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TECHNICAL NOTE

High Resolution MR Imaging of the Testis Using a Small Radiofrequency Coil

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We have developed a new device, consisting of a 3-cm RF coil and an immobilizer, to acquire high-resolution MR images of the testis. With the approval of our institutional review board, we conducted an MRI study on a cohort of healthy volunteers to test this device. With the participants in the supine position, we placed the dedicated immobilizer and RF coil on the scrotum for typically no more than 3 min. Subsequently, T2-weighted images were acquired with an in-plane resolution of 117 μm using a 3-T MR scanner and the periodically rotated overlapping parallel lines with enhanced reconstruction (PROPELLER) sequence. The total scan time ranged from 12 to 30 min (average 20 min). High-resolution MR images of the testis were acquired without deterioration by motion artifacts. Our results showed that the combined use of a small RF coil and an immobilizer is a feasible option for acquiring high-resolution MR images of the testis.

Keywords: *high resolution, magnetic resonance imaging, seminiferous tubules, testis*

Introduction

MRI is used for the diagnosis of various testicular disorders, including testicular tumors and testicular torsion. Most published articles have reported the capability of a 1.5 tesla (T) MR system for imaging of the testis, demonstrating that MRI provides detailed anatomical information on the scrotum, including the testis and epididymis.[1–4] Recently, the usefulness of MR spectroscopy for acquiring metabolic information, which might be a potential biomarker for evaluating spermatogenic activity, has been documented.[5] The anatomical and metabolic information provided by the non-invasive MR technique might assist urologists and andrologists in making treatment plans for patients with male infertility and various testicular disorders.

From a technical point of view, MR scanning of the testis is highly demanding because special care must be taken to ensure adequate support and correct positioning of the scrotum. Intermittent contraction of the cremaster and dartos muscles leads to involuntary movement of the testicles, causing motion artifacts. Occasionally, the testicles move away from the sensitive area of the receiver coil, causing deterioration of image quality because signals from the testis cannot be sensitively detected. In the worst-case scenario, the testicles might disappear from the subscribed FOV.

Recent guidelines published by the European Society of Urologic Radiology (ESUR) recommend the use of gauze and adhesive tape for adequate support and correct positioning of the scrotum;[6] however, this technique might have limited stability and reproducibility. Moreover, they recommend a circular surface coil of 8–17 cm in diameter that can be placed in close proximity to the testis; however, the coil size seems relatively larger than one that can enable high-resolution imaging and high-sensitivity spectroscopy for a small testicle. This limits the availability of high-resolution MRI and spectroscopy, especially for the testis of infertile males whose testicles are generally smaller than those of healthy individuals.

We, therefore, supposed that there is a need to develop a stable and reproducible technique for adequate support and correct positioning of the scrotum during MR scans. With such a technique, even a small surface coil can be placed on a small testis, which might facilitate the acquisition of high-

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resolution images and highly sensitive spectra even in a small testicle, in addition to normal testicles weighing approximately 8.0 to 8.5 g. Indeed, Yamaguchi and Fujii have reported high-resolution MRI of the testis in experimental animals whose testicles weighed approximately 1 to 1.5 g, using the combination of a 3-T MR scanner and a small RF coil with a diameter of 3 cm. They acquired MR images with 78-μm in-plane resolution and observed the seminiferous tubules in healthy rats.[7] However, to the best of our knowledge, there is no previous report of high-resolution MRI of human testes using this device combination. This could probably be due to the fact that adequate support and correct positioning of the human scrotum on such a small coil might be challenging.

Here, we report a novel technique to immobilize the testicle during MR scanning by means of an immobilizer that we recently developed. The purpose of this study was to test the feasibility of using a combination of a small RF coil and an immobilizer to acquire high-resolution MR images of the human testis. The small RF coil and immobilizer are in the developmental stage and are, therefore, not yet approved for clinical use. In this study, we conducted a feasibility test on a small cohort of healthy individuals in advance of a clinical trial under the Clinical Trial Act of Japan, which is typically conducted to demonstrate the effectiveness of a novel non-approved clinical device. Therefore, any comparison with currently available MR techniques was beyond the scope of this study.

Materials and Methods

Our Institutional Review Board approved this multi-center, interventional clinical study. This study was registered in the UMIN Clinical Trial Registry (#UMIN000042373). Eligibility criteria were: males aged 20 to 50 years; subjects whose spouse or female partner gave birth to more than one child by normal pregnancy or whose sperm test result was normal, i.e., sperm count of more than 15 million per milliliter and motility rate of more than 40% according to the World Health Organization criteria version 5; subjects who did not have a congenital anomaly in the urogenital tract, no medical history of any urogenital disorder, or any trauma to the urogenital tract; no medical history of varicocele; no medical history of malignant tumors, endocrine disorders or autoimmune diseases; and no history of medication with hormonal agents. Exclusion criteria were as follows: individuals who consented for study participation under duress; those with a ferromagnetic metal item in their body; claustrophobic individuals; subjects with tattoos; subjects with cognitive impairment; those with psychological disorders including depression, schizophrenia, or bipolar disorders; and those judged inappropriate for participation in this research by physicians. Written informed consent was obtained from all the participants (n = 3).

MR scanner and receive-only RF coil

All MR images were acquired with a 3.0-T scanner (Signa HDx 3.0T; GE Healthcare, Milwaukee, WI, USA). RF transmission was performed using the body coil of the scanner. We used a circular, 3-cm diameter, receive-only surface coil (Takashima Seisakusho, Tokyo, Japan). The coil was encased (length, width, height: 126 × 50 × 15 mm), and a 21-mm aperture was created at the top and bottom of the case. The coil was the same type as that developed previously;[7] however, it was not the same one as was used in a preclinical research, since we purchased another coil from Takashima Seisakusho for this clinical research. We made sure that we were able to safely preform MR scans using this coil based on the following results: the coil passed a standard voltage proof test and a standard test on RF-induced heating according to the American Society for Testing and Materials (ASTM) F2182-11a.

