Ultra-high field 7 T MRI localizes regional brain volume recovery following corticotroph adenoma resection and hormonal remission in Cushing’s disease: A case series

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ABSTRACT

Background: Cushing’s disease (CD) is defined by glucocorticoid excess secondary to the increased section of corticotropin by a pituitary adenoma. Magnetic resonance imaging (MRI) studies performed at 1.5 or 3 Tesla (T) have demonstrated correlations between regional changes in brain structure and the progression of CD. In this report, we examine the changes in brain volume following corticotroph pituitary adenoma resection using ultra-high field 7 T MRI to increase the accuracy of our volumetric analyses.

Methods: Thirteen patients were referred to the endocrinology clinic at our institution from 2017 to 2020 with symptoms of cortisol excess and were diagnosed with ACTH-dependent endogenous Cushing syndrome. Five patients had follow-up 7 T imaging at varying time points after a transsphenoidal resection.

Results: Symmetrized percent change in regional volumes demonstrated a postoperative increase in cortical volume that was relatively larger than that of cerebral white matter or subcortical gray matter (percent changes = 0.0172%, 0.0052%, and 0.0120%, respectively). In the left cerebral hemisphere, the medial orbitofrontal, lateral orbitofrontal, and pars opercularis cortical regions experienced the most robust postoperative percent increases (percent changes = 0.0166%, 0.0122%, and 0.0068%, respectively). In the right cerebral hemisphere, the largest percent increases were observed in the pars triangularis, rostral portion of the middle frontal gyrus, and superior frontal gyrus (percent changes = 0.0156%, 0.0120%, and 0.0158%).

Conclusion: Cerebral volume recovery following pituitary adenoma resection is driven by changes in cortical thickness predominantly in the frontal lobe, while subcortical white and gray matter volumes increase more modestly.

Keywords: Brain volume, Cushing's disease, Pituitary adenoma, Ultra-high field MRI

INTRODUCTION

Cushing's disease (CD) is caused by a pituitary adenoma that secretes excess levels of adrenocorticotropic hormone (ACTH or corticotropin), which, in turn, stimulates the excess downstream release of cortisol. Supraphysiologic levels of cortisol from any cause result in a set of signs and symptoms that comprise the Cushing syndrome (CS), including characteristic fatty tissue deposits, purple striae, hirsutism, and fatigue, as well as reduced survival. [22,23,13] ACTH-
producing adenomas are the cause of 65–70% of CS, which has an estimated incidence of 0.7–2.4 cases/million/year. \cite{24,29} This state has also been associated with a number of cognitive and psychiatric disorders including memory impairment and depression. \cite{9,32,35} While targeted resection of these adenomas is effective at resolving the direct symptoms of CD, significant cognitive decline and mood disorders have been reported to persist in children and adolescents after surgery. \cite{8,14,15,22,27} Studies in adult patients have also found an increased incidence of depression and residual anxiety in the posttreatment period. \cite{22,37}

Considering these associations, several investigators have analyzed cerebral morphometric parameters in relation to the progression and treatment of CD. One study of adult patients showed that there was an increase in white matter volume and a decrease in cortical thickness, mainly in the frontal and parietal lobes, of patients with persistent CS versus those who achieved endocrinological remission. \cite{40} In a separate study, decreases in the third ventricle volume and bicaudate diameter were shown to correlate with CS resolution in adults. \cite{4} Among pediatric patients with CS, certain brain compartments such as the cerebrum, hippocampus, and amygdala had lower volumes compared to controls. \cite{22} Brain structural changes in relation to treatments are of high interest areas in CD research, and with the increasing adoption of ultra-high field (UHF) magnetic resonance imaging (MRI) and automated analysis pipelines, future investigations have the potential to be more sensitive, precise, and reproducible.

