Mineralocorticoid receptor status in the human brain after dexamethasone treatment: a single case study

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Abstract

Background: Synthetic glucocorticoids like dexamethasone can cause severe neuropsychiatric effects. They preferentially bind to the glucocorticoid receptor (GR) over the mineralocorticoid receptor (MR). High dosages result in strong GR activation, but likely also lower MR activation based on GR-mediated negative feedback on cortisol levels. Therefore, reduced MR activity may contribute to dexamethasone-induced neuropsychiatric symptoms.

Objective: In this single case study, we evaluate whether dexamethasone leads to reduced MR activation in the human brain. Brain tissue of an 8-year-old brain tumor patient was used, who suffered chronically from dexamethasone-induced neuropsychiatric symptoms and deceased only hours after a high dose of dexamethasone.

Main outcome measures: The efficacy of dexamethasone to induce MR activity was determined in HEK293T cells using a reporter construct. Subcellular localization of GR and MR was assessed in paraffin embedded hippocampal tissue from the patient and 2 controls. In hippocampal tissue from the patient and 8 controls, mRNA of MR/GR target genes was measured.

Results: In vitro, dexamethasone stimulated MR with low efficacy and low potency. Immunofluorescence showed the presence of both GR and MR in the hippocampal cell nuclei after dexamethasone exposure. The putative MR target gene JDP2 was consistently expressed at relatively low levels in the dexamethasone-treated brain samples. Gene expression showed substantial variation in MR/GR target gene expression in two different hippocampus tissue blocks from the same patient.

Conclusions: Dexamethasone may induce MR nuclear translocation in human brain. Conclusions on in vivo effects on gene expression in the brain await the availability of more tissue of dexamethasone-treated patients.
Introduction

Synthetic glucocorticoids are used extensively for their anti-inflammatory effects in many medical conditions, including immune diseases, different types of cancer, and in the treatment of edema in brain tumor patients [1, 2]. A recent study from Denmark established a three percent annual prevalence of systemic glucocorticoid use that was stable over a period of 15 years [3]. Although glucocorticoids are very efficacious, high-dose treatment can lead to severe neuropsychiatric effects like depression, anxiety, mania, delirium and even suicidality. Cognitive and memory impairments and sleep disturbances are also well-known side effects [4, 5]. The high prevalence of the potentially severe adverse effects makes it important to study the biological mechanisms of action that underlie them, and this might help to decrease these adverse effects during glucocorticoid therapy.

Synthetic glucocorticoids target the glucocorticoid receptor (GR), one of the two receptor types for the naturally produced glucocorticoid hormone cortisol. Cortisol also acts via the mineralocorticoid receptor (MR) in many tissues including the brain [6], but synthetic glucocorticoids have clear preference for GR over MR [7]. Both receptor types are expressed in the brain. They are members of the nuclear receptor family and act as transcriptional regulators. Activation by cortisol leads to translocation of the receptors from the cytoplasm to the cell nucleus, and subsequent interaction with DNA and proteins in the nucleus [8]. However, MR and GR only partially overlap in their target sites at the chromatin [9] and they can mediate very different, sometimes opposite effects of cortisol on neuronal excitability, mood and cognition [6, 10]. In relation to psychopathology, MR-mediated effects have been suggested to be protective based on genetic variants and pharmacological interventions [11-13].

Synthetic glucocorticoids via GR activation potently suppress the production of cortisol by the adrenal gland via activation of negative feedback mechanisms within the hypothalamic-pituitary-adrenal (HPA) axis [14, 15]. High dosages of synthetic glucocorticoids will therefore lead to a situation of strong GR activation but, for lack of cortisol, lower activation of MR. While chronically
elevated cortisol in Cushing’s disease may also lead to psychiatric complaints, next to the strongly activated GR, the reduced MR activity caused by synthetic glucocorticoids might contribute to the neuropsychiatric effects of dexamethasone [16]. There is upcoming evidence that certain subgroups of childhood leukemia patients suffering from side effects from dexamethasone may benefit from cortisol add-on to refill and re-activate brain MR [17].

Here, we evaluated the validity of the ‘MR refill’ hypothesis in human pediatric brain tissue. We had the unique opportunity to investigate biological effects of dexamethasone in hippocampal brain tissue of an 8-year-old brain tumor patient, who experienced severe mental side effects in conjunction with his episodes of dexamethasone treatment and who died while on dexamethasone treatment. We assessed the expression and functionality of MR and GR, in part guided by the expression of recently identified MR-selective target genes in the rodent brain [18].
Materials and Methods

