Published February 16, 2024 as 10.3174/ajnr.A8209
Published as a preprint [DATE]

ORIGINAL RESEARCH

HEAD AND NECK IMAGING

7T MRI for Cushing's Disease: A Single Institutional Experience and Literature Review

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ABSTRACT

BACKGROUND AND PURPOSE: Cushing disease is typically caused by a pituitary adenoma that frequently is small and challenging to detect on conventional MRI. High field strength 7T MRI can leverage increased signal-to-noise and contrast-to-noise ratios compared to lower-field strength MRI to help identify small pituitary lesions. We aim to describe our institutional experience with 7T MRI in patients with Cushing disease and perform a review of the literature.

MATERIALS AND METHODS: A retrospective analysis of 7T MRI findings in patients with pathology proven cases of Cushing disease from a single institution, followed by a review of the literature on 7T MRI for Cushing disease.

RESULTS: Our institutional experience identified Cushing adenomas in 10/13 (76.9%) patients on 7T, however only 5/13 (38.5%) lesions were discrete. Overall, the imaging protocols used were heterogeneous in terms of contrast dose as well as type of post-contrast T1-weighted sequences (Dynamic, 2D vs 3D, and type of 3D sequence). From our institutional data, specific post-gadolinium T1-weighted sequences were helpful in identifying a surgical lesion as follows: Dynamic Contrast Enhanced 2/7 (28.6%), 2D FSE 4/8 (50%), 3D SPACE 5/6 (83.3%), and 3D MPRAGE 8/11 (72.7%). The literature review identified Cushing adenomas in 31/33 (93.9%) patients on 7T.

CONCLUSIONS: 7T MRI for pituitary lesion localization in Cushing disease is a new technique with imaging protocols that varied widely. Further comparative research is needed to identify the optimal imaging technique as well as to assess the benefit of 7T over lower-field strength MRI.

ABBREVIATIONS: MRI = Magnetic Resonance Imaging, CT = Computed Tomography, 7T = 7 Tesla, DCE = Dynamic Contrast Enhanced

Received month day, year; accepted after revision month day, year.
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No relevant disclosures.

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SUMMARY SECTION

PREVIOUS LITERATURE: Prior reports have described high sensitivity of 7T MRI for the detection of corticotroph pituitary adenoma in Cushing disease, but in small numbers. The existing literature describes heterogeneous imaging protocols that vary in terms of contrast dose, use of dynamic contrast enhanced imaging, and 2D versus 3D post contrast imaging.

KEY FINDINGS: Our 7T institutional data identified pituitary lesions in 10/13 patients with Cushing disease, and half of these lesions were ill-defined and not discrete. By describing pituitary adenomas as discrete vs non-discrete, we believe the current study reflects routine practice and therefore is pertinent to clinical neuroradiology.

KNOWLEDGE ADVANCEMENT: We summarize the current state of 7T pituitary imaging in Cushing disease based on a literature review and our institutional experience. The heterogeneity amongst imaging protocols calls for further evaluation with multi-center involvement to determine the ideal imaging protocol.

INTRODUCTION

Adrenocorticotropic hormone producing pituitary adenomas causing Cushing disease are often small and difficult to detect with MRI.[1,2] Cushing disease can manifest as hypertension, diabetes mellitus, obesity, hypercoagulability , osteoporosis, mood disorders and a plethora of other symptoms and associated with increased mortality.[3,4] Successful pituitary surgery with selective adenoma resection and subsequent biochemical remission has been associated with imaging defined lesion localization.[5] Given the gravity of this medical condition, optimizing MRI protocols to help identify small pituitary lesions is imperative for improving patient outcomes.[1,6]

Prior work has shown the benefit of 3T MRI over lower-field-strength 1.5T MRI in the detection of pituitary adenomas.[7-9] Increasing the magnetic field strength can provide the benefit of improved signal-to-noise and contrast-to-noise ratios.[10] Clinical ultra-high field 7T MRI first became FDA approved in the United States in 2017.[11] Several papers have described the use of 7T MRI to evaluate the pituitary, but in small numbers given the overall lack of availability of 7T MRI scanners. Some of these previous papers from other institution have reported 100% sensitivity of identifying a pituitary adenoma in Cushing disease, while anecdotally our experience has not been as rewarding. Herein we present our institutional experience on imaging of patients with Cushing disease using ultra-high field 7T MRI to

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add to the limited body of current literature on this topic, and also perform a review of the literature on 7T pituitary MRI in Cushing disease to provide an overview of the heterogeneous nature of current 7T pituitary imaging technique and areas for possible improvement.

MATERIALS AND METHODS

Institutional case series

Following IRB approval, we retrospectively reviewed clinical pituitary images from our department's Siemens 7T Magnetom Terra scanner (Siemens Healthineers, Erlangen Germany). Utilizing an internal database to access cases of pathology proven Cushing disease, we reviewed patients from 2018 to 2022 who had dedicated 7T MR imaging of the pituitary gland. Images on 7T and comparison lower field strength comparison studies were independently reviewed by two board certified neuroradiologists who attempted to detect a pituitary microadenoma. Detected adenomas were categorized as discrete or non-discrete, the former having distinct margins. Lesions were not only identified by having different enhancement relative to the native pituitary, but T2 signal intensity relative to the native pituitary as well. Discrepancies were resolved with a consensus read. The following 7T MRI protocol details were recorded: postcontrast pulse sequence, slice thickness (mm), and dose of IV gadolinium. All pulse sequences were FDA approved. For all enrolled patients' scans a determination was made as to whether a pituitary adenoma could be visualized. If an adenoma was visible, its laterality and size were recorded along with a determination of the pulse sequence that best demonstrated the lesion. A Nova Medical 1Tx/32Rx head coil and 5 mL gadobutrol (1 mol/mL) was used for all 7T images. Comparison with lower field strength (1.5T or 3T) imaging was also reviewed in the same fashion on a different day with the readers blinded to the 7T results. Basic patient demographic information including age and sex were tabulated.

