

Evaluation of MRI Safety of Ru-106 Eye Applicators

Michael C.Y. Tang^{a,b} Lisa Klaassen^{a,b,c} Marina Marinkovic^a T.H. Khanh Vu^a
Gregorius P.M. Luyten^a Carien L. Creutzberg^c Martijn Ketelaars^c
Jan-Willem M. Beenakker^{a,b,c}

^aDepartment of Ophthalmology, Leiden University Medical Center, Leiden, The Netherlands; ^bDepartment of Radiology, Leiden University Medical Center, Leiden, The Netherlands; ^cDepartment of Radiation Oncology, Leiden University Medical Center, Leiden, The Netherlands

Keywords

Brachytherapy · Choroidal melanoma · Medial rectus safety · Ocular oncology · Radiation oncology · Uveal melanoma

Abstract

Introduction: Ruthenium-106 brachytherapy is a primary treatment for uveal melanoma (UM), the most common intra-ocular malignancy in adults. This study evaluated the safety of Ru-106 applicators at 3 Tesla (T) MRI and their impact on image quality. **Methods:** Magnetic attraction and eddy currents were tested on a 20-mm-diameter Ru-106 applicator using a nylon string and a porcine eye. Safety criteria were defined by ocular oncologists, comparing magnetic field interactions to the forces exerted on the eye during surgery. Five UM patients were scanned at 3T MRI with the applicator in situ using both conventional anatomical sequences and scans optimised to reduce metal artefacts. **Results:** Minimal magnetic interactions were observed. Eddy currents caused slight lagging during fast movements and temporary detachment of the applicator of the porcine eye in conditions that were considered unrealistic for clinical scans. Significant susceptibility artefacts compromised image quality of the affected eye. **Conclusion:** Patients with Ru-106 applicators can be safely used in 3T MRI

with some simple precautions. MR image quality of the eye was poor due to major susceptibility artefacts; however, imaging of extra-ocular anatomy is feasible.

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Introduction

Uveal melanoma (UM) is the most common primary intra-ocular tumour in adults with an incidence between 4 and 10 per million per year [1–3]. UM most commonly arises from the choroid (85%), but can also arise from the iris or ciliary body [4]. The primary treatment for UM consists of either episcleral brachytherapy, proton beam therapy, stereotactic radiation therapy, or the surgical removal of the eye [5].

Episcleral brachytherapy is an eye-preserving treatment which involves the surgical attachment of a radioactive applicator to the outer scleral layer of the eye, which is removed after the therapeutic dose has been delivered to the tumour. Various radioactive sources have been described for ocular episcleral brachytherapy, such as beta-emitting Ru-106 and Sr-90 or gamma-emitting I-125 and Pd-103 [6, 7]. Ru-106 is most frequently used in Europe, is well established for the