To the best of our knowledge, all previous studies measuring cerebral atrophy in relation to CD have been conducted at conventional magnetic field strengths of 1.5 or 3 Tesla, which have poorer signal-to-noise and contrast-to-noise characteristics than UHF strength 7 Tesla MRI. This difference is particularly important when examining fine structural features such as cortical thickness or pituitary microarchitecture. For example, it has been shown that up to 40% of patients with CD have adenomas that are not detectable by conventional MRI. \cite{26} UHF MRI with sub-millimeter resolution, however, has been demonstrated to identify the site of adenoma reliably in several cases for which 1.5 or 3 Tesla localization was inconclusive. \cite{7,24} The ability to characterize pituitary adenomas accurately in patients with Cushing disease would not only decrease the morbidity associated with an invasive procedure such as inferior petrosal sinus sampling but would also decrease the morbidity associated with the pituitary surgery by allowing the surgeon to respect the pathologic component of the pituitary gland while sparing the healthy pituitary gland.

The improved spatial and contrast resolution of UHF MRI has yet to be applied to the volumetric analysis of brain regions in the setting of CD recovery. High-resolution structural detail is especially important for volumetric studies, as errors in linear measurements become geometrically magnified, and this can result in reduced sensitivity or spurious conclusions. In this report, we present the first such analysis of regional brain volumes in a cohort of patients with CD who underwent high-resolution UHF MRI before and following transsphenoidal surgery.

**MATERIALS AND METHODS**

**Subjects**

Thirteen patients were referred to the endocrinology clinic at our institution with symptoms of cortisol excess. Following clinical and laboratory workup, each patient was diagnosed with ACTH-dependent endogenous CS according to societal guidelines, with concern for CD. \cite{19,28} Among the 13 patients who were referred for 7 T imaging between 2017 and 2020, five also had follow-up 7 T imaging after surgery. The exclusion criteria included overt signs of cognitive impairment, claustrophobia, and general contraindications for MRI which includes MR-incompatible medical devices, claustrophobia, pacemakers, contrast allergy, and weight limitations. Neuroimaging data measures include an MR structural imaging utilizing a sella protocol, which consists of sagittal and coronal T1- as well as coronal T2-weighted sequences, dynamic contrast-enhanced coronal T1-weighted sequence, as well as sagittal and coronal T1-weighted sequences all with attention to the sella after administration of IV gadolinium. Both 3 T and 7 T MRI data were obtained if the patient did not have prior imaging, with the 3 T imaging as part of the standard of care clinical imaging for patients with CD. This study was approved by the Institutional Review Board at our institution, and all patients in this work provided written informed consent.

**MRI studies**

The patients underwent 7 T MRI per previously published protocols, including whole-brain 0.7 mm isotropic resolution magnetization-prepared rapid gradient echo (MP-RAGE) sequences and postcontrast (0.2 mL/kg gadoterate meglumine) sellar sequences that identified focal hypoenhancing pituitary lesions in all cases. \cite{32,33} Imaging was performed on a Siemens MAGNETOM Terra 7 T system with a Nova Medical 8Tx/32Rx head coil. All 13 patients subsequently underwent transsphenoidal resection with routine postoperative clinical imaging and processing. At various intervals after surgery, follow-up 7 T MRI was performed on five patients with the same scanning parameters as those used preoperatively. The patient 1 had a 3.9 mm lesion on 7 T MRI with histology identifying only Crooke hyaline change, but the patient experienced endocrinological remission following surgery, suggesting the presence of a true underlying adenoma. Patients 2–5 had
was performed using the standard group analysis protocol in FreeSurfer. Various full-width/half-max values from 0 to 25 mm in 5 mm intervals were generated during this resampling, and the 15 mm value was used for FreeSurfer’s built-in GLM module to create the significance maps, as shown in [Figure 2]. The method to correct for multiple comparisons is to run Monte Carlo simulations under the null hypothesis and to interpret how often the value of a statistic deviates from the true analysis. The FreeSurfer simulator that is used for these multiple comparisons is roughly based on FSL’s permutation simulator (randomize) and AFNI’s null-z simulator (AlphaSim). The frequency of the deviation is interpreted as the reported P-values for the thickness and volume changes for the group whole-brain analysis. An alpha-value such as 0.05 or 0.1 was not set since there were a limited number of patients in this investigation.