Literature Review

A comprehensive search of several databases from January 1st, 2012 to July 19th, 2023, in any language, was conducted. The databases included Ovid MEDLINE(R) and Epub Ahead of Print, In-Process & Other Non-Indexed Citations, and Daily, Ovid EMBASE, Ovid Cochrane Central Register of Controlled Trials, Ovid Cochrane Database of Systematic Reviews, and Scopus. The search strategy (Online Supplemental Data) was designed and conducted by an experienced librarian with input from the study's principal investigator. Controlled vocabulary supplemented with keywords was used to search for 7T MRI detection of Cushing disease. For each study, we extracted the following information: first author, year of publication, comparison MRI field strength, surgical pathology results, number of pathologically proven lesions that were identified on 7T MRI, any use of 7T dynamic contrast enhanced (DCE) postcontrast imaging, 7T postcontrast T1-weighted sequence employed, and IV gadolinium dose. Descriptive statistics were used to compare different 7T imaging protocols.

RESULTS

Institutional case series

13 patients with Cushing disease who underwent 7T MRI and transsphenoidal surgical resection were included in our study. Six (46.2%) were male. The mean age was 38.6 years old (range 12-66). Eleven patients had lower-field strength comparison MRI, and a surgical lesion was visualized in 5/8 (62.5%) cases on 3T and 1/3 (33.3%) on 1.5T. Of the 13 patients with pathology proven corticotroph adenomas included in the study, 7T MRI was able to identify a pituitary lesion that corresponded, including laterality, with a pathologically proven adenoma in 10 (76.9%) patients (Fig 1). Only 5/13 (38.5%) had discrete lesions on 7T MRI, while 5/13 (38.5%) had non-discrete lesions (Fig 2). All identified lesions were hypoenhancing relative to the pituitary. Four lesions were identified on T2-weighted imaging with 3 lesions showing hyperintense signal and 1 lesion with hypointense signal. Consensus reads were required in three 7T studies that were each agreed as being non-discrete, and one 3T study that was agreed as being non-discrete as well.

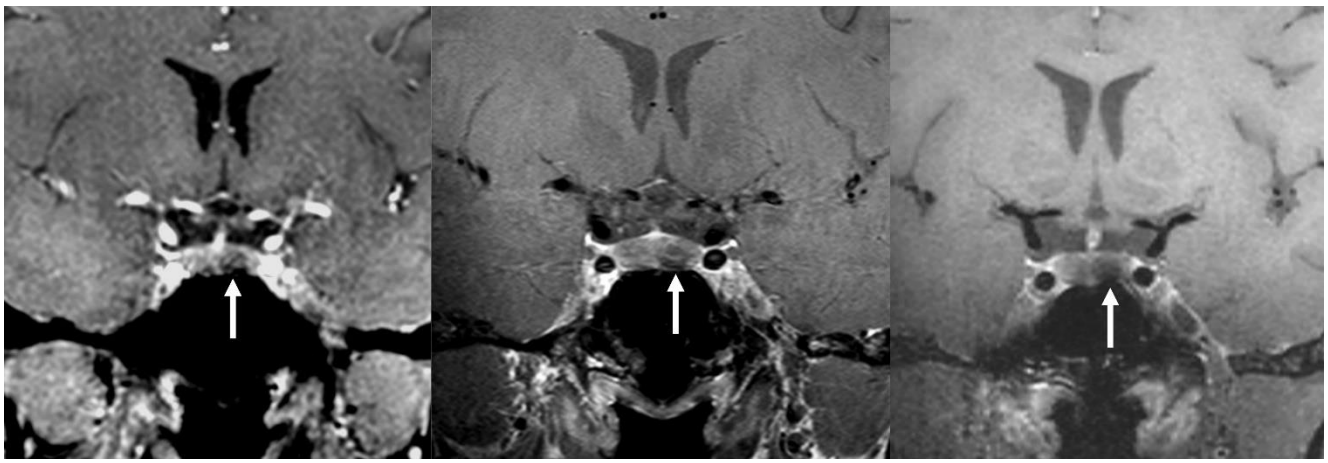

FIG 1. Three different types of 7T postcontrast T1-weighted imaging in a patient with a left sided pituitary adenoma (arrows): (L->R) DCE, 2D turbo-spin echo, and 3D SPACE with 1.5 mm, 1.5 mm, and 0.7 mm slice thickness respectively.

Contrast doses were fixed (5 mL, 1 mmol/mL Gadovist) for protocols including DCE and were weight-based (0.1 ml/kg, 1 mmol/mL Gadovist) when DCE was not performed. Our contrast enhanced imaging protocol was heterogenous (Table 1). The initial 3 patients, shortly after the FDA approval of 7T MRI, were imaged initially on lower field strength magnets, then transferred to 7T where only delayed postcontrast imaging was acquired (30-70 minutes after contrast injection). Even with the atypically long delay in imaging on 7T after contrast, we were able to see pituitary lesions in 2 patients.

Postcontrast T1-weighted imaging 7T sequences were also heterogeneous: 7 (53.8%) had DCE, 9 (69.2) had 2D T1-weighted imaging, 7 (53.8%) had 3D T1-weighted Sampling Perfection with Application optimized Contrast using different flip angle Evolution (SPACE), and 12 (92.3%) had 3D T1-weighted magnetization-prepared rapid acquisition gradient echo (MPRAGE). One patient had non-diagnostic motion degraded 2D imaging, 3D SPACE, and 3D MPRAGE (Table 1). Of note, 5 of our patients that were imaged with 7T had already undergone a prior partial pituitary resection and underwent further imaging prior to a second resection.