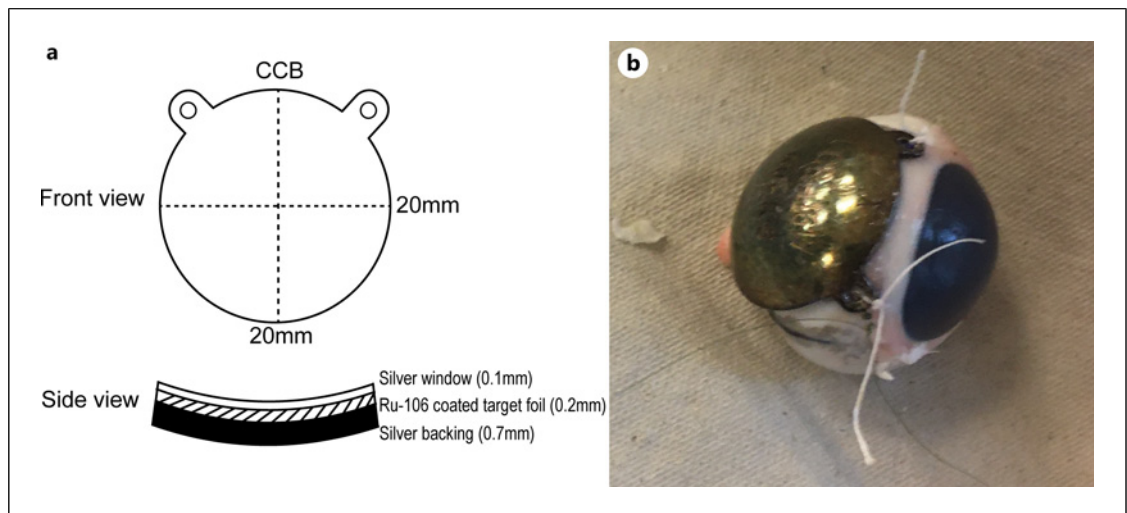


Fig. 1. Detailed impression and schematic illustrations of the Ru-106 brachytherapy applicator (CCB type from BEBIG). **a** (Top) front view of the applicator with two ipsilateral eyelets for sutures and measuring 20 mm in diameter (dashed line). (Bottom) cut-out view of the applicator, composed of a 0.1-mm-thick silver window

on the inside (open), 0.2-mm Ru-106-coated target foil in the middle (striped), and a 0.7-mm silver backing on the outside of the applicator (solid). **b** A CCB-type Ru-106 brachytherapy applicator sutured onto the scleral layer of a porcine eye using the two ipsilateral applicator suture openings.

treatment of small to medium-sized UM, and can achieve a high rate of local tumour of 94.8% at 5 years after treatment [4, 8–10]. The Ru-106 applicators are composed of three layers: a 0.2-mm-thick Ru-106 foil encapsulated between a 0.1-mm silver target window and a 0.7-mm silver backing acting as a radiation shield (shown in Fig. 1).

Conventionally, ultrasound (US) is used for the treatment planning of ocular brachytherapy, where the tumour height and largest basal diameter determine the application time and applicator diameter, respectively. Recent studies suggest that MRI can contribute to the treatment planning of ocular tumours, as it provides a three-dimensional visualisation of the tumour and surrounding structures, resulting in more accurate tumour dimensions in specific cases [11–13]. Some studies report the use of MRI to verify the accurate positioning of an I-125 plaque [14], but also in medical emergencies such as cerebrovascular accidents, where immediate medical attention is required, the ability to perform an MRI scan is critical [15]. However, to our knowledge, no safety assessments of Ru-106 eye applicators have been reported. Furthermore, as the Ru-106 plaques are made of different materials, the earlier safety evaluation of I-125 plaques cannot be used for Ru-106 plaques [14].

The primary MRI safety hazards for subjects with an implant consist of magnetic attraction, radio-frequency (RF)-induced heating, and eddy current interactions that exert a force on the implant when it is moved. The American

Society for Testing and Materials (ASTM) describes standards to test for these interactions [16–18]. For example, magnetic attraction is performed by suspending the tested object by wire in front of the MRI bore, allowing the observer to note the angle of deflection, which is proportional to the magnetic attraction. In the last years, various intra-ocular implants have been tested and approved Magnetic Resonance safe, including glaucoma drainage devices, tantalum markers used for ocular proton therapy, and intra-ocular lenses [19–22]. In this study, we aimed to evaluate the safety Ru-106 eye applicators at 3 Tesla (T) MRI and assess the impact of the applicator on the image quality.

Methods

Devices and Safety Considerations

All tests were performed on a 3T Ingenia MRI (Philips Healthcare, Best, the Netherlands) with a Ru-106 CCB-type eye applicator (Eckert & Ziegler BEBIG GmbH, Berlin, Germany). The CCB-type applicator has a diameter of 20 mm with two ipsilateral suture openings and was chosen as it is the largest commercially available Ru-106 applicator (shown in Fig. 1). Additionally, two commonly used ophthalmic suture materials, Vicryl 6-0 (Ethicon Inc., Ohio, USA) and Dagrofil 4-0 (Braun Melsungen, Germany), were tested. Tests were performed by two ocular oncologists (M.M. and T.H.K.V.), the local

MRI safety officer (W.T.), an MR physicist (J.-W.M.B.), and a clinical physicist from radiation oncology specialised in ocular brachytherapy (M.K.).