Human brain tissue

Frozen and paraffin embedded hippocampal tissue from an 8-year-old brain tumor patient was obtained from the biobank of the Amsterdam UMC. The patient was diagnosed with primitive neuroectodermal tumor (PNET) located in the pons. This pediatric patient received dexamethasone treatment to prevent tumor edema numerous times. Treatment was abrogated or dosages were lowered multiple times due to severe behavioral side effects, but eventually was always reinstated. He was on continuous high dose dexamethasone for nearly a year. The dexamethasone could only be tapered for a few weeks. In the end, the patient deceased while on a dexamethasone dose of 3.5mg/day orally, 2mg in the morning and 1.5mg in the evening. The parents and treating physicians noted disinhibited behavior, sleep disturbances, increased appetite, mood swings and angry outbursts that seemed to be consistently occurring while the patient was on dexamethasone and decreased when dexamethasone was tapered. The mentioned complaints could not be explained by the location of the tumor, as these specific functions (behavior, sleep, appetite) are not located in the brainstem. He did not have tumor location in other parts of the brain, which excludes these complaints to be explained by the tumor and/or edema in other parts of the brain. Additionally, there were no signs of raised intracranial pressure, neither on MRI nor on ophthalmological examination. Also, a ventricular peritoneal drain was present to prevent hydrocephalus. The boy’s immediate cause of death was respiratory insufficiency due to extensive necrosis of the brain stem. The boy had received radiotherapy twice, and it is important to notice that the hippocampus and hypothalamus were not in the direct radiotherapy field. Only the brainstem was selectively irradiated with high dose.

Paraffin embedded hippocampal tissue from 2 controls not taking glucocorticoids was obtained from the Department of Pathology of the LUMC. One control was a 5-year-old girl who died from a car crash and the second control was an 11-year-old girl who died from cardiac arrhythmia causing...
cardiac failure. Frozen hippocampal tissue from 8 controls (5 boys and 3 girls) who were not treated with glucocorticoids was obtained from the NIH NeuroBioBank at the University of Maryland, Baltimore, MD (Table 1). We have no information of which exact part of the respective hippocampus tissues we received. In two of the controls, the cause of death was asthma. According to the donor information one control used salbutamol and OTC inhalers, and for the other control medication use was not mentioned. The study was approved by METC VUmc and NIH NeuroBiobank. Consent has been obtained for the use of tissue according to institutional guidelines.

**Luciferase reporter assay**

Human embryonic kidney cell line HEK293T were grown and maintained in Dulbecco’s modified Eagle’s medium (DMEM, Gibco) supplemented with 10 % (Fetal Calf Serum) FCS, 100 µg/mL penicillin and 50 µg/mL streptomycin. Cells were grown in a humidified incubator at 37 °C and 5 % CO2. HEK293T cells were seeded 80 000 cells in 500 µL serum-stripped medium in a 24-wells plate. Cells were transfected using Fugene HD transfection reagent (Promega) with 25 ng TAT1-luciferase [19], 10 ng human MR expression vector, 1 ng CMV-renilla and 365 ng pcDNA. After 24 hours, medium was replaced and cells were stimulated with dexamethasone, aldosterone and cortisol in different concentrations ranging from 0.01 nM to 10 µM for 24 hours. The firefly and renilla luciferase levels in the lysates were measured using Dual Luciferase Assay (Promega), normalized by comparison with the control wells.

**Immunofluorescence staining**

5 µm paraffin embedded hippocampal sections were mounted on coated slides (Starfrost), deparaffinized in Histomount (National Diagnostics) and rehydrated in a graded ethanol series. Antigen retrieval was performed in citrate buffer (10 mM, pH6.0) in an autoclave at 120 °C for 15 minutes. After cooling to room temperature, sections were washed with 0.1 % PBS-Tween (PBST) and blocked with 5 % bovine serum albumin (BSA) in PBS. Sections were incubated at 4 °C overnight.
with rabbit monoclonal GR antibody (1:500, D6H2L, Cell Signalling technology) and mouse monoclonal MR antibody (1:500, MR1-18 1D5 and MR 4G5) [20] in 1 % BSA/PBST. After washing, sections were incubated with AlexaFluor-488 labelled goat-anti-rabbit IgG and AlexaFluor-555 goat-anti-mouse IgG (1:250, Thermo Scientific) in 1 % BSA/PBST for 90 minutes. Finally, sections were washed and nuclei were stained with DAPI (1:1000, Thermo Fisher Scientific) in PBS after which the sections were mounted with ProLong Gold anti-fade mounting medium (Thermo Fisher Scientific). Control sections were incubated with equal amount of normal rabbit IgG (X0903, DAKO) as substitute for primary antibody. Additionally, sections were incubated without any primary antibodies to check for nonspecific binding of the secondary antibodies. Confocal microscopy (Leica SP8) was used for analysis of immunofluorescence staining using a 40x objective. ImageJ was used to calculate the percentage staining in the nuclei for each individual cell. Two pictures were taken from the tissue of the dexamethasone-treated patient and from the two controls. In ImageJ the region of interest was drawn, in which MR and GR are expressed and individual cell nuclei are clearly distinguishable. Within this region of interest all cell nuclei were numbered based on the DAPI staining and ImageJ software was used to calculate the percentage of red and green staining in all numbered nuclei. By comparing distribution of percentage staining with visual evaluation we established a cut off value for the red and green staining, 10% and 7% respectively. Staining above 10% and 7% for red and green signal respectively was considered specific signal. The mean percentage red/green positive nuclei in the two pictures of dexamethasone and controls tissues was calculated and used in the quantification.