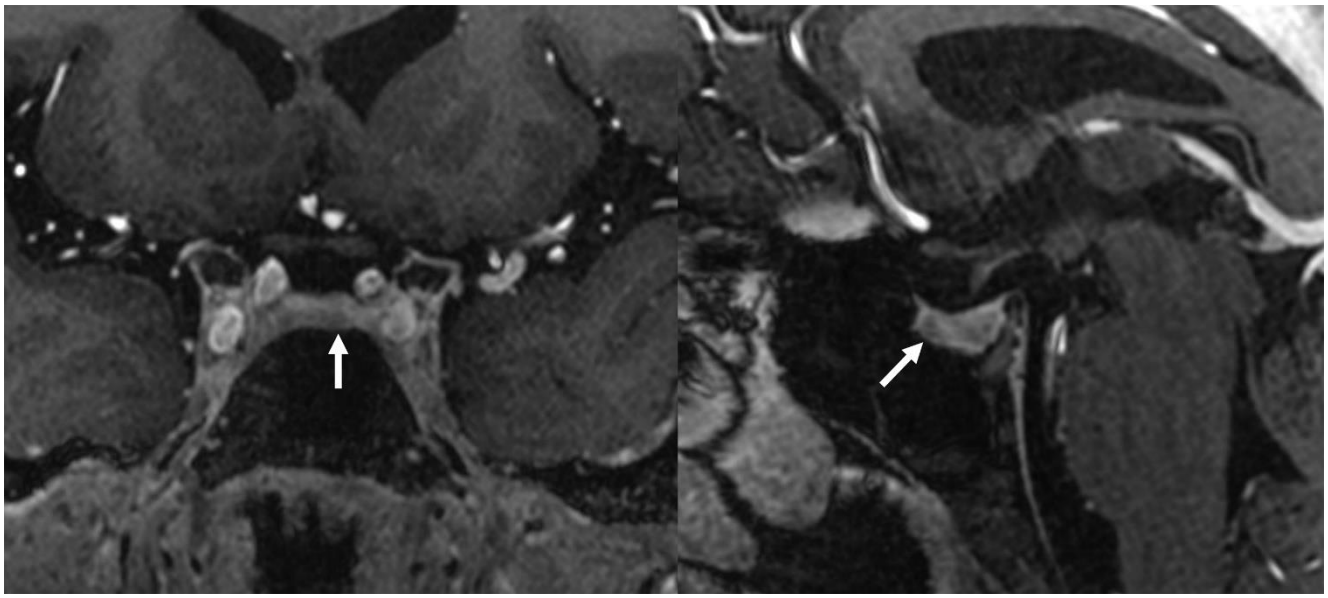

FIG 2. An example of 7T MRI showing a non-discrete lesion (arrows) in the left paramidline pituitary on postcontrast MPRAGE T1-weighted imaging at 0.33 mm that was a pathology proven Cushing adenoma.

Comparison Lower-Field Strength	7T							Previous TSS	Size (mm) on MRI
	Seen on 7T?	Discrete lesion?	Seen on 7T T2?	Seen on 7T DCE?	Seen on 7T T1 2D FSE?	Seen on 7T T1 3D SPACE?	Seen on 7T 3D MPRAGE?		
3T: Discrete	Y	Y	Y, hyper	-	Y	Y	Y	N	4
3T: Visible, not discrete	Y	Y	Y, hyper	-	-	-	Y	Y	5
3T: Discrete	Y	N	N	N	N	Y	Y	N	3
3T: Discrete	N#	NA	-	-	-	-	N	N	N/A
3T: Visible, not discrete	Y#	N	-	-	-	-	Y	Y	5
1.5T: Visible, not discrete	Y#	N	-	-	-	-	Y	Y	4
1.5T: Equivocal	Y	Y	N	-	Y	-	-	Y	5
3T: Not visible	Y	N	N	Y	N*	N*	N*	N	2
3T: Not visible	Y	N	Y, hyper	N	N	Y	Y	Y	2
3T: Not visible	N	NA	N	N	N	-	N	N	N/A
1.5T: Not visible	N	NA	N	N	N	N	N	N	N/A
N/A	Y	Y	N	Y	Y	Y	Y	N	5
N/A	Y	Y	Y, hypo	N	Y	Y	Y	N	8

* Motion degraded

#delayed 7T postcontrast imaging only; TSS = Transsphenoidal Surgery

Table 1

Patient specific details from our 7T MRI institutional experience in patients with Cushing disease.

Literature Review Patients

The literature review identified further 33 patients with Cushing disease and 7T MR imaging (Figure 3, Table 2). The 2014 de Rotte[12] study patients were included in the 2016 paper by the same group [13], and therefore were only counted once for this review. Overall, 7T MRI identified pathologically confirmed pituitary lesions in 31/33 (93.9%) patients. There was a large amount of variance between each MRI protocol, not only between each manuscript, but even within the same study at a single institution. Only two of the studies used 3D postcontrast T1-weighted imaging sequences, with the remainder using 2D sequences. One prior study used DCE imaging. The gadolinium doses also varied between weight-based and fixed-dose.

The first work on 7T pituitary MRI (Philips Healthcare, Cleveland, OH) was performed by de Rotte et al in 2014.[12] They imaged 10 healthy volunteers and 5 patients with suspected Cushing disease. The latter patient group was included as part of a larger population that was published two years later.[13] In total, they evaluated 16 patients with clinically and biochemically proven Cushing disease whose initial 1.5T MRI report was negative or inconclusive for adenoma detection. This work had dynamic post contrast imaging at 1.5T, but not at 7T. Pituitary lesions were identified at 7T in 13 of the 16 patients with biochemically proven Cushing disease. Only 13 of their patients underwent surgical resection. Of those, 4 patients had incomplete operative details and the laterality of the positive pathology was not known. Of the 9 patients with pathology proven adenomas, all were identified on 7T MRI. Interestingly, in their study, the adenomas were hyperenhancing relative to the pituitary gland on 7T. This authorship laid the groundwork for 7T pituitary imaging while acknowledging the limitations of a long acquisition time (10:40 minutes), incomplete surgical reports to confirm the MRI findings in several patients, and lack of 7T DCE sequences.