Phantom study

We conducted a phantom study to compare coil sensitivities between the dedicated 3-cm coil and a clinically available coil (3T GP flex coil; GE Healthcare, 553 × 210 mm). We examined a spherical phantom 6 cm in diameter containing a 2-mM copper sulfate solution. Fast gradient echo (FGE) images were acquired with the following parameters: TR, 6.0 ms; TE, 1.8 ms; flip angle, 30°; FOV, 100 × 100 mm; matrix, 256 × 128 (zero-interpolation to 256); slice thickness, 4 mm. An experienced radiologist measured SNRs on the phantom images. He placed ROIs of 40 × 40 pixels (equivalent to 244 mm^2) at the periphery of the phantom and measured average pixel values ($SI_{average}$). He also placed ROIs (1113 mm^2) in the background noise area and measured standard deviations (SD_{noise}). Finally, SNRs were calculated using the following equation:

$$SNR = SI_{average}/SD_{noise} \qquad (1)$$

In addition, he plotted the signal intensity profile of the phantom on a sagittal FGE image acquired with the 3-cm coil to examine the changes in signal strength as a function of distance from the surface of the coil. Relative signal strengths to the maximum value were calculated along a line through the center of the phantom and expressed as a percentage.

Immobilizer

To facilitate the positioning of the testis and to minimize involuntary motion of the testis during MR scanning, we requested each subject to put on a purpose-made underwear and immobilizer (Japanese Patent Application No. 2020-063534). Figures 1 and 2 visually explain how these are used. The underwear facilitates positioning of the penis in the upward direction, along the midline of the lower abdomen. In addition, it elevates the scrotum upward and forward, allowing the examiner to place the coil on top of the testis. The immobilizer consists of a polyvinyl chloride

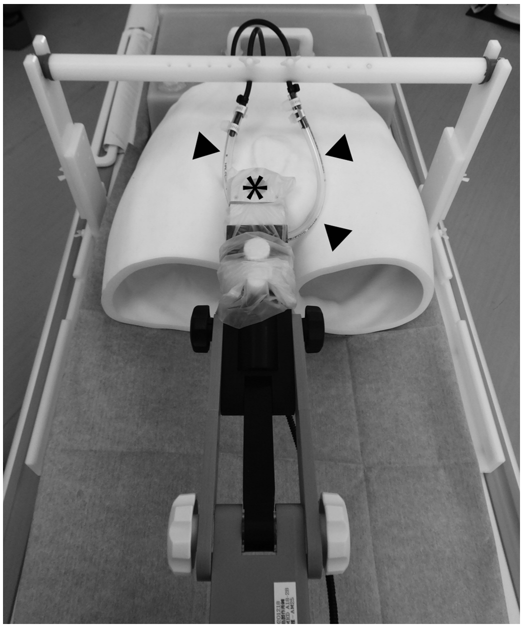

Fig. 1 A picture of the immobilizer and a mock-up of the lower abdomen and proximal thigh viewed from above. The immobilizer, which is placed on the patient table of a GE scanner, consists of horizontal and side bars. There are small holes in the horizontal bar, through which rubber strings are passed. A u-shaped PVC tube (arrowheads), which is placed on the dorsolateral aspect of the scrotum, is connected to the rubber strings. In this simulation image, the RF coil is placed on the right testis, such that the 21-mm aperture (asterisk) is placed just above the middle part of the testis, and is supported with an RF coil holder. PVC, polyvinyl chloride.

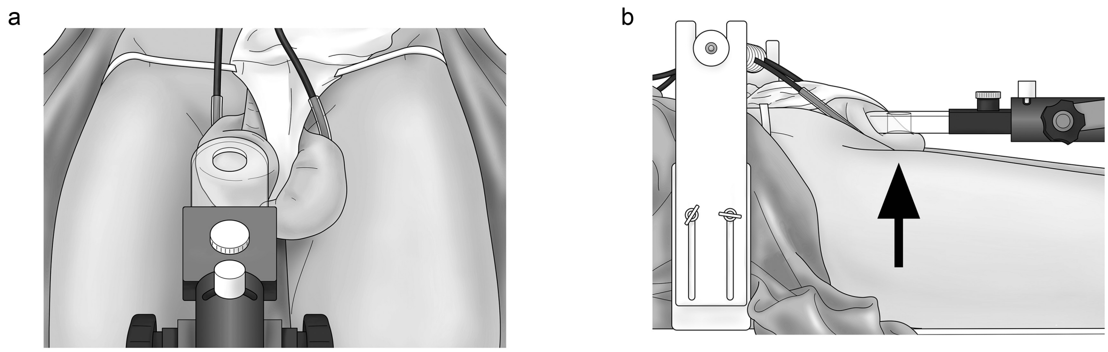

Fig. 2 Schematic diagram of caudal (**a**) and right lateral (**b**) views of a subject undergoing a testicular MR scan with the RF coil and immobilizer. The subject puts on a purpose-made underwear that results in the penis being placed upwards on the lower abdomen. Both the testicles are deliberately exposed to ensure that the examiner can inspect them and position the RF coil appropriately. Note that the right testis is tightly held in the gap between the RF coil and the skin of the medial groin (arrow in **b**).