RESULTS
Both patients 2 and 3 underwent follow-up 7 T MRI at 81 days following surgery, while patients 1, 4, and 5 went through imaging at 882, 333, and 392 days following surgery, respectively. Direct visual comparison of the preoperative and postoperative scans revealed a clear reversal of cerebral atrophy, identifiable as increased cortical thickness and corresponding sulcal narrowing. A representative example of this phenomenon is provided in [Figure 1]. Symmetrized percent change in regional volumes as detected by automated segmentation demonstrated a postoperative increase in cortical volume that was 0.0172%, which was larger than the 0.0052% increase in cerebral white matter or the 0.0120% increase in subcortical gray matter. In the left cerebral hemisphere, the medial orbitofrontal, lateral orbitofrontal, and pars opercularis cortical regions experienced the largest postoperative percent increases (percent changes = 0.0166%, 0.0122%, and 0.0068%, respectively), while in the right cerebral hemisphere, the largest percent increases were observed in the pars triangularis, rostral portion of the middle frontal gyrus, and superior frontal gyrus (percent changes = 0.0156%, 0.0120%, and 0.0158%, respectively). [Figure 2] depicts a map of the average postoperative increase in cortical thickness over the cerebral hemispheres. We also noted marked postoperative decreases in volumes of the

Table 1: Size and histology of focal hypoenhancing pituitary lesions and postsurgical outcomes.

| Patient | Longest dimension (mm) | Histology             | Endocrinological remission | Time between surgery and postoperative MRI (days) |
|---------|------------------------|-----------------------|-----------------------------|-----------------------------------------------|
| 1       | 3.9                    | Crooke hyaline change | Y                           | 882                                           |
| 2       | 6.2                    | Corticotroph adenoma  | Y                           | 81                                            |
| 3       | 6.5                    | Corticotroph adenoma  | Y                           | 81                                            |
| 4       | 4.0                    | Corticotroph adenoma  | Y                           | 333                                           |
| 5       | 4.0                    | Corticotroph adenoma  | Y                           | 392                                           |
ventricular system (percent changes = −0.0816%, −0.0208%, −0.0628%, and −0.0630% for the 3rd, 4th, right lateral, and left lateral ventricles, respectively), which is consistent with our visual observations. These results are summarized in Table 2.

**DISCUSSION**

**Imaging analysis**

Our findings demonstrate recovery of frontotemporal cortical volume in CD patients following surgical treatment with UHF 7 T MRI. We are able to better depict postoperative percentage increases with better spatial resolution. Two commonly used standards for gray matter analysis are cortical thickness and surface area. Thickness is a measure of neuron and glia size, number, and arrangement in specific brain regions, while surface area is associated with the number of columns in a region of interest. The data collected using 7 T MRI and analysis pipelines such as FreeSurfer in this work have shown that the frontotemporal areas of the brain may increase in cortical thickness and volume after CD surgical treatment and hormonal remission. In this study, any changes in behavior or cognition in tandem with endocrinological remission posttreatment were not assessed. However, clinically, this work has a potential direction to help monitor cognitive changes in relation to brain structure volume and thickness restoration at high imaging resolutions following transsphenoidal surgery.

**Literature review**

CD is an important disease model for understanding the effect of cortisol on brain structures. The reversal of symptoms following transsphenoidal resection is key to understanding the volumetric changes in the brain that happens due to the syndrome. Yet, the structural differences between active
In general, the MRI scans in a handful of studies to assess the time course of frontoparietal volumetric changes. Further follow-up with a larger-scale analysis is needed to make a more statistically significant call for the frontoparietal changes as seen in the data here. In this specific study, patients 2 and 3 had their follow-up MRI both at 81 days after surgery, which is an order of magnitude shorter than the other three patients’ follow-up MRI. The changes in the brain for all five patients were still consistent with each other, so there may be a plateau in the parameter changes during the posttreatment period. Nonetheless, additional UHF scans at defined and consistent intervals after the patient’s operations are an area of interest since some areas of the brain may recover more quickly than others. In addition, set intervals will show a more comprehensive timeline of the relief of CD symptoms in correlation with brain parameter changes.