Law et al added to this work with a case report of a patient with Cushing disease who had prior negative 1.5T and 3T MRI, but detected a microadenoma on 7T imaging.[14] This protocol used postcontrast 3D MPRAGE, but did not have DCE imaging.

Later, from the same institution as Law et al, Patel et al imaged 8 patients with pathology proven Cushing disease on a Siemens Terra 7T system.[15] They performed three types of post-contrast T1 weighted imaging but did not have dynamic post-contrast imaging in their protocol. Their 7T MRI studies identified lesions in all 8 patients. 7 (88%) were shown to be corticotroph adenomas and one patient had Crooke hyaline change with endocrinological remission after surgery. 3D SPACE imaging detected a lesion in all 8 patients who were included. MPRAGE postcontrast imaging was performed in 5 patients, of which a lesion was detected in 4 patients. 2D TSE postcontrast T1-weighted imaging detected a lesion in 3/4 patients.

More recently, Eisenhut et al imaged 18 patients for suspected microadenomas with 3T and 7T MRI.[16] Their 7T protocol employed a 2D fast low-angle shot (FLASH) sequence. This was the first paper to include dynamic postcontrast imaging. The authors did not employ 3D thin slice, submillimeter, postcontrast imaging as was the case with prior studies. Of the 18 patients, 16 had pathology proven adenomas, and 13 of which were patients with Cushing disease. 7T was able to identify the lesion in 12/13 (92.3%) lesions. All were seen on the T1 coronal postcontrast sequences, and 13/15 (86.7) of all microadenomas (including non-Cushing) were seen on the DCE sequences. 7T also detected 3 lesions that were not seen on 3T.

Feng et al reported on the surgical resection technique for a single patient with MRI negative Cushing disease.[17] Their patient had a 3T and 7T MRI, both of which were negative, however imaging details were not provided.

Eisenhut et al described their 7T MRI experience with pituitary macroadenomas for the purpose of evaluating cavernous sinus invasion.[18] They did not have DCE or 3D postcontrast T1-weighted imaging, however they found the 7T image quality to be improved over 1.5/3T. One patient had Cushing disease, and they were able to identify the lesion on 7T. They also found improved ability to detect cavernous sinus invasion on 7T.

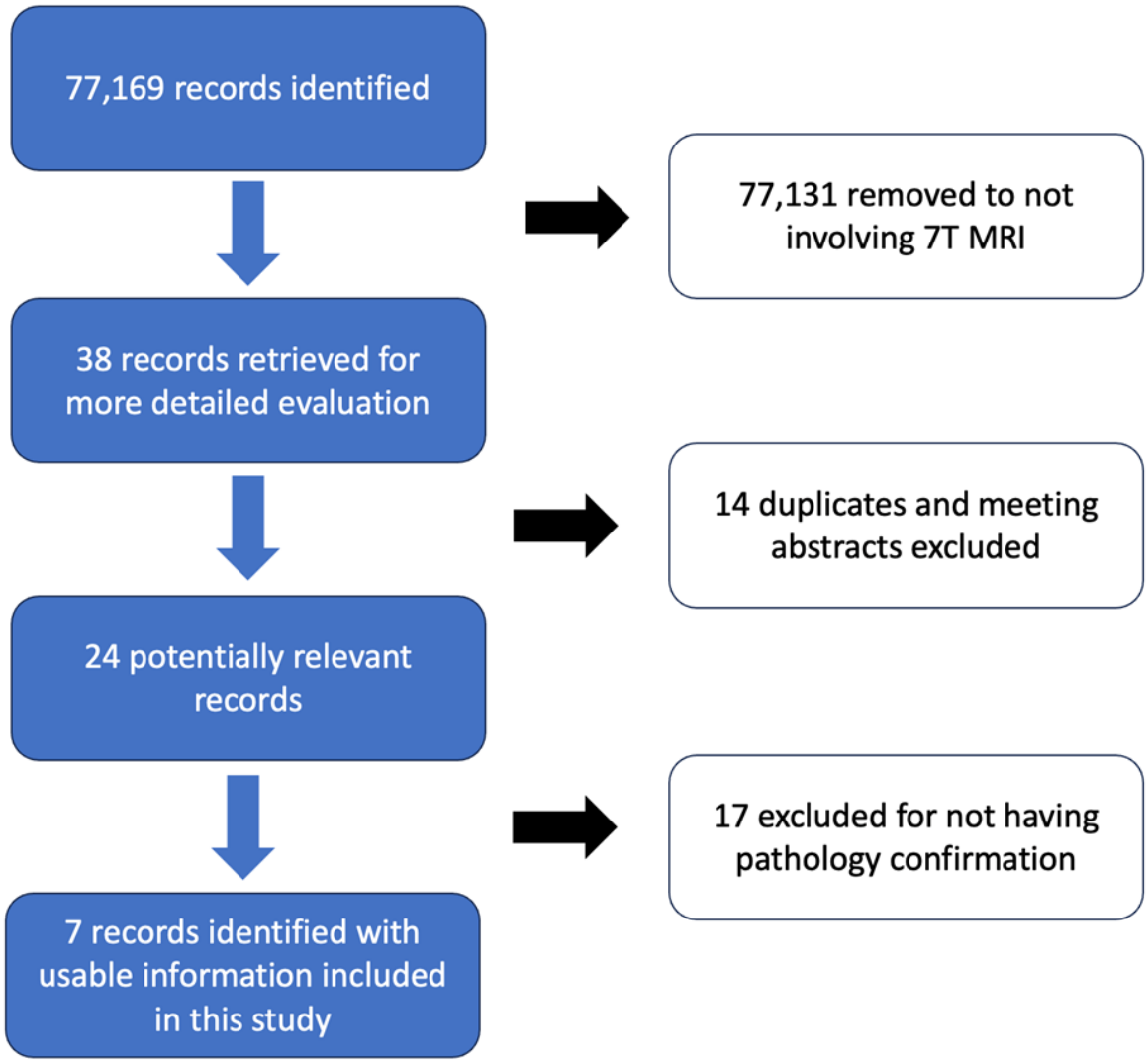

FIG 3. Flowchart of the search and selection of studies.