(PVC) tube that is placed in a kind of u-shape on the dorsolateral aspect of the scrotum and gently pulls the scrotum in the cranial and ventral directions. During MR scanning, the PVC tube was fixed onto a horizontal polyacetal bar that was placed across the subject's body. To make sure that the immobilizer works properly, we conducted the following preliminary experiment: a transparent mock-up of the coil case was produced from an acrylic resin. The mock-up was set on the coil holder as shown in Fig. 2a. A 49-year-old healthy volunteer was asked to lie in the supine position on a patient bed and to put on the immobilizer. First, his right testis was pulled up with the PVC tube and the mock-up was put on it. Researchers, including an experienced urologist, observed the frequency and the extent of the movement of the scrotum for 5 min. Next, we repeated the same observation except for pulling up the testis with the PVC tube. Further, two consecutive FGE MR scans of the testis were performed with and without the use of the immobilizer. The scan parameters were the same as those in the above-mentioned phantom experiments.

MRI

After the subject lay on the patient table in the supine position, the scrotum was set on the immobilizer, as mentioned above. All three subjects were evaluated by a radiographer and a urologist or radiologist. The examiners put the coil on the surface of the right scrotum to ensure that the central part of the testicle was placed just below the aperture of the coil.

Although the coil and immobilizer can be put on either of the testis, we examined only the right testis.

First, three-plane localizer scans were performed with an FGE sequence with the following parameters: TR, 5.1–6.0 ms; TE, 1.6–1.8 ms; flip angle, 30°; FOV, 100–350 × 100–350 mm; matrix, 256 × 128; slice thickness, 4 mm; slice gap, 0 mm; and number of excitations, 2. Typically, the first localizer scans were performed with an FOV of 350 × 350 mm and the second ones with an FOV of 100 × 100 mm. After the scan area was determined based on these localizer images, T2-weighted axial images were acquired using the periodically rotated overlapping parallel lines with enhanced reconstruction (PROPELLER) sequence with the following parameters: TR, 6000 ms; effective TE, 141.2 ms; FOV, 60 × 60 mm; matrix, 512; slice thickness, 2 mm; slice gap, 0.5 mm; and number of excitations, 2.5. The scan time was 5 min and 30 s. We chose this pulse sequence because PROPELLER is known as a pulse sequence that can produce T2-weighted images without significant deterioration by motion artifacts.[8] We chose T2-weighted pulse sequences because previous preclinical studies demonstrated that T2-weighted contrast images can well visualize the seminiferous tubules, which cannot be achieved by either T1-weighted contrast or proton density-weighted contrast images.[9] Although the 3 cm surface coil can only detect signals in a range of approximately 3 cm from the surface, we chose an FOV of 60 mm because this was the smallest FOV that the sequence allowed. To ensure that the PROPELLER T2-weighted sequence allows the detection of a fine tubular structure with no deterioration of image quality by streaking artifacts, we conducted phantom experiments as follows. First, a bottle-shaped phantom was constructed. A total of 445 polyethylene (PE) tubes with inner and outer diameters of 0.35 mm and 1.05 mm, respectively (KN-392; Natsume Seisakusyo, Tokyo, Japan), were filled with agar gel. These were then tightly packed and immersed in water in one half of the bottle. The other half of the bottle was filled with 1% agar. Next, the phantom was set on the 3-cm surface coil to ensure that the PE tubes were placed in proximity to the coil surface. Finally, we acquired axial PROPELLER T2-weighted images of the phantom with 512 matrices and 80-mm FOVs, 256 matrices and 60-mm FOVs, and 256 matrices and 90-mm FOVs. The other scan parameters were the same as those mentioned above. The sets of matrices and FOV yielded 156 μm, 234 μm, and 351 μm in-plane resolutions, respectively; therefore, the number of pixels equivalent to one cross section of the PE tube (1050 μm) was 6.7, 4.5, and 3.0, respectively. For comparison, we also acquired axial spin echo T2-weighted images with an FOV of 40 × 40 mm, 512 × 512 matrices, a slice thickness of 1 mm, and the number of excitations of 16.

Image analysis

All images were evaluated by experienced radiologists and urologists looking to see what structures were visualized on PROPELLER T2-weighted images of the testis. In addition, they evaluated the presence or absence of any type of artifacts in the images. An experienced radiologist measured SNRs on PROPELLER T2-weighted images as follows. After selecting a representative slice through the craniocaudal center of the testis, elliptical ROIs with an area of 28–29 mm^2 were placed at the testicular parenchyma just beneath the tunica albuginea. These ROIs were placed at a depth of no more than 7 mm from the coil. Another ROI was placed in the background noise area, and SNR was calculated using equation (1) above.

Results

Figure 3a shows a signal profile of the spherical phantom on an FGE image acquired with the 3-cm coil. Fig. 3b indicates the line where the signal profile was drawn. Maximum signal strength was observed in close proximity to the surface of the object. The signal decreased to approximately 50% at a depth of 10 mm, and 20% at a depth of 20 mm. Fig. 3c and 3d indicates representative FGE images of the spherical phantom acquired with the 3-cm coil and GP flex coil, respectively. ROIs were placed near the surface of the phantom, as indicated. It was found that the 3-cm surface coil had a higher SNR of 480 ± 39 (arbitrary unit [AU]) (average ± standard deviation [SD], n = 5) than the GP flex coil (55 ± 1) (AU).

In the experiment with regard to the immobilizer, the right scrotum heavily contacted, and was immobilized on, the coil mock-up, being pulled up with the PVC tube (Fig. 2). During the 5-min observation with the coil mock-up, vermicular contraction of the scrotal skin, i.e., the dartos reflex, was seen several times in the craniocaudal direction from the inferior pole to the superior pole. Remarkably, these movements of the scrotal skin were almost suppressed in the area just beneath the mock-up. In contrast, when the scrotum was not pulled up by the PVC tube, the right scrotum only lightly contacted the coil mock-up. This allowed unsuppressed movement of the scrotal skin even beneath the mock-up.

Figure 4 shows FGE images of the human testis with and without using the immobilizer. The immobilizer allowed the testicular parenchyma to be placed in close proximity to the 3-cm coil, so that the sensitive area that detected signals more than 50% of the maximum included a part of the testis. In contrast, the sensitive area did not include the testis when the immobilizer was not used. In this situation, only adnexal tissues were detectable instead.