Cognitive and psychiatric changes were not evaluated in our sample of five patients. Cognitive difficulties and depression can persist in patient’s following pituitary resections, even when brain volumes have normalized. In a recent literature review of 682 patients who had undergone transphenoidal resections, the most commonly reported neurologic deficits included impairments in verbal and nonverbal memory. Furthermore, patients who had undergone resections for CD compared with patients who had resections for nonfunctioning pituitary macroadenomas had lower scores on the Mini-Mental State Examination and the memory quotient of the Wechsler Memory Scale. The authors theorized that the effects of excess GCs on the central nervous system, and the hippocampus, in particular, can have a long-term impact on memory and cognition. Significant psychiatric affective disorders were also reported in a case series of nine children who underwent surgery for

| Brain region                      | Postoperative percent change in volume |
|-----------------------------------|----------------------------------------|
| Cortical volume                   | +0.0172%                               |
| Cerebral white matter             | +0.0052%                               |
| Subcortical gray matter           | +0.0120%                               |
| Left medial orbitofrontal region  | +0.0166%                               |
| Left lateral orbitofrontal region | +0.0122%                               |
| Left pars opercularis cortical region | +0.0068%                |
| Right pars triangularis           | +0.0156%                               |
| Right rostral portion of the middle frontal gyrus | +0.0120%               |
| Right superior frontal gyrus      | +0.0158%                               |
| 3rd ventricle                     | −0.0816%                               |
| 4th ventricle                     | −0.0208%                               |
| Left lateral ventricle            | −0.0208%                               |
| Right lateral ventricle           | −0.0630%                               |

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and remitted CD patients are still considered controversial due to the rare incidence of CD, varying criteria to define remission, and lack of longitudinal studies. There is no consensus on the appropriate time for cortisol testing and the requirement of specific protocols to determine the true recurrence of the disease. In fact, many previous studies in the field are cross-sectional, comparing images from preoperative and postoperative CD patients from different populations. Imaging for these studies has mainly been at traditional field strengths such as 1.0 T and 1.5 T that may not have high enough resolution to detect the sensitive changes seen in CD. Additional support for UHFs scans is shown by one recent meta-analysis which noted that patients undergoing primary TSS have the highest chance of remission when the adenoma is visible on preoperative imaging. In general, the MRI scans in a handful of studies to assess the time course of frontoparietal volumetric changes. Further follow-up with a larger-scale analysis is needed to make a more statistically significant call for the frontoparietal changes as seen in the data here. In this specific study, patients 2 and 3 had their follow-up MRI both at 81 days after surgery, which is an order of magnitude shorter than the other three patients’ follow-up MRI. The changes in the brain for all five patients were still consistent with each other, so there may be a plateau in the parameter changes during the posttreatment period. Nonetheless, additional UHF scans at defined and consistent intervals after the patient’s operations are an area of interest since some areas of the brain may recover more quickly than others. In addition, set intervals will show a more comprehensive timeline of the relief of CD symptoms in correlation with brain parameter changes.

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treatment of CS, which may be attributed to the differential effects of GCs on the pediatric brain. A 2005 study of nine children with surgically treated Cushing disease found that despite the reversal of cerebral atrophy in patients 1 year after surgery, these patients had statistically significant declines in Wechsler IQ scores and school performance. UHF strength imaging of the postsurgical brain may reveal previously unseen anatomic changes. In future studies, a standardized cognitive examination may be added to further determine if anatomical changes correlate with patient improvement.