Author	Comparison MRI	Pathology	Sensitivity for Cushing adenoma	Dynamic contrast enhanced sequence	Post contrast T1-weighted sequence (ST in mm)	Gad dose
de Rotte et al, 2016 [13]	1.5T	Cushing Disease	9/9	No	3D MPIR TSE (0.8)	0.1 mL/kg
Law et al, 2019[14]	1.5T, 3T	Cushing Disease	1/1	No	3D MPRAGE (0.5)	0.1 ml/kg
Patel et al, 2020[15]	NA	Cushing Disease	8/8	No	2D TSE (NA); 3D SPACE (NA); 3D MPRAGE (NA)	0.2 ml/kg
Eisenhut et al, 2022[16]	3T	13 Cushing Disease; 3 Prolactinoma	12/13	Yes	2D FLASH (1.5)	5 mL 1.0 mmol/mL or 10 mL 0.5 mmol/mL
Feng et al, 2023[17]	3T	Cushing Disease	0/1	NA	NA	NA
Eisenhut et al, 2023[18]	1.5T, 3T	Multiple types of Macroadenoma, 1 Cushing disease	1/1	NA	2D Cor T1 (1.5)	10 mL 1.0 mmol/mL or 20 mL 0.5 mmol/mL

NA = details not available; ST = Slice Thickness

Table 2. Study specific details from the results of our literature review of 7T MRI in patients with Cushing disease.

DISCUSSION

In the current study, we have described our institutional experience with 7T MRI for pituitary lesion localization in patients with Cushing disease. Additionally, we performed a literature review of the use of 7T MRI in Cushing disease. Exploring accurate and reliable imaging techniques is critical as lower field strength MRI can miss up to 50% of adenomas in Cushing disease.[1,2] We highlight the effectiveness of using 7T over lower-field-strength MRI to evaluate for pituitary lesions in patients with Cushing diseases as well as the need for further improvement and standardization in clinical 7T MRI of the sella.

Both the literature review and our single center experience demonstrate the extreme heterogeneity in pituitary MR imaging protocols. This is not unexpected given the recent FDA approval of clinical 7T MRI and lack of consensus on optimal imaging protocols. Pituitary adenomas in Cushing disease are frequently microadenomas, which pose a substantial challenge for detection due to their small size—often only a few millimeters in diameter.[19] Improved sensitivity of 3T MRI over 1.5T for detection of microadenomas has previously been established[19]. Therefore, many have hoped that further increase in magnetic field strength MRI would continue to improve detection of these miniscule tumors. In our institutional patients, while we identified pathology confirmed lesions in 10/13 (76.9%) patients, half of the lesions on contrast enhanced 7T MRI were non-discrete, and quite subtle. Our work is the first 7T manuscript to describe pituitary adenomas as discrete vs non-discrete, which we believe reflects routine practice in the reading room and therefore is relevant to clinical neuroradiology. Within this context, it remains unclear how the varying technical aspects of 7T pituitary imaging protocols impact this sensitivity.

Dynamic contrast enhancement (DCE)

Only one paper in our literature review used DCE post contrast imaging at 7T.[16] They found a pathology confirmed pituitary lesion in 12/13 patients; however, this was surpassed by their 2D FLASH postcontrast sequence that identified a pituitary lesion in all 13 patients. Prior studies on lower-field-strength MRI have found DCE to be superior to delayed postcontrast imaging in detecting microadenomas.[19-21] Our institutional cohort is the second report of using DCE at 7T for patients with Cushing disease. Our institution's DCE sequences were low yield, identifying a lesion in only 2/7 (28.6%) patients. However, in one of the two successful cases, DCE was the only sequence that was able to identify a pituitary lesion as the other pulse sequences were limited by motion artifact. This speaks to the decreased acquisition time of DCE as a potential additional benefit over other conventional sequences as the latter may be more prone to motion degradation in certain patients. In the earlier papers listed in the literature review[12,13], the nondynamic 7T sequences required over 10 minutes to acquire. DCE performed at 7T can repeatedly image the pituitary gland 15-25 second intervals, similar to lower field strengths. It is therefore substantially less motion sensitive than other pituitary pulse sequences.

Non-dynamic, T1-weighted postcontrast sequences

The studies in our literature review used a variety of postcontrast T1-weighted images, which reflects the overall lack of evidence regarding their comparative effectiveness. Work evaluating multiple 3D postcontrast T1-weighted sequences in brain tumors found that SPACE and VIBE sequences obtained higher contrast rating, contrast-to-noise ratio, and visual conspicuity ratings over MPRAGE in both gliomas and metastases.[22] Specific to pituitary imaging, prior work has advocated for the use of VISTA[23] while others have shown the benefit of VIBE[24]. Patel et al[15] had similar success with different post-gadolinium 3D T1-weighted pulse sequences: 88% sensitivity with SPACE and 80% with MPRAGE. In our institutional data with a small sample size, we found more success with MPRAGE over SPACE in patients in whom both sequences were used. Overall, there is a lack of data to provide strong evidence to support any specific post-gadolinium T1 sequence.