In this human testis imaging study, the setup time to complete patient positioning was typically no more than 3 min. The total scan time ranged from 12 to 30 min (average 20 min) from the start of localizer scanning to the end of PROPELLER scanning. Typically, two localizer scans were performed; however, in one case, five scans were performed because the examiner tried to adjust the position of the coil several times so as not to

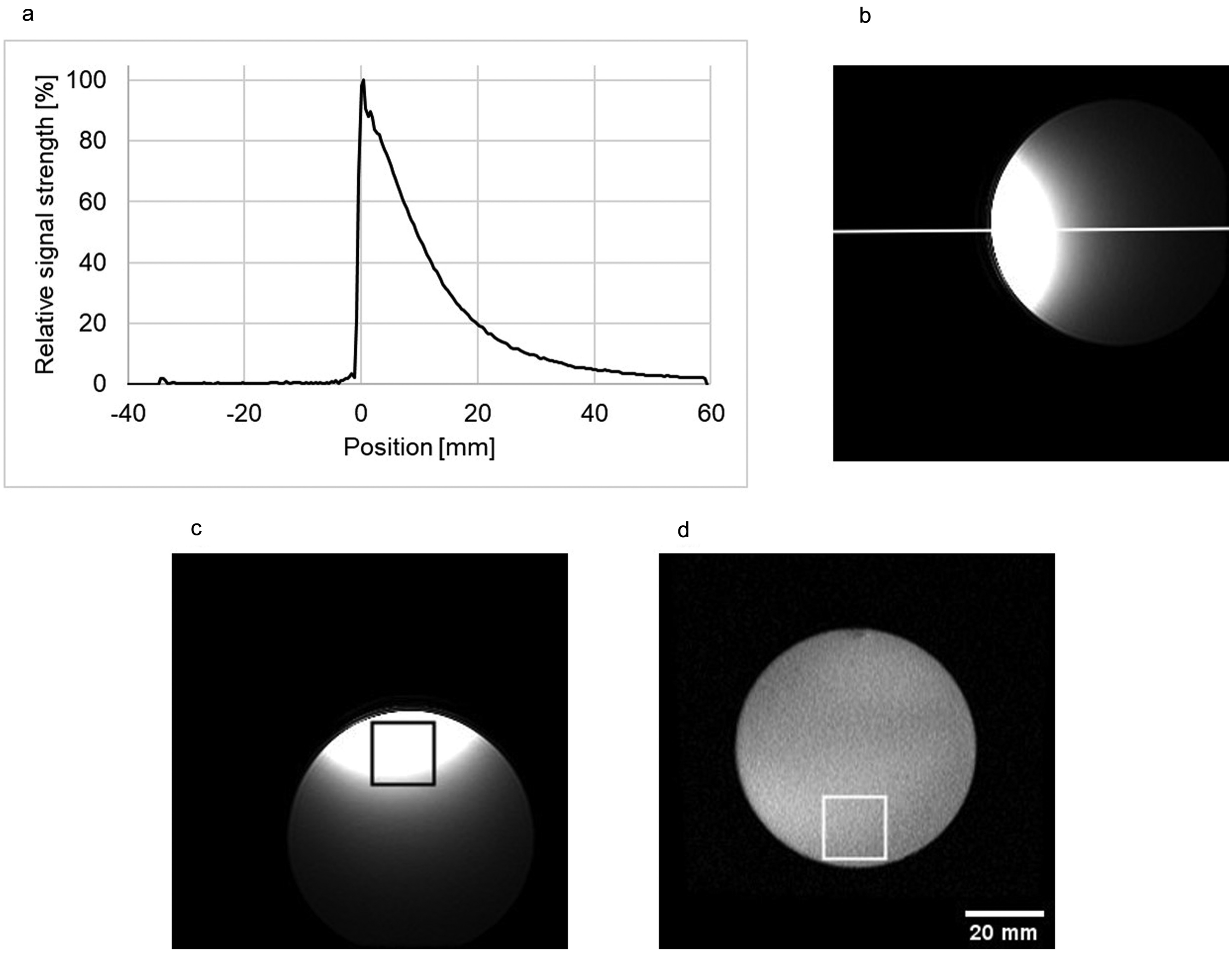

Fig. 3 A signal profile showing the reduction in relative signal strength as the distance from the 3-cm coil increases (**a**). Signal strength relative to the maximum value is plotted in the unit of %. The position of the surface of the phantom is set at 0 mm, and the depth of the phantom is shown on the right side of the profile. A corresponding sagittal FGE image of the phantom shows the line indicating where the signal profile is drawn (**b**). Representative transverse FGE images of the spherical phantom were acquired with the 3-cm coil (**c**) and GP flex coil (**d**). The squares represent ROIs where signal strengths were measured. FGE, fast gradient echo.

include the epididymis in the FOV, and he repeated localizer scans every time he changed the coil position. The participants did not report any discomfort in the lower abdomen, including the scrotum. No abnormal appearance of the surface of the scrotum was noted immediately after completion of the MR scans.

High-resolution MR images of the testis were acquired without deterioration in their quality by motion artifacts in all three participants. The SNR for the testicular parenchyma was 33 $\pm$ 4 (average $\pm$ standard error, n = 3). Small structures, including small vasculature, were visualized. In addition, very fine textures were seen in the testicular parenchyma. These findings seemed likely related to microstructures of the testis, including seminiferous tubules and testicular interstitium (Fig. 5).

PROPELLER T2-weighted images clearly visualized cross sections of the PE tubes with no deterioration of image quality by streaking artifacts (Fig. 6). With the in-plane resolution of 156 μm (6.7 pixel/tube), the lumen and wall of the PE tubes were recognized; however, with the in-plane resolution of 234 and 351 μm (4.5 and 3.0 pixels/tube, respectively), they were not clearly discernible owing to the partial volume artifact.