Although the evaluated applicator was approximately 10 years old, it was still radioactive due to its relatively long radioactive half-life of slightly more than a year. This prevented the adoption of the generally used test methods described in the ASTM [16, 17]. Therefore, a qualitative approach was used instead, which relied on visual and tactile observations to assess the potential interactions between the applicator and the MRI. The interactions would be compared to the forces induced to the eye and orbital structures during the surgery to attach the applicator to the eye. Due to the applicators' small size, which is about an order of magnitude smaller than the RF half-wavelength at 3T (13 cm), no tests for RF-induced heating were performed [17].

Ex vivo Tests

A 10-cm nylon string, 0.03 mm in diameter, was attached to one of the suture openings of the applicator, and the applicator was suspended in front of the MRI bore to assess attraction or a preferential orientation with respect to the main magnetic field. Eddy current interactions were assessed by holding the applicator with a pair of non-magnetic tweezers and moving it rapidly in different directions at the entrance of the MRI bore. This test was performed with different orientations of the applicator and by all five observers.

Subsequently, the applicator was sutured to the outer sclera of a porcine eye by one of the ophthalmologists, with the same procedure and materials as used in clinical care (shown in Fig. 1b). The same tests as with the applicator attached to a nylon string were performed, in particular moving the eye in different directions at different speeds, in which specific attention was paid to the position of the applicator with respect to the eye, which was observed visually by all five observers.

In vivo Evaluation

Five UM patients with a Ru-106 applicator in situ were scanned using a modified version of the protocol described by Ferreira et al. [11, 23]. Among the five participants, 3/5 (60%) were male, and the left eye was affected in 3/5 (60%) of cases. The median age of the participants was 81 years (range: 66–84 years). Applicators were localised in the superior nasal quadrant (3), central superior (1), and central temporal (1) regions.

This study was carried out according to the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans and was approved by the local Ethics Committee. Written informed consent was obtained from all participants.

From this protocol, the native anatomical scans were performed and additional scans with different metal artefact reduction techniques were evaluated (Table 1). Before and after scanning, care was taken that the patients only moved slowly, e.g., when sitting up after the table was retracted from the MRI bore. The image quality and extent of the applicator-induced signal voids in the MR images were assessed by J.-W.M.B. and M.T.

Results

Ex vivo Tests

No magnetic attraction was observed when the Ru-106 eye applicator was suspended in front of the MRI. The applicator did, however, show a propensity to align itself parallel to the static magnetic field, which could be overcome when minimal force was applied on the applicator using plastic tweezers. When the suspended applicator was moved rapidly near or in the magnet bore, it lagged behind, which was attributed to eddy current interactions. This observation was reproduced several times, but could not be replicated outside the MR environment. These eddy current-induced forces were not observed nor felt when the applicator was manipulated using tweezers.

When the applicator attached to the porcine eye, no attraction or angular deflection was observed at any orientation or distance from the MR bore. However, when the eye was moved rapidly upwards and stopped abruptly in a specific orientation, eddy current-induced forces could be observed (shown in Fig. 2). In these cases, as the movement of the eye was suddenly halted, part of the applicator temporarily detached from the surface of the eye and pivoted along the two sutures. Seconds afterwards, the applicator slowly moved back to its original position on the porcine eye. For this to occur, the applicator needed to be oriented parallel to the static magnetic field and moved with a high velocity upwards along the vertical plane before abruptly its movement. This effect could not be replicated in different orientations of the applicator and/or with rapid movements along different planes and/or with movements at clinically more realistic velocities. Both ophthalmologists assessed the forces associated with this pivoting to be small compared to the forces induced to the eye during surgery. Furthermore, with exception of anteriorly located applicators, the observed pivoting was considered unrealistic for in vivo situations as the surrounding anatomy, in particular the orbital fat and eye muscles, would prevent such movement.