Additionally, our literature review revealed heterogeneity between the use of 3D vs 2D postcontrast imaging. 3D has the benefit of providing multiplanar reformats. Also, it typically provides increased spatial resolution when assessed by voxel size metrics compared with 2D techniques. The latter would seem to be most beneficial in Cushing disease, as small adenomas less than 4 mm are challenging to detect with MRI.[19] Wang et al found that 3D SPACE imaging outperformed 2D imaging in defining pituitary lesions at 3T.[25] Additional 3D sequences, including VIBE/SPGR have been found to detect Cushing microadenomas at a higher rate than 2D spin echo T1-weighted postcontrast images.[26] At 7T field strength, Eisenhut[16] had the largest collection of cases and had good success (92.3% sensitivity) with 2D postcontrast imaging with 1.5mm slice thickness. In our institutional data, we had 8 patients with both 2D and 3D postcontrast imaging (Fig 4). In two patients, we saw lesions on 3D imaging that were not seen on 2D. On the other hand, we did not have any patients where lesions were only seen on 2D.

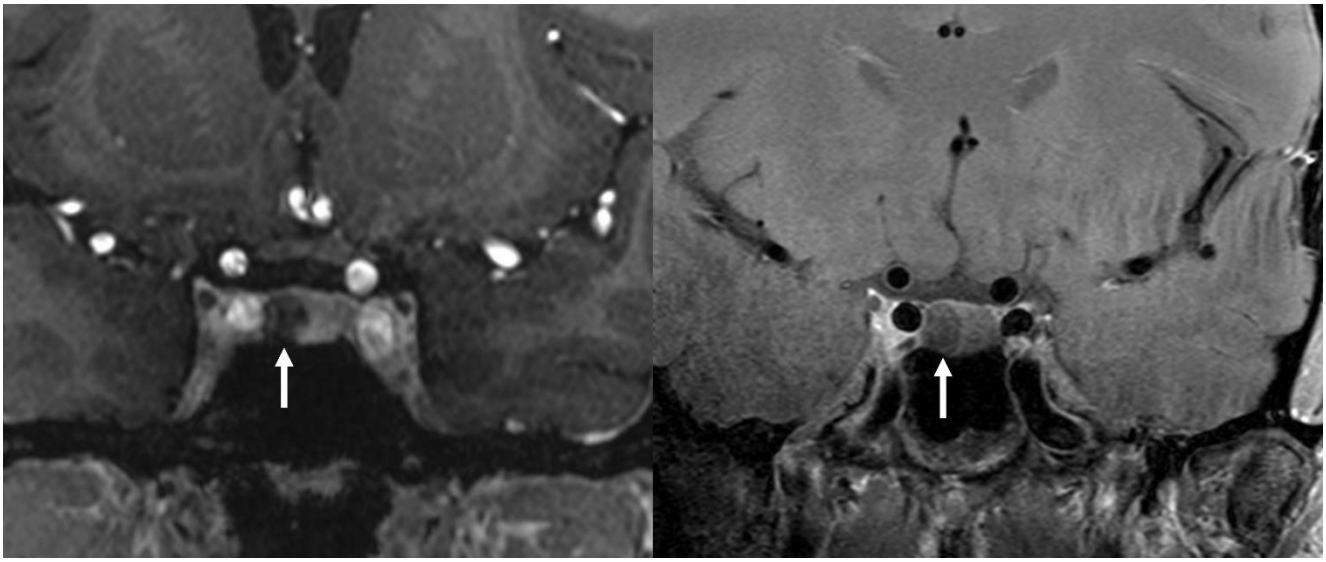

FIG 4. 7T postcontrast T1-weighted imaging in a patient with a right sided pituitary adenoma. The left image is a 3D MPRAGE sequence while the right image is a 2D turbo-spin echo sequence. The MPRAGE image demonstrates greater contrast between the normally enhancing pituitary compared to the hypoenhancing adenoma.

Additional sequences

Neither our institutional patient experience nor prior studies have described the use of postcontrast T2-weighted FLAIR imaging or constructive interference in steady state (CISS) sequences, both of which have been described as being useful at lower-field strengths.[24,27] CISS is volumetric imaging technique that has been more frequently used to outline the subarachnoid spaces in the posterior fossa. Similarly, T2-weighted FLAIR imaging has some T1-weighted properties as well. In fact, it is very sensitive to low concentrations of gadolinium contrast and have been predominantly used to identify leptomeningeal disease.[28] More recently, contrast-enhanced 3D STIR FLAIR imaging was found to have increased pituitary adenoma conspicuity compared to 2D T1-weighted sequences.[29] This study was performed at 3T, and a similar technique has not been described at 7T.

Gadolinium dose

The ideal gadolinium dose for pituitary MRI is not known. Two standard approaches to IV contrast dosing can be used: fixed vs weight based. Our literature review included studies with both types of dosing. When weight-based dosing is employed, standard brain MRI is performed with 0.1 mmol/kg of gadolinium contrast. In 2006, Bartynski[30] used half dose (0.05 mmol/kg), normal dose (0.1 mmol/kg), and double dose (0.2 mmol/kg) IV gadolinium-based contrast on a 1.5T scanner. Calculated contrast ratio between lesion and pituitary were the same at each dose, but the absolute signal difference was largest at the double dose, suggesting a theoretic benefit. Four years later, Portocarrero-Ortiz found that half-dose weight-based contrast increased the detection of ACTH-secreting pituitary adenomas in patients with Cushing disease.[31] Prior work has shown that higher field strength MRI increases the effectiveness of gadolinium contrast agents, with higher lesion enhancement at 7T MRI employing a half dose of contrast compared to a full dose of contrast on 3T; however, this research was evaluating primary brain tumors and metastases rather than pituitary adenomas.[32]

Our paper has several limitations. First, our literature review and institutional data has small patient numbers. This is due to clinical 7T MRI only recently receiving regulatory clearance in the United States and European Union in 2017 as well as the low incidence of Cushing disease. Additionally, one of the studies[13] reported 7T MRI results on 16 patients but had incomplete or absent pathologic confirmation in 7 patients. One of the other studies[14], was a single case report of a 7T positive case. Therefore, the composite sensitivity of 41/46 (89.1%) across studies should be interpreted with caution, acknowledging the limitations of the individual studies.