Discussion

Yamaguchi and Fujii reported a technique for immobilization and correct positioning of the testis in their preclinical study.[7] They suctioned rat testes using a range of negative pressures from −25 to −10 kPa to immobilize them. Consequently, they

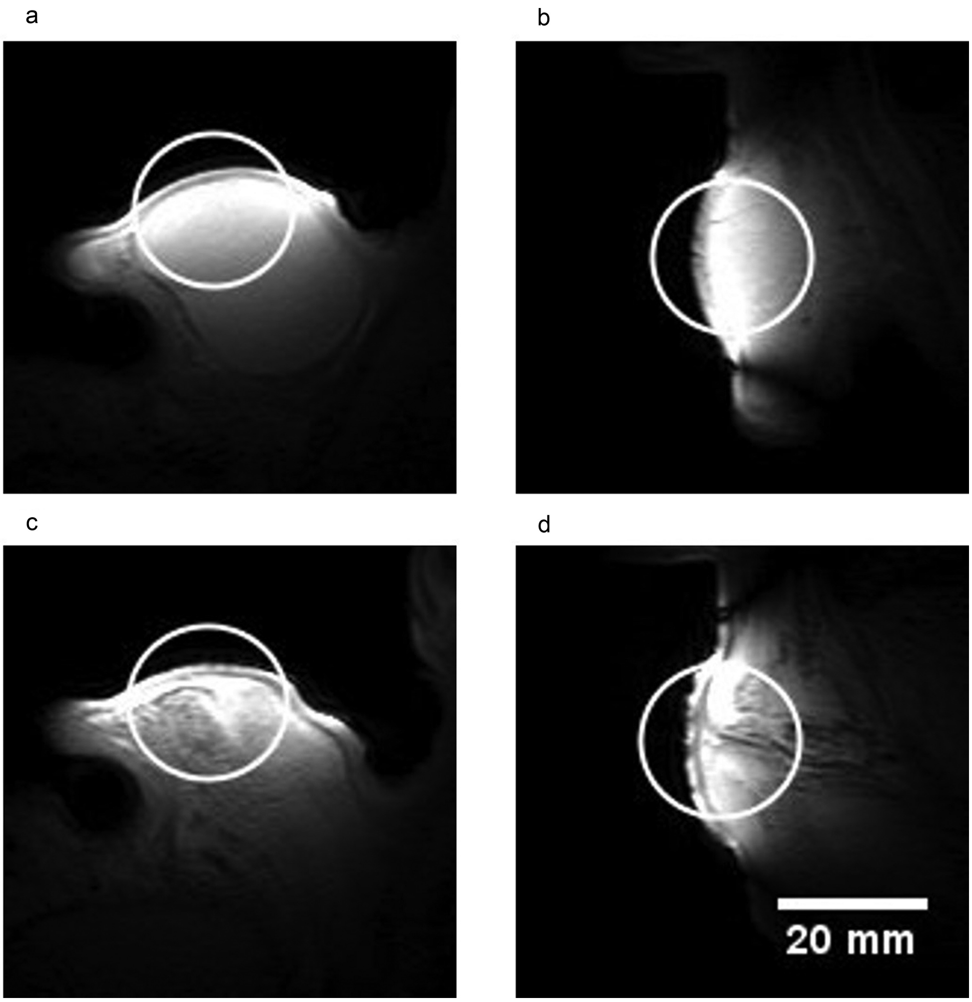

Fig. 4 Representative transverse and sagittal FGE images of the testis are shown. Images in (**a**) and (**b**) were acquired with the 3-cm surface coil and immobilizer. The 10-mm radius circles indicate the area where a signal strength of more than 50% of the maximum is recovered. Note that the testicular parenchyma is positioned in the circle. Images in (**c**) and (**d**) were acquired with the 3-cm surface coil but without the immobilizer. Only adnexal tissues are seen in the circle. The testicular parenchyma is not depicted clearly because it is out of the circle. FGE, fast gradient echo.

acquired high-resolution spin-echo MR images with an in-plane resolution of 78 μm, in which the seminiferous tubules and small blood vessels were clearly seen. Although their technique might be applicable to humans, the technique might pose the risk of tissue injury caused by negative pressure suction, unless an optimal range of negative pressures is applied. It definitely requires a full investigation both to determine the optimal pressure range and to confirm its safety.

Our proposed technique is an alternative option to their technique. Instead of using negative pressure suction, an immobilizer consisting of a PVC tube and polyacetal bars is used. When the subject is in the supine position, the u-shaped PVC tube supports the scrotum against the force of gravity, which tends to naturally draw the scrotum in the caudal-dorsal direction. With our immobilizer device, the testicle is positioned just above the skin in the medial part of the groin, where the coil can push the testicle down from above. Consequently, the testicle can be tightly held in the gap between the coil and inguinal skin. Our data suggest that the immobilizer does not pose any potential risk of tissue injury.

