Utrilla et al. 2021). In Wimmer and colleagues, on the side of the BCI the images acquired without MARS were not assessable (only the parietal lobe was poorly assessable), this also applied to the brainstem and the skull base. Whereas the authors have described limited assessability of the structures of the nonimplanted side. The image quality improved significantly on both sides with the application of SEMAC-VAT WARP: on the side of the BCI, four of the rated structures became assessable, while on the contralateral side four got good visibility and three were deemed assessable. As regards to the brainstem and the skull base, good visibility was achieved. In the clinical case described in the paper, after the application of SEMAC-VAT WARP sequence, the intracanalicular contralateral schwannoma resulted evaluable in both size and configuration in the follow-up MRI scans (Wimmer et al. 2019).

Quantitative analysis

In Amin and colleagues, the application of MARS reduced the extent of the signal void, therefore the mean distance between the edge of the signal void and the midline of the posterior fossa increased significantly (from 15.4±8.7 to 31.3±9.4 mm). On the contrary, the application of SEMAC-VAT resulted in the appearance of penumbra in three cases in which there was no penumbra during the standard MRI scan; in the same way, in four out of the remaining six cases the already existing penumbra increased in size. More specifically, when the SEMAC-VAT was employed, the mean size of the penumbra increased from 6.7±5.7 to 16.3±10.5 mm (Amin et al. 2021). Canzi and colleagues claim that the radius of the signal void should be reduced from 49.6 mm to 34.4 mm in axial T1w sequences and from 56.7 mm to 36.3 mm in axial T2w sequences after activating the O-MAR protocol (Canzi et al. 2021). In the study performed by Utrilla and colleagues the artifact was reduced with the MAVRIC sequence in a range from 6.3 to 59.7% (Utrilla et al. 2021). The study of Wimmer and colleagues is the only one not to present a quantitative comparison of artifact features between conventional sequences and images through the application of an artifact reduction protocol. Describing the MRI scans in which MARS was not employed, the authors merely indicated the presence of artifacts consisting of signal voids masking nearly the whole supra- and infratentorial brain on the ipsilateral side of the BCI, as well as adjacent geometric distortion artifacts and reduced signal intensity extending up to 10 cm from the implant centre (Wimmer et al. 2019).

Discussion

MRI represents an established and non-invasive tool with a wide variety of clinical applications. Despite the developments in MR technology, the diagnostic capabilities of MR images are often limited by artifacts. According to their origin, artifacts are classified in patient-related, hardware (machine)-related and signal processing dependent (Erasmus et al. 2004). The last group includes metallic artifacts, which occur due to magnetic susceptibility differences in the interface between the metallic object and the surrounding tissue, as well as to the eddy currents induced within the metal by switched magnetic field gradients (Erasmus et al. 2004). In the last decades, the employment of metallic implants in medicine has increased, driving the need for techniques to mitigate the severity of metal susceptibility artifacts. Reduction of these artifacts had been traditionally attempted through simple concessions in MR acquisition techniques, such as reducing field strength, decreasing slice thickness, using fast imaging sequences, adopting fast spin echo sequences instead of gradient echo sequences, increasing the frequency encoding bandwidth, or orienting the long axis of the metal along the frequency encoding direction (Jungmann et al. 2017, Kolind et al. 2004). In recent years, in order to optimize the imaging around metal, dedicated MR protocols have been developed: MARS is a general term referred to techniques whose aim is to reduce metal artifacts that superimpose the adjacent tissue (Jungmann et al. 2017). MARS include many modified sequence acquisition schemes. Among them, the view angle tilting (VAT) protocol is adopted to compensate for in-plane distortions, whereas the slice-encoding metal artifact correction (SEMAC) and the multiacquisition variable-resonance image combination (MAVRIC) are techniques known as multispectral imaging (MSI), which are applied for correcting through-plane distortion artifacts. SEMAC is used in combination with VAT (SEMAC-VAT) including the through plane distortion corrections of SEMAC with the in-plane distortion corrections of VAT (Jungmann et al. 2017). Moreover, VAT can be merged in more sophisticated techniques such as MS-VAT-SPACE, Multi-Slab Acquisition with View Angle Tilting gradient, based on Sampling Perfection with Application optimized Contrast using different flip angle Evolution (Hilgenfeld T et al. 2018). Artifact reduction protocols that are to date available are described in Table 3.