Given the 7T MRI protocol heterogeneity between and within institutions, larger numbers of patients must be studied to determine the 7T pituitary protocol with the best sensitivity and specificity. This could potentially be addressed with standardization of imaging protocols, larger samples sizes, and multisite collaboration. Second, as already discussed, several sequences (such as postcontrast FLAIR and CISS) that have been described as beneficial in the lower-field strength pituitary imaging literature were not performed in any of the 7T imaging cohorts reviewed in this manuscript. Our institutional experience has found that sphenoid sinus pneumatization limits the usefulness overall on 7T. It is important to recognize that we are in the early stages of clinical implementation of 7T imaging. 7T MRI cannot yet be pronounced to be entirely superior to 3T MRI in the detection of pituitary microadenomas. Rather, it should be viewed as a valuable tool that has yet to be perfected. In addition to clarifying the role of DCE, 2D versus 3D post contrast imaging, and IV contrast dose, future areas to further improve 7T pituitary imaging may include the addition of novel pulse sequences, AI-based reconstruction algorithms and hardware improvements such as increased scanner gradient performance and parallel transmit techniques which may help through a combination of higher resolution, better lesion-to-background contrast, shorter acquisition times, and reduction in skull-base artifacts.[11] Further refinement of 7T pituitary imaging could also lead way to detecting more incidental pituitary findings, and therefore may be most beneficial in pathologies such as Cushing disease, where surgical resection is imminent and lesion identification will directly impact patient care.

CONCLUSIONS

7T MRI for pituitary lesion localization in Cushing disease is a new technique with only small case series that have been published, and little consensus between imaging protocols for optimal evaluation of pituitary tumors. Accurate preoperative assessment of pituitary lesions in Cushing disease is paramount to successful patient outcomes. Further comparative research, possibly through multisite collaboration, is needed to identify the optimal imaging technique as well as to assess the benefit of 7T over lower-field strength MRI.

Disclosure forms provided by the authors are available with the full text and PDF of this article at www.ajnr.org.