Our preliminary data showed that slow and involuntary movements of the scrotal skin caused by contraction of the dartos muscle were almost suppressed in the area just beneath the coil; however, movement was still observed in other parts of the scrotum. This is contradictory to the result of the above-mentioned previous paper that demonstrated almost complete suppression of testicular motion during MR scans in rats.[7] The cause of this inconsistency might stem from the difference in the consciousness level of the study subjects; the experimental animals were under general anesthesia and the human subjects were completely awake. From a physiological point of view, the dartos reflex is well

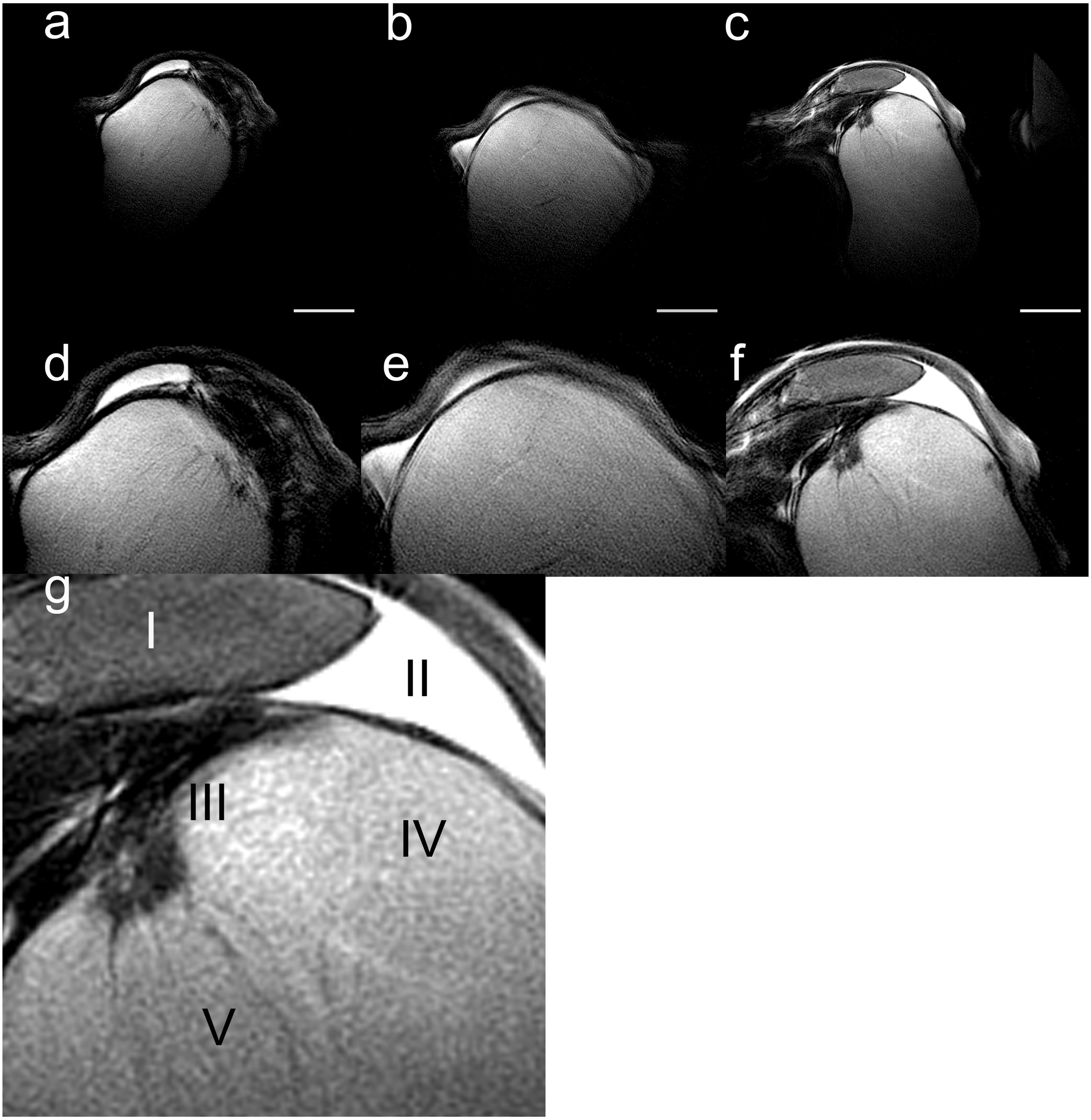

Fig. 5 Representative transverse image of the right scrotum (**a–c**). The scale bars represent 10 mm. Magnified views of the above images are shown (**d–f**). Further magnified views of the images in c and f show the head of the epididymis (I in **g**) and a small volume of hydrocele (II) near the surface of the scrotum. The testicular hilum appears as a low signal structure (III). The testis is seen just beneath these, exhibiting the fine texture of the testicular parenchyma (IV). Small blood vessels (V) are seen radiating from the testicular hilum.

known as a somato-autonomic reflex governed by the sympathetic segment between the 11th thoracic and 2nd lumbar spine levels. The reflex plays an important role in scrotal thermoregulation.[10] Under normal conditions, contraction of the dartos muscles cannot be blocked unless an α-blocker and a noradrenaline antagonist are administered.[11] Therefore, contraction of the dartos muscle is unavoidable in MRI scans in awake human subjects. Although this suggests that the generation of motion artifacts is unavoidable, notably, we did not observe significant motion artifacts in the final images. This could be due to the fact that the pulse sequence, such as PROPELLER, which is well known to be prone to