AI

The diagnosis and management of CD can be challenging since some patients may have an atypical presentation that overlaps with other metabolic syndromes. Thus, an AI platform could be useful to isolate features that are characteristic of preoperative and postoperative CD patients and to better determine when patients are in full remission of the disease. AI-assisted segmentation and brain quantification software may outperform template-based segmentation and can provide even greater accuracy when applied to 7 T data. Reuter et al. built on the FreeSurfer template-based segmentation by introducing a new, patient-specific longitudinal template to help reduce variability. Recent AI-assisted segmentation and brain quantification software such as AccuBrain have built on this framework and have introduced atlas-based segmentation software which has been validated by anatomic templates built by experienced radiologists. This atlas pool can be registered to an individual's MRI to calculate segmentation volumes of key metrics such as brain structure, lobe, and tissue within milliliters of accuracy. Finally, since medical imaging datasets with UHF images are small since 7 T MRI is a relatively new technology, deep learning algorithms are limited compared to what has been demonstrated on large-scale datasets such as ImageNet. As databases grow larger with increased implementation of UHF MRI in the clinical setting, significant improvements will be seen in the analysis of anatomic changes in neuropsychiatric conditions.

CONCLUSION

UHF MRI yields observable increases in cortical thickness and overall brain volume following corticotroph adenoma resection and achievement of hormonal remission in patients with Cushing disease. This cerebral volume recovery appears predominantly to involve the cortical gray matter compartment with a frontotemporal predominance. This proof-of-concept work highlights the sensitivity and accuracy of the 7 T technique, which may be applied in future, large-scale studies to elucidate the mechanisms underlying the cognitive and psychiatric symptoms associated with CD. In combination with AI tools, UHF imaging techniques have a high potential to analyze microlevel structural differences associated with certain neurological disorders consistently.

Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent.

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Conflicts of interest

There are no conflicts of interest.

REFERENCES

1. Alsumali A, Cote DJ, Regestein QR, Crocker E, Alzarea A, Zaidi HA, et al. The impact of transphenoidal surgery on neurocognitive function: A systematic review. J Clin Neurosci 2017;42:1-6.
2. Andela CD, van Haalen FM, Ragnarsson O, Papakokkinou E, Johansson G, Santos A, et al. Cushing's syndrome causes irreversible effects on the human brain: A systematic review of structural and functional MRI studies. Eur J Endocrinol 2017;173:R1-14.
3. Andela CD, van der Werff SJ, Pannekoek JN, van den Berg SM, Meijer OC, van Buchem MA, et al. Smaller grey matter volumes in the anterior cingulate cortex and greater cerebellar volumes in patients with long-term remission of Cushing's disease: A case-control study. Eur J Endocrinol 2013;169:811-9.
4. Bourdeau I, Bard C, Noël B, Leclerc I, Cordeau MP, Belair M, et al. Loss of brain volume in endogenous Cushing's syndrome and its reversibility after correction of hypercortisolism. J Clin Endocrinol Metab 2002;87:1949-54.
5. Cox RW, Hyde JS. Software tools for analysis and visualization of fMRI data. NMR Biomed 1997;10:171-8.
6. Crespo I, Esther GM, Santos A, Valassi E, Yolanda VG, De Juan-Delago M, et al. Impaired decision-making and selective cortical frontal thinning in Cushing's syndrome. Clin Endocrinol (Oxf) 2014;81:826-33.
7. de Rotte AA, Groenewegen A, Rutgers DR, Witkamp T, Zelissen PM, Meijer Fj, et al. High resolution pituitary gland MRI at 7.0 tesla: A clinical evaluation in Cushing’s disease. Eur Radiol 2016;26:271-7.
8. Devoe DJ, Miller WL, Conte FA, Kaplan SL, Grumbach MM, Rosenthal SM, et al. Long-term outcome in children and adolescents after transphenoidal surgery for Cushing's disease. J Clin Endocrinol Metab 1997;82:2196-202.
9. Dorn LD, Burgess ES, Friedman TG, Dubbert B, Gold PW, Chrousos GP. The longitudinal course of psychopathology in Cushing's syndrome after correction of hypercortisolism. J Clin Endocrinol Metab 1997;82:912-9.
10. Fuchs E, Flugge G, Czeh B. Remodeling of neuronal networks by stress. Front Biosci 2006;11:2746-58.
11. Hinojosa-Amaya JM, Cuevas-Ramos D. The definition of remission and recurrence of Cushing's disease. Best Pract Res Clin Endocrinol Metab 2017;31:283-91.
Lee, et al.: 7 T MRI localizes brain volume changes in Cushing's disease