REFERENCES

1. Castle-Kirszbaum M, Amukotuwa S, Fuller P, et al. MRI for Cushing Disease: A Systematic Review. *AJNR Am J Neuroradiol*. Mar 2023;44(3):311-316. doi:10.3174/ajnr.A7789
2. Bashari WA, Gillett D, MacFarlane J, et al. Modern imaging in Cushing's disease. *Pituitary*. Oct 2022;25(5):709-712. doi:10.1007/s11102-022-01236-w
3. Lonser RR, Nieman L, Oldfield EH. Cushing's disease: pathobiology, diagnosis, and management. *J Neurosurg*. Feb 2017;126(2):404-417. doi:10.3171/2016.1.Jns152119
4. Ntali G, Asimakopoulou A, Siamatras T, et al. Mortality in Cushing's syndrome: systematic analysis of a large series with prolonged follow-up. *Eur J Endocrinol*. Nov 2013;169(5):715-23. doi:10.1530/eje-13-0569
5. Lonser RR, Wind JJ, Nieman LK, et al. Outcome of surgical treatment of 200 children with Cushing's disease. *J Clin Endocrinol Metab*. Mar 2013;98(3):892-901. doi:10.1210/jc.2012-3604
6. Newell-Price J, Bertagna X, Grossman AB, et al. Cushing's syndrome. *The Lancet*. 2006/05/13/ 2006;367(9522):1605-1617. doi:https://doi.org/10.1016/S0140-6736(06)68699-6
7. Pinker K, Ba-Ssalamah A, Wolfsberger S, et al. The value of high-field MRI (3T) in the assessment of sellar lesions. *Eur J Radiol*. Jun 2005;54(3):327-34. doi:10.1016/j.ejrad.2004.08.006
8. Stobo DB, Lindsay RS, Connell JM, et al. Initial experience of 3 Tesla versus conventional field strength magnetic resonance imaging of small functioning pituitary tumours. *Clin Endocrinol (Oxf)*. Nov 2011;75(5):673-7. doi:10.1111/j.1365-2265.2011.04098.x
9. Kim LJ, Lekovic GP, White WL, et al. Preliminary Experience with 3-Tesla MRI and Cushing's Disease. *Skull Base*. Jul 2007;17(4):273-7. doi:10.1055/s-2007-985196
10. Trattnig S, Springer E, Bogner W, et al. Key clinical benefits of neuroimaging at 7T. *NeuroImage*. 2018/03/01/ 2018;168:477-489. doi:https://doi.org/10.1016/j.neuroimage.2016.11.031
11. Burkett BJ, Fagan AJ, Felmlee JP, et al. Clinical 7-T MRI for neuroradiology: strengths, weaknesses, and ongoing challenges. *Neuroradiology*. Feb 2021;63(2):167-177. doi:10.1007/s00234-020-02629-z
12. de Rotte AAJ, van der Kolk AG, Rutgers D, et al. Feasibility of high-resolution pituitary MRI at 7.0 tesla. *European Radiology*. 2014/08/01 2014;24(8):2005-2011. doi:10.1007/s00330-014-3230-x
13. de Rotte AAJ, Groenewegen A, Rutgers DR, et al. High resolution pituitary gland MRI at 7.0 tesla: a clinical evaluation in Cushing's disease. *European Radiology*. 2016/01/01 2016;26(1):271-277. doi:10.1007/s00330-015-3809-x
14. Law M, Wang R, Liu CJ, et al. Value of pituitary gland MRI at 7 T in Cushing's disease and relationship to inferior petrosal sinus sampling: case report. *J Neurosurg*. Mar 1 2018:1-5. doi:10.3171/2017.9.Jns171969
15. Patel V, Liu CJ, Shiroishi MS, et al. Ultra-high field magnetic resonance imaging for localization of corticotropin-secreting pituitary adenomas. *Neuroradiology*. Aug 2020;62(8):1051-1054. doi:10.1007/s00234-020-02431-x
16. Eisenhut F, Schlaffer SM, Hock S, et al. Ultra-High-Field 7 T Magnetic Resonance Imaging Including Dynamic and Static Contrast-Enhanced T1-Weighted Imaging Improves Detection of Secreting Pituitary Microadenomas. *Invest Radiol*. Sep 1 2022;57(9):567-574. doi:10.1097/rli.0000000000000872
17. Feng JJ, Cheok SK, Chartrain AG, et al. Endoscopic endonasal approach for MRI-Negative Cushing's microadenoma. *Neurosurg Focus Video*. Jul 2023;9(1):V5. doi:10.3171/2023.4.Focvid2324
18. Eisenhut F, Schmidt MA, Buchfelder M, et al. Improved Detection of Cavernous Sinus Invasion of Pituitary Macroadenomas with Ultra-High-Field 7 T MRI. *Life (Basel)*. Dec 24 2022;13(1)doi:10.3390/life13010049
19. Bonneville JF, Potorac I, Petrossians P, et al. Pituitary MRI in Cushing's disease - an update. *J Neuroendocrinol*. Aug 2022;34(8):e13123. doi:10.1111/jne.13123
20. Tabarin A, Laurent F, Catargi B, et al. Comparative evaluation of conventional and dynamic magnetic resonance imaging of the pituitary gland for the diagnosis of Cushing's disease. *Clin Endocrinol (Oxf)*. Sep 1998;49(3):293-300. doi:10.1046/j.1365-2265.1998.00541.x
21. Kucharczyk W, Bishop JE, Plewes DB, et al. Detection of pituitary microadenomas: comparison of dynamic keyhole fast spin-echo, unenhanced, and conventional contrast-enhanced MR imaging. *AJR Am J Roentgenol*. Sep 1994;163(3):671-9. doi:10.2214/ajr.163.3.8079866
22. Danieli L, Riccitelli GC, Distefano D, et al. Brain Tumor-Enhancement Visualization and Morphometric Assessment: A Comparison of MPRAGE, SPACE, and VIBE MRI Techniques. *AJNR Am J Neuroradiol*. Jul 2019;40(7):1140-1148. doi:10.3174/ajnr.A6096
23. Guo R, Wu Y, Guo G, et al. Application of Contrast-Enhanced 3-Dimensional T2-Weighted Volume Isotropic Turbo Spin Echo Acquisition Sequence in the Diagnosis of Prolactin-Secreting Pituitary Microadenomas. *J Comput Assist Tomogr*. Jan-Feb 01 2022;46(1):116-123. doi:10.1097/rct.0000000000001237
24. Lang M, Habboub G, Moon D, et al. Comparison of Constructive Interference in Steady-State and T1-Weighted MRI Sequence at Detecting Pituitary Adenomas in Cushing's Disease Patients. *J Neurol Surg B Skull Base*. Dec 2018;79(6):593-598. doi:10.1055/s-0038-1642032
25. Wang J, Wu Y, Yao Z, et al. Assessment of pituitary micro-lesions using 3D sampling perfection with application-optimized contrasts using different flip-angle evolutions. *Neuroradiology*. Dec 2014;56(12):1047-53. doi:10.1007/s00234-014-1432-1
26. Grober Y, Grober H, Wintermark M, et al. Comparison of MRI techniques for detecting microadenomas in Cushing's disease. *J Neurosurg*. Apr 2018;128(4):1051-1057. doi:10.3171/2017.3.Jns163122
27. Chatain GP, Patronas N, Smirniotopoulos JG, et al. Potential utility of FLAIR in MRI-negative Cushing's disease. *J Neurosurg*. Sep 2018;129(3):620-628. doi:10.3171/2017.4.Jns17234
28. Fukuoka H, Hirai T, Okuda T, et al. Comparison of the added value of contrast-enhanced 3D fluid-attenuated inversion recovery and magnetization-prepared rapid acquisition of gradient echo sequences in relation to conventional postcontrast T1-weighted images for the evaluation of leptomeningeal diseases at 3T. *AJNR Am J Neuroradiol*. May 2010;31(5):868-73. doi:10.3174/ajnr.A1937
29. Osawa I, Nagawa K, Hara Y, et al. Utility of contrast-enhanced 3D STIR FLAIR imaging for evaluating pituitary adenomas at 3 Tesla. *Eur J Radiol Open*. Dec 2023;11:100500. doi:10.1016/j.ejro.2023.100500

30. Bartynski WS, Boardman JF, Grahovac SZ. The effect of MR contrast medium dose on pituitary gland enhancement, microlesion enhancement and pituitary gland-to-lesion contrast conspicuity. *Neuroradiology*. Jul 2006;48(7):449-59. doi:10.1007/s00234-006-0085-0
31. Portocarrero-Ortiz L, Bonifacio-Delgadillo D, Sotomayor-González A, et al. A modified protocol using half-dose gadolinium in dynamic 3-Tesla magnetic resonance imaging for detection of ACTH-secreting pituitary tumors. *Pituitary*. Sep 2010;13(3):230-5. doi:10.1007/s11102-010-0222-y
32. Noebauer-Huhmann IM, Szomolanyi P, Kronnerwetter C, et al. Brain tumours at 7T MRI compared to 3T--contrast effect after half and full standard contrast agent dose: initial results. *Eur Radiol*. Jan 2015;25(1):106-12. doi:10.1007/s00330-014-3351-2
33. Liu Z, Zhang X, Wang Z, et al. High positive predictive value of the combined pituitary dynamic enhanced MRI and high-dose dexamethasone suppression tests in the diagnosis of Cushing's disease bypassing bilateral inferior petrosal sinus sampling. *Sci Rep*. Sep 7 2020;10(1):14694. doi:10.1038/s41598-020-71628-0