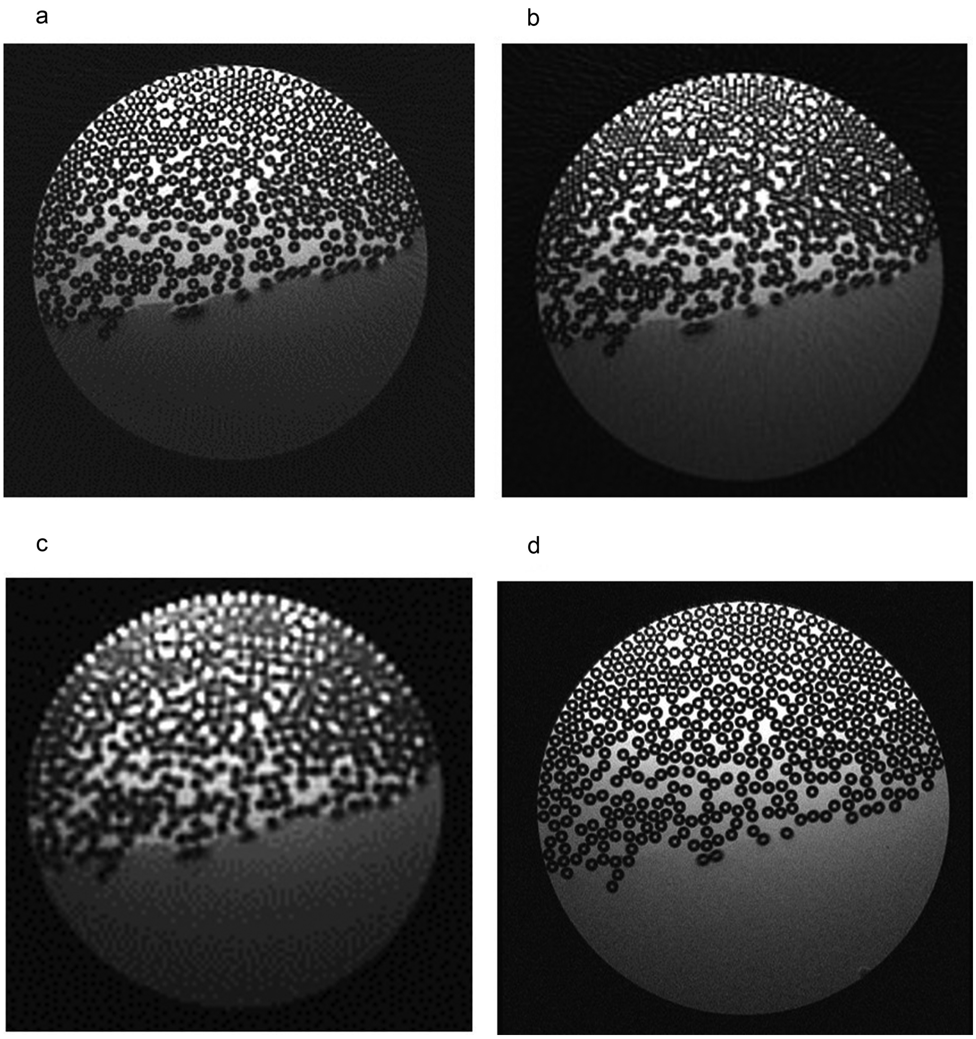

Fig. 6 PROPELLER T2-weighted images of the PE tubes (0.35 mm and 1.05 mm in inner and outer diameters, respectively) with in-plane resolutions of 156 μm (**a**, 6.7 pixels/tube), 234 μm (**b**, 4.5 pixels/tube), and 351 μm (**c**, 3.0 pixels/tube). For comparison, a spin echo T2-weighted image with an in-plane resolution of 78 μm (**d**, 13.5 pixels/tube) is shown. PE, polyethylene; PROPELLER, periodically rotated overlapping parallel lines with enhanced reconstruction.

tiny body motions, might have worked properly. Our phantom study demonstrated that the use of the PROPELLER sequence has no deleterious effects on image quality when applied for observation of fine tubular structures.

The use of a small 3-cm coil is reasonable because it is capable of acquiring high-resolution MR images by the use of the combination of a small FOV and large matrices. Indeed, high-resolution images with an in-plane resolution of 117 μm^2 were acquired with sufficiently high SNRs. However, a drawback of such a small coil is that it has a very limited sensitive area. Even with a small coil in the current form, high-resolution MRI of the testis is clinically applicable to examine a small area just beneath the tunica albuginea before open testicular biopsy in infertile patients. In open testicular biopsy, a 5-mm transverse incision is made through the tunica albuginea, followed by the acquisition of 50–70 mg of testicular tissue for diagnosis and sperm retrieval.[12] This small volume of testicular tissue is equivalent to a 3.7–4.1 mm cube, in which the highly sensitive area of the 3-cm coil can surround.

We developed the 3-cm coil for this research by ourselves because the manufacturer of our 3-T scanner did not produce such coils; however, the coil does not necessarily need to be developed by users if it is produced by the manufacturer. An alternative option would be the use of a small coil supplied by other manufacturers, such as a 23-mm microscopy coil (Philips Healthcare, Eindhoven, The Netherlands). With this option as well, our proposed immobilizer might facilitate correct positioning of the testis in relation to the coil.

That being said, the sensitive area of a small coil no more than 3 cm in diameter does not cover the entire volume of the testis in a normal subject, in particular, those in whom the testis weighs 8.0–8.5 g. A multi-array coil that consists of an array of small circular coils is theoretically useful for expanding the sensitive area in this regard; however, only multi-array coils with larger diameters are available in current clinical practice for MRI. We believe that the accumulation of favorable results with high-resolution MRI of the testis might promote the commercial development of small multi-array coils for the testis.

In our study, thin blood vessels running through the testicular parenchyma were clearly visualized as low-signal structures. Either a flow void or magnetic susceptibility effect of deoxy-hemoglobin in the blood likely caused the production of low-intensity signals. More importantly, fine textures that have never been depicted on low-resolution MRI were recognized in the testicular parenchyma. The testicular parenchyma consists of seminiferous tubules and interstitium. Since healthy seminiferous tubules in humans are 200–300 μm in diameter, they are likely to be detected on MR images with a spatial resolution of 117 μm; however, since the spatial resolution is equivalent to 1.7 to 2.6 pixels per tube, the tubular wall and lumen are not quite discernible due to the partial volume effect, as suggested by the results of the PE tube phantom study. Our results collectively suggest that what we detected as fine textures could be interpreted as partial volume averaging of cross sections of the seminiferous tubular walls and lumen. These structures are likely to be more clearly depicted without the partial volume averaging effect, as shown in ex vivo MR images of an excised human testis (Supplemental Figure 1, which shows an example of MR images of an excised human testis). We postulate that a spatial resolution of 50–75 μm (equivalent to 4 pixels per tube) might allow clear visualization of the lumens and walls of the seminiferous tubules *in vivo*. Further study is needed to confirm this.