Table 1. Scan sequence parameters

Scan name	Acquisition voxel size, mm ³	Echo train length	TE (ms)/ TR (ms)	NSA	Additional parameters	Scan duration (mm:ss)
3D						
3DT1 GE	0.9 × 0.9 × 0.9	1	2/7	1		0:43
3DT1 SE	0.8 × 0.8 × 0.8	14	30/400	1		2:07
3DT2 SE	0.8 × 1.2 × 1.2	117	260/2,300	2		1:18
SEMAC T1	0.78 × 1.0 × 2.0	4	12/450	1	DC: weak	1:25
SEMAC T1	0.78 × 1.5 × 2.0	6	12/450	1	DC: medium	3:22
SEMAC T2	0.78 × 0.93 × 3.0	15	90/2,500	1	DC: weak	2:20
SEMAC T2	0.78 × 0.93 × 2.5	15	90/2,500	1	DC: medium	2:46
2D						
MARS+VAT T1	0.5 × 0.5 × 2.0	6	6.4/400	1		1:37
MARS+VAT T2	0.4 × 0.4 × 2.0	17	90/1,774	2		1:54

3D, three-dimensional; 2D, two-dimensional; GE, gradient echo; SE, spin echo; TE, echo train; TR, repetition time; NSA, number of signal averages; SEMAC, slice encoding for metal artefact correction; DC, distortion correction; MARS, metal artefact reduction sequence; VAT, view angle tilting.

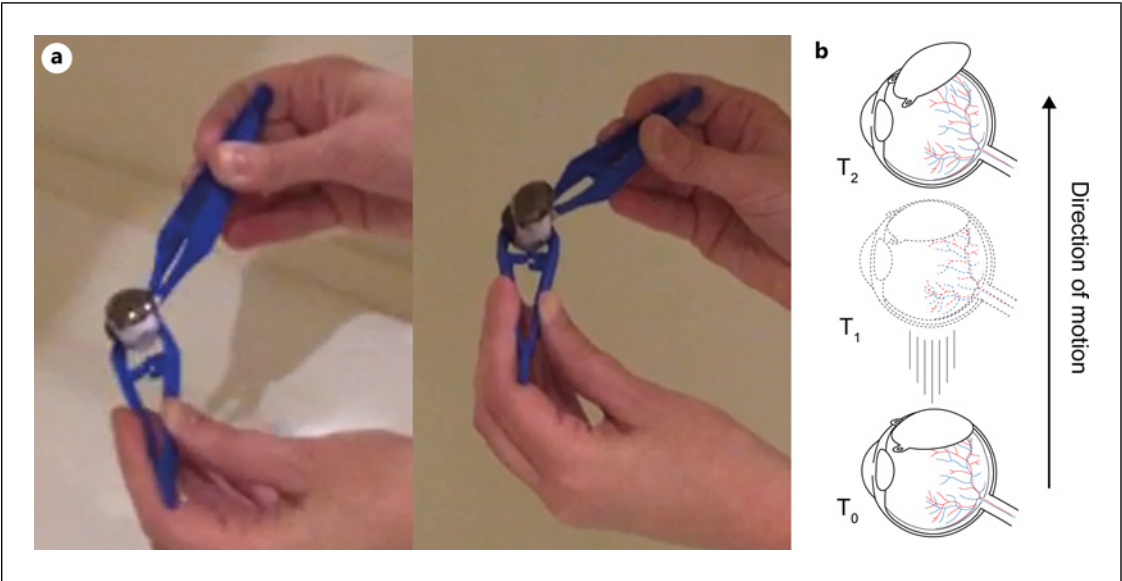


Fig. 2. a, b Eddy current-induced forces could in specific conditions result in a temporary partly detachment of the applicator from the eye. One of the ophthalmologists applying a large and rapid upward movement to the porcine eye with the Ru-106 applicator sutured onto it (T₁). When the movement is abruptly stopped (T₂), the applicator slightly detaches from the eye with the two sutures as pivoting points.

In vivo Evaluation

With the exception of the applicator-induced signal voids, all MRI exams of the patients with the applicator in situ were uneventful. Patients reported no discomfort both during scanning and after explicit asking after scanning. No abnormalities or complications were

observed during the surgical removal of the applicator by the ophthalmologist.