Altered amygdala and hippocampus function et al.
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Ultra-high field 7 T MRI localizes regional brain volume et al.
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Volumetric et al.
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Bayesian analysis of neuroimaging data in et al.
et al.
et al.
et al.

28. Patel V, Liu CJ, Shiroishi MS, Huth K, Carmichael JD, Zada G, et al. Ultra-high field magnetic resonance imaging for localization of corticotropin-secreting pituitary adenomas. Neuroradiology 2020;62:1051-4.

29. Pivonello R, Isidori AM, De Martino MC, Newell-Price J, Biller BM, Colao A. Complications of Cushing's syndrome: State of the art. Lancet Diabetes Endocrinol 2016;4:611-29.

30. Ragnarsson O, Berglund P, Eder DN, Johansson G. Long-term cognitive impairments and attentional deficits in patients with Cushing's disease and cortisol-producing adrenal adenoma in remission. J Clin Endocrinol Metab 2012;97:E1640-8.

31. Resmini E, Santos A, Gómez-Anson B, Vives Y, Pires P, Crespo I, et al. Verbal and visual memory performance and hippocampal volumes, measured by 3-Tesla magnetic resonance imaging, in patients with Cushing's syndrome. J Clin Endocrinol Metab 2012;97:663-71.

32. Reuter M, Schmansky NJ, Rosas HD, Fischl B. Within-subject template estimation for unbiased longitudinal image analysis. Neuroimage 2012;61:1402-18.

33. Simmons NE, Do HM, Lipper MH, Laws ER Jr. Cerebral atrophy in Cushing's disease. Surg Neurol 2000;53:72-6.

34. Starkman MN, Giordani B, Berent S, Schork MA, Schteingart DE. Elevated cortisol levels in Cushing's disease are associated with cognitive decrements. Psychosom Med 2001;63:985-93.

35. Starkman MN, Giordani B, Gebarski SS, Berent S, Schork MA, Schteingart DE. Decrease in cortisol reverses human hippocampal atrophy following treatment of Cushing's disease. Biol Psychiatry 1999;46:1595-602.

36. Starkman MN, Giordani B, Gebarski SS, Schteingart DE. Improvement in learning associated with increase in hippocampal formation volume. Biol Psychiatry 2003;53:233-8.

37. Starkman MN, Schteingart DE, Schork MA. Depressed mood and other psychiatric manifestations of Cushing's syndrome: Relationship to hormone levels. Psychosom Med 1981;43:3-18.

38. Stroud A, Dhaliwal P, Alvarado R, Winder MJ, Jonker BP, Grayson JW, et al. Outcomes of pituitary surgery for Cushing's disease: A systematic review and meta-analysis. Pituitary 2020;23:595-609.

39. Tiemensma J, Kokshoorn NE, Biermasz NR, Keijser BJ, Wassenaar MJ, Middelkoop HA, et al. Subtle cognitive impairments in patients with long-term cure of Cushing's disease. J Clin Endocrinol Metab 2010;95:2699-714.

40. Tiros R, RaviPrakash H, Papadakis GZ, Tatsi C, Belayavskaya E, Charalampos L, et al. Computerized analysis of brain MRI parameter dynamics in young patients with Cushing syndrome a case-control study. J Clin Endocrinol Metab 2017;105:dgz303.

41. Woolrich MW, Jbabdi S, Patenaude B, Chappell M, Makni S, Behrens T, et al. Bayesian analysis of neuroimaging data in FSL. Neuroimage 2009;45:S173-86.

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