This study has some limitations. First, regarding the immobilizer, the height and length of its horizontal and side bars in relation to the size of the bore of the magnet should be determined. When the space between the inner aspect of the magnet bore and the patient's body is limited, only limited space is available for placing the immobilizer. This scenario is plausible during MR scanning of obese patients, such as patients with Klinefelter syndrome (KS), whose testes are examined with MRI. Patients with KS are often overweight because KS is associated with a higher risk of development of metabolic disorders and obesity.[13] Second, as we described in the Introduction, since the aim of the present study was to demonstrate the feasibility of the combination of a small radiofrequency coil and an immobilizer to acquire high-resolution MR images of the human testis, the number of samples was small. However, we were able to reproducibly acquire high-resolution MR images of the healthy testis without motion artifacts even with the small number of samples. Thus, a further comparative study involving both healthy individuals and patients is warranted to further demonstrate the effectiveness of this novel device combination. Third, we did not compare image quality between the PROPELLER sequence and other Cartesian sampling sequences, such as fast spin echo. This was because the use of Cartesian sampling sequences was not justified in this clinical study, based on the fact that severe deterioration of image quality probably due to motion artifacts was demonstrated in our preliminary tests.

Conclusion

We found that the combined use of a small RF coil and an immobilizer is a feasible option for acquiring high-resolution MR images of the human testis.

Acknowledgments

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Conflicts of Interest

Masayuki Yamaguchi received a research grant from the Japan Agency for Medical Research and Development (AMED) and Tsukuba Clinical Research & Development Organization (T-CReDO) (Grant# A18-28). Tomoyuki Haishi is a director of MR Technology, Inc. Tomoyuki Haishi is also a stock owner of MR Technology, Inc. Masayuki Yamaguchi, Kosuke Kojo, Tomoyuki Haishi, Hiroyuki Nishiyama, and Hirofumi Fujii have applied for patents for the immobilizer described in this paper (Japanese Patent Application No. 2020-063534). Tatsushi Kobayashi and Hirofumi Fujii received a research grant from Canon Medical Systems Corporation. Masayuki Yamaguchi, Kosuke Kojo, Mizuki Akatsuka, Takahito Nakajima, and Hiroyuki Nishiyama have no conflicts of interest directly relevant to the subject matter of this paper.

Supplementary Information

A Supplementary file below is available online.

Supplementary Fig. 1

An example of ex vivo MR images of the excised human testis showing cross sections of the seminiferous tubules (**a**). This picture was taken in another clinical study (IRB approved # 2020-585). Written informed consent for participation in this study was obtained from a 62-year-old patient who underwent high orchiectomy with a diagnosis of an intrascrotal tumor. A testicular tissue fragment was cut out from the surgical specimen during routine processing for pathological examination. The small fragment was fixed with Bouin's fixative and placed in a small syringe. We placed the syringe in the 3-cm circular coil and scanned it with a 3-T scanner as mentioned in this manuscript. The scan parameters were as follows: TR, 4000 ms; TE, 46 ms; FOV, 30 × 30 mm; matrix, 512 × 512; slice thickness, 1 mm; and number of excitations, 1. A hematoxylin-and-eosin-stained specimen (**b**) is shown for comparison.

References

1. Seidenwurm D, Smathers RL, Lo RK, Carrol CL, Bassett J, Hoffman AR. Testes and scrotum: MR imaging at 1.5 T. Radiology 1987; 164:393–398.
2. Tsili AC, Argyropoulou MI, Giannakis D, Sofikitis N, Tsampoulas K. MRI in the characterization and local staging of testicular neoplasms. AJR Am J Roentgenol 2010; 194:682–689.
3. Tsili AC, Ntorkou A, Astrakas L, et al. Magnetic resonance diffusion tensor imaging of the testis: Preliminary observations. Eur J Radiol 2017; 95:265–270.
4. Regent B, Skrobisz K, Kozak O, Matuszewski M, Studniarek M. MRI in the evaluation of the azoospermic male. Diagn Interv Radiol 2020; 26:271–276.
5. Storey P, Gonen O, Rosenkrantz AB, et al. Quantitative proton spectroscopy of the testes at 3 T: Toward a noninvasive biomarker of spermatogenesis. Invest Radiol 2018; 53:87–95.
6. Tsili AC, Bertolotto M, Turgut AT, et al. MRI of the scrotum: Recommendations of the ESUR Scrotal and Penile Imaging Working Group. Eur Radiol 2018; 28:31–43.
7. Yamaguchi M, Fujii H. Immobilization technique for high-resolution MR imaging of the testes. Magn Reson Med Sci 2018; 17:338–343.
8. Pipe JG. Motion correction with PROPELLER MRI: application to head motion and free-breathing cardiac imaging. Magn Reson Med 1999; 42:963–969.
9. Yamaguchi M, Mitsumori F, Watanabe H, Takaya N, Minami M. Visualization of seminiferous tubules in rat testes in normal and diseased conditions by high-resolution MRI. Magn Reson Med 2009; 62:637–644.
10. Soler JM, Previnaire JG, Amarenco G. Dartos reflex as autonomic assessment in persons with spinal cord injury. Spinal Cord Ser Cases 2017; 3:17097.
11. Gibson A, Akinrinsola A, Patel T, Ray A, Tucker J, McFadzean I. Pharmacology and thermosensitivity of the dartos muscle isolated from rat scrotum. Br J Pharmacol 2002; 136:1194–1200.
12. Janosek-Albright KJC, Schlegel PN, Dabaja AA. Testis sperm extraction. Asian J Urol 2015; 2:79–84.
13. Pizzocaro A, Vena W, Condorelli R, et al. Testosterone treatment in male patients with Klinefelter syndrome: a systematic review and meta-analysis. J Endocrinol Invest 2020; 43:1675–1687.