Significant, susceptibility artefacts were observed at the location of the applicator on all sequences (shown in Fig. 3). In the conventional ocular scans, the extent of these artefacts reached approximately 13 mm perpendicular to

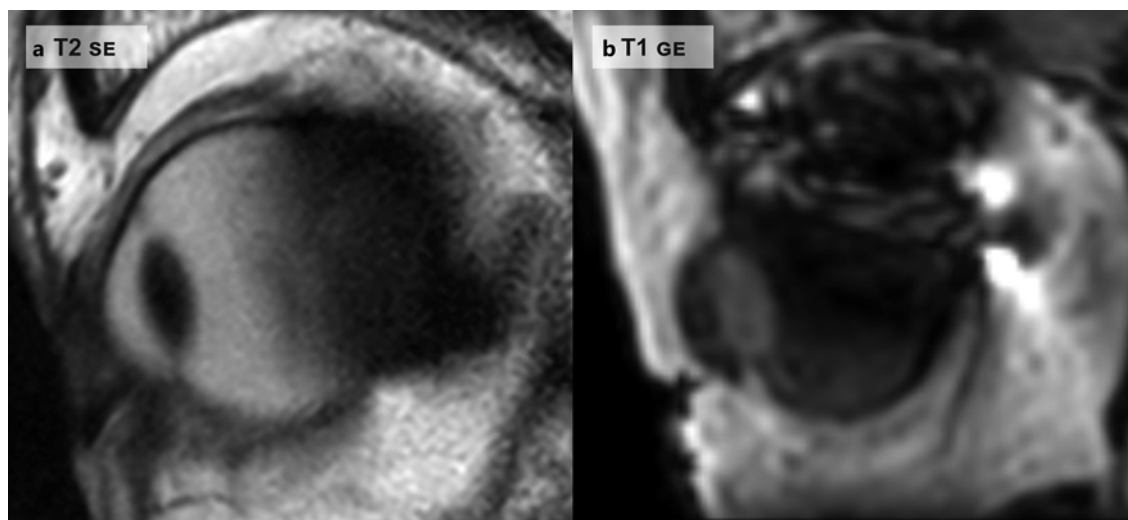


Fig. 3. Overview of scan quality of 2 UM patients scanned with applicator in situ at 3T MRI using the conventional UM scan protocol. **a** Sagittal T2-weighted 3D SE scans showing a representative clinical MR image of a UM patient with CCB-type applicator with a large susceptibility artefact caused by the applicator. **b** Sagittal T1-weighted GE scan of a UM patient with CCB-type applicator showing a large susceptibility artefact, which extends into the nasal cavity. 3D, three-dimensional; GE, gradient echo; SE, spin echo.

the applicator, obscuring most of the ocular anatomy. A slightly smaller sized artefact was seen in 1 patient treated with the 3-mm-smaller diameter CCD-type applicator. The extent of the signal void could be reduced to approximately 7 mm in both directions by the use of the metal artefact reduction sequence with view angle tilting (shown in Fig. 4a) metal artefact reduction techniques, resulting in the visualisation of most of the ocular anatomy. Similarly, the use of the slice encoding for metal artefact correction technique resulted in a reduced but slightly larger signal void of approximately 9 mm in both directions (shown in Fig. 4c). No difference was found when a higher distortion correction factor was applied to slice encoding for metal artefact correction T1- or T2-weighted scans (as shown in online suppl. Fig. 1; for all online suppl. material, see <https://doi.org/10.1159/000542712>). As the tumour lesion remained partially obscured with either technique, no reliable dimension measurements could be taken of the tumour. However, the extra-orbital anatomy, such as the brain (shown in Fig. 4b), was depicted without visible artefacts.

Discussion

Overall, no significant interactions between the Ru-106 eye applicators and the 3T MRI were observed. The absence of magnetic attraction was expected as

the composition of the applicator does not contain magnetic elements. Although the applicator was found to have a preferential alignment in relation to the main magnetic field, only minimal force was required to change its orientation. Some eddy current-induced interactions were observed after abruptly halting large and rapid upward movements, resulting in a temporary partial detachment of the applicator from the porcine eye. However, these rapid movements of the eye were considered unrealistic in an in vivo setting. Moreover, with exception of a very anteriorly positioned applicator, the surrounding orbital anatomy would produce a counter force sufficient to maintain the applicator in its original location.