Table 3. Available MARS

MARS	Manufacturer	Technique			
		Conventional MARS	VAT	MSI	
				SEMAC	MAVRIC
O-MAR	Philips	✓	✓		
O-MAR XD	Philips	✓	✓	✓	
WARP	Siemens	✓	✓		
Advanced WARP	Siemens	✓	✓	✓	
MAVRIC	General Electric	✓			✓
MAVRIC-SL	General Electric	✓		✓	✓

MARS: metal artifact reduction sequence; VAT: view-angle-tilting; MSI: multispectral imaging; SEMAC: slice-encoding for metal artifact correction; MAVRIC: multiacquisition variable-resonance imaging combination; ✓adopted technique

The four papers included in our review are the only existing studies which analyse the application of MARS in presence of auditory implants, with the oldest one dated January 2019. At the present time, the available data just concern CI and BCI; there are no studies on auditory brainstem implants. It should be considered that the MARS have been developed and applied predominantly in orthopaedic and neurosurgical fields, in which their advantages have already been demonstrated (Jungmann et al. 2015, Lee et al. 2016, Sutter et al. 2012). On the other hand, the application of these advanced artifact reduction techniques in MRI in presence of auditory implants is an emerging topic, probably as a result of the recent overcoming of the historical auditory implant-MR incompatibility. What we would like to point out is that the employment of MARS for auditory implants might pose an additional challenge as compared to their utilization in orthopaedic field. In fact, auditory devices present metallic components just like orthopaedic and spine prosthesis, but still, they are equipped with a magnet which is a further cause of external magnetic field distortion.

The available works have revealed promising qualitative and quantitative findings resulting in an overall improvement of image quality and in an artifact size reduction with the application of MARS. However, despite a trend consistent with the other studies, it should be noted that Utrilla and colleagues have observed an improvement in visibility of ipsilateral structures with the application of MARS only when the BCI 602 was implanted via the middle fossa approach, without clinical benefits in any other condition. The result is related both to the employment of the new generation device and the surgical placement of BCI (Utrilla et al. 2021). Interestingly, Amin and colleagues have implemented the analysis of the artifacts with a description of "penumbra". It is defined as an area of partial visibility resulting from partial signal void or alternating bands of signal void and pile-up. Despite a size-increasing penumbra, an improvement of visibility through it has been reported with the employment of SEMAC-VAT (Amin et al. 2021). Given the above, the application of artifact reduction algorithms seems to be beneficial, though more extensive studies are needed to corroborate this observation. In our opinion, the current findings present some restrictions. First of all, the small sample size and the limited number of scanning sequences in which the MARS protocols were applied could affect the robustness of the results. Secondly, except for the work of Canzi and colleagues (Canzi et al. 2021), the analyses have been conducted by a single examiner or assessed with a consensus, thus precluding the evaluation of interobserver agreement statistics. In addition to this, the existing data are difficult to compare. Three of the studies were conducted ex-vivo (one of them included a case report), only the most recent one is entirely clinical. They also differ in MR scan models, types and models of device, employed artifact reduction sequences, as well as in the application of the quantitative analysis of the artifact, which has not been conducted in all cases. As for the qualitative assessment of images, although the adopted scales are conceptually similar, a standardization of the rating system would be desirable. Furthermore, a few other remarks deserve to be discussed. First, the fact that some MARS require additional scan time could be a limiting factor in the clinical application of these protocols, considering also the "conditional" MR safety recommendations, which discourage more than 15 minutes of continuous scanning (Advanced Bionics. MRI Safety Information for the HiRes™ Ultra 3D Cochlear Implant). Secondly, and finally, the commercial costs of this technology have to be taken into account too, although it should be noted that the application of these algorithms is not limited to auditory implantation, but they are also widely adopted in orthopaedic and neurosurgical fields.

Conclusion

Current technological advances have raised new clinical issues, such as the presence of artifacts influencing MRI quality in auditory implant recipients. Preliminary data about the employment of specific metal artifact reduction protocols in presence of CI or BCI are encouraging. The adoption of these algorithms may represent an additional strategy to be combined with others already in use. We claim that further studies should be mandatory in order to corroborate the existing evidence, especially as regards the effect of MARS application in MRI surveillance of the main neurological diseases in patients with auditory implants.

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