Based on these observations, we judge it safe to scan patients with the Ru-106 eye applicators in situ at 3T MRI as the observed forces were much smaller than those exerted on the eye during the suturing of the applicator to the eye. We do, however, advise some precautions as these easily prevent the observed, although small, eddy current interactions. For patients with an anteriorly located applicator, we advise to position the patient on the MR bed outside the MR suite and have the head immobilised, e.g., in the head coil or on a radiotherapy head support [23]. In this way, any abrupt head motion in or near the MR magnet can be prevented. For patients with a more posteriorly located applicator, we consider it sufficient to

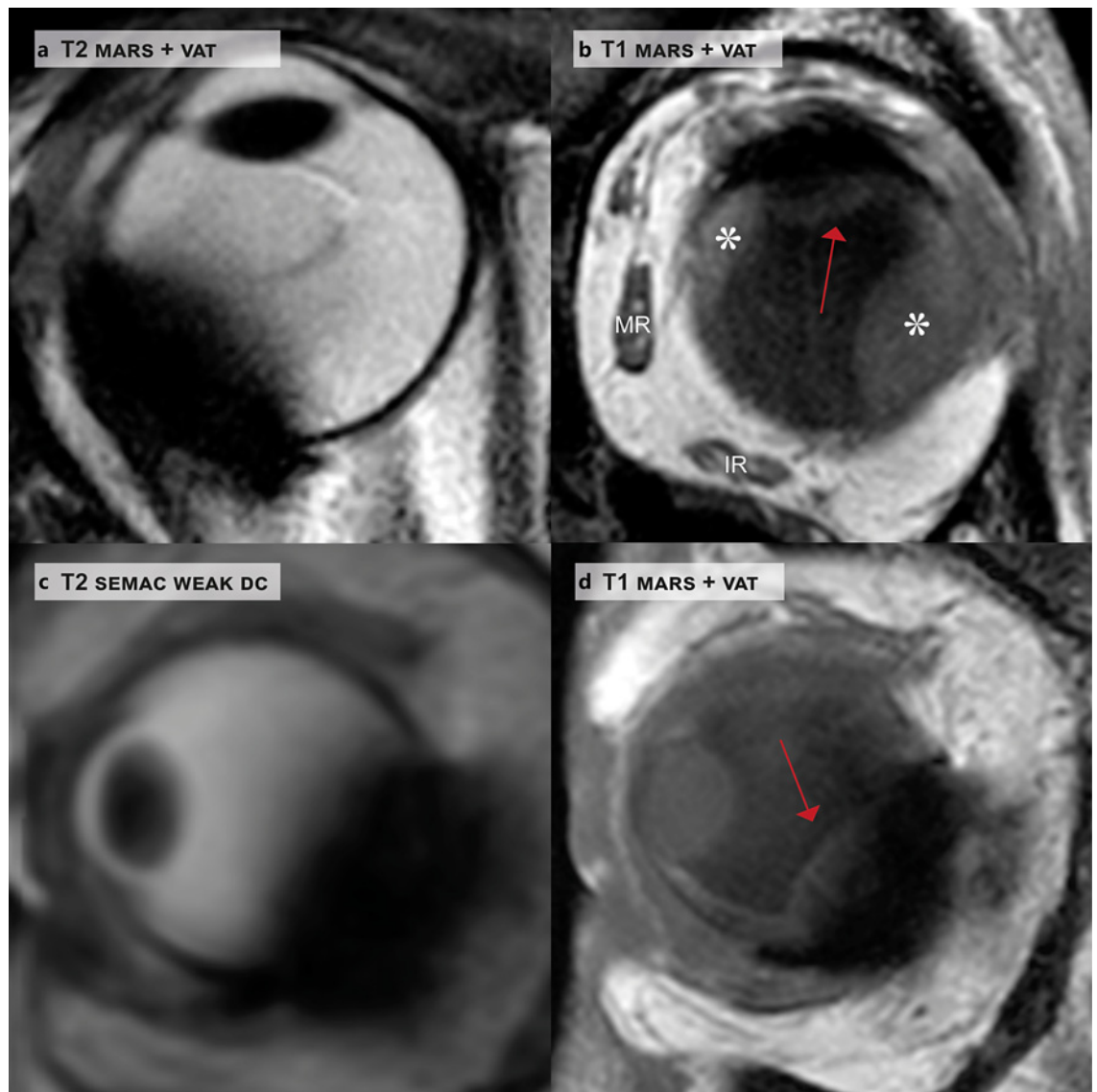


Fig. 4. Examples of improvements in MR image quality by the implementation of MARS with VAT and SEMAC in 3 UM patients with applicator at 3T MRI. **a** Axial T2-weighted 2D MARS with VAT scans of a UM patient with a CCB-type applicator. Despite the reduction of the susceptibility artefact size, the majority of the tumour lesion is still obscured by the signal void. **b** Coronal T1-weighted 2D MARS with VAT of a UM patient with CCD applicator. The smaller diameter (18 mm) CCD applicator allowed for the determination of the tumour apex (red arrow). In addition, the signal void did not

obscure structures like retinal detachment (asterisk) and ocular muscles such as the medial rectus (MR) and IR. **c, d** Sagittal T2-weighted 3D SEMAC and T1-weighted MARS with VAT scans. Both techniques show similar outcomes in susceptibility artefact reduction. No reliable measurements can be taken of the tumour dimensions using either techniques. MARS, metal artefact reduction sequence; VAT, view angle tilting; SEMAC, slice encoding for metal artefact correction; IR, inferior rectus; 3D, three-dimensional; 2D, two-dimensional.

instruct the patient to move slowly, especially when sitting upright after scanning, as the surrounding anatomy will mitigate the impact of any, unlikely, eddy current interaction.

A limitation of the study is the lack of testing for RF-induced heating of the applicator. However, the dimensions of the object are significantly smaller than the half-wavelength of the RF waves at 3T, <2 cm, and 13 cm,

respectively, making it physically impossible to absorb the RF waves [24].

Although the Ru-106 eye applicator does not pose any MR-related safety risk, it does have a significant negative impact on the image quality of the acquired MR images. The size, and thus the clinical impact, of the observed signal void depended on the used scan protocol. For the regular ocular MRI protocol proposed by Ferreira et al. [23], the signal void extended up to 13 mm and 50 mm from the applicator for spin-echo and gradient-echo sequences, respectively. With the use of metal artefact reduction techniques such as metal artefact reduction sequence with view angle tilting, the extent of the artefact could be reduced to 7.2 mm. Although the reduction in the size of the susceptibility artefact allowed for the determination of intra-ocular pathologies such as retinal detachment, no reliable evaluation could be performed on the UM lesion, although its apex could be seen for a more prominent mass (shown in Fig. 4d). However, MRI remains feasible for the assessment of extra-ocular anatomy, e.g., the brain, as anatomical structures outside the eye remain unaffected by the susceptibility artefact.

Overall, we conclude that the Ru-106 applicators and patients with applicators in situ can be safely scanned at 3T MRI. Minimal magnetic attraction and eddy current interactions were observed. Furthermore, these forces were significantly smaller than the forces exerted during the surgical attachment of the applicator onto the sclera. Precautions should still be taken into account when scanning patients with an applicator in situ, with supervised positioning of the patients before and after MRI scanning. MR image quality of the eye was poor due to major susceptibility artefacts; however, MR imaging of other anatomies is feasible.

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Statement of Ethics

This study protocol was reviewed and approved by the Medisch-Ethische Toetsingscommissie Leiden-Den Haag-Delft as well as by the board of directors at the Leiden University Medical Center, Approval No. P22.038 on July 22, 2022. This study was carried out according to the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans and was approved by the local Ethics Committee. Written informed consent was obtained from all participants.

Conflict of Interest Statement

The following authors are part of the C.J. Gorter research centre and received research support from Philips Healthcare: Michael C.Y. Tang, Lisa Klaassen, and J.-W.M. Beenakker. There are no conflicts to disclose for the remaining authors.

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Author Contributions

Conceptualisation and analysis and interpretation of data: M.C.Y.T., J.-W.M.B., and M.M. Data acquisition: M.C.Y.T., L.K., M.M., T.H.K.V., M.K., and J.-W.M.B. Manuscript drafting: M.C.Y.T. Revision of manuscript: M.C.Y.T. and J.-W.M.B. Final approval of the manuscript: L.K., M.M., T.H.K.V., G.P.M.L., C.L.C., M.K., and J.-W.M.B.

Data Availability Statement

Data are not made available for public sharing, as the rarity of the disease does not allow for safeguarding of the anonymity of the participants. However, data may be available upon request from the Ophthalmology Science Committee (contact via oog-stafsecretariaat@lumc.nl) for researchers who meet the criteria for access to confidential data.

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