**Quantitative-PCR**

Frozen human hippocampal tissue was homogenized in TriPure (Roche) by using a hand-held rotary homogenization device for 30 seconds or until homogenization was achieved. Total RNA was isolated with chloroform, precipitated with isopropanol, washed with 75% ethanol and dissolved in nuclease-free H$_2$O. The RNA concentration was determined with a NanoDrop spectrophotometer.
(Thermo Scientific) and 1µg RNA was reverse-transcribed using random hexamers and M-MLV reverse transcription (Promega). RT-qPCR was performed in duplicates on 50x diluted cDNA (1ng/µL) with final primer concentrations of 0.5µM using iQ SYBR-Green supermix (BioRad) in a CFX96 real-time PCR machine (BioRad). Melting curve analysis was performed to ensure a single PCR product.

Two samples from the same hippocampal tissue block from the dexamethasone-treated patient were obtained from the neuropathology. Given the intrinsic vulnerability of comparing tissue from a single subject to reference tissues, these were processed independently and from each sample cDNA was made twice independently. We only had sufficient tissue from the controls to process RNA once. Expression of mRNA was evaluated for different glucocorticoid target genes. ‘Classical target genes’ that are often included in glucocorticoid research are known to be regulated by both GR and MR [18]. These classical mixed GR/MR target genes were FK506 binding protein 5 (FKBP5), Glucocorticoid-Induced Leucine Zipper (GILZ), Period Circadian Clock 1 (PER1) and Serum/Glucocorticoid regulated Kinase 1 (SGK1). Furthermore, the receptor genes NR3C1 (GR) and NR3C2 (MR) were measured, and several target genes were measured that have been suggested to be specifically regulated by either MR or GR. These putative target genes were selected from previous ChIP-sequencing data in rat hippocampus and from recent identified MR target genes in mouse hippocampus [9, 18]. The putative MR target genes were Jun Dimerization Protein 2 (JDP2), Suv3 Like RNA Helicase (SUPV3L1) and Nitric Oxide Synthase 1 adaptor protein (NOS1AP). The putative GR-specific target gene was Metallothionein 2A (MT2A). mRNA expression of genes of interest was normalized to mRNA expression of the housekeeping gene β-Actin in duplo. We additionally validated the data using 18S primers on samples that were diluted 500x in order to stay in the same Ct values range of the genes of interest. Primer sequences are listed in Table 2.

**Statistical analysis**

For transfection studies EC<sub>50</sub> values were calculated using GraphPad Prism 7 software using a nonlinear fit model. No formal statistical tests were performed on the results from the human
brains, as this study only includes one patient. The q-PCR data was interpreted based on the expression levels in the dexamethasone patient relative to the average and standard deviation of the control samples.
Results

Dexamethasone activates MR in HEK293T cells with low potency and low efficacy

Dexamethasone is known to bind MR, but with very rapid kinetics, which is thought to render ligand-receptor complexes too unstable to be a strong MR agonist in vivo [21]. To evaluate the ability of dexamethasone to activate MR under continuous presence of ligand (steady state concentrations), we generated a concentration-effect curve in MR transfected HEK293T cells using a MR-sensitive luciferase reporter gene (Fig. 1). Increasing concentrations of the endogenous agonists aldosterone and cortisol enhanced activation of MR with an EC$_{50}$ of 0.16 and 3.4 nM respectively. Dexamethasone was also able to activate MR, but higher concentrations were required. The EC$_{50}$ of 12.5 nM demonstrates the lower potency of dexamethasone to activate MR. In addition, dexamethasone had lower efficacy, as it only reached about 70% of the maximal effect of aldosterone and cortisol. In HEK293T cells that were transfected with only reporter and no MR or GR expression vector, no effect of hormones was observed (not shown). Overall, high concentrations of dexamethasone were able to activate MR in HEK293T cells, however with low efficacy at the reporter gene even under continuous presence of ligand.

Cell nuclear presence of both GR and MR in dexamethasone-exposed human hippocampal tissue

We next visualized the subcellular distribution of the corticosteroid receptors in human hippocampus. As expected, immunofluorescence staining (IF) of GR in the dexamethasone-treated tissue showed clear nuclear localization (Fig. 2A), whereas in the two control tissues the GR seemed more cytosolic (Fig. 2B,C). Nuclear staining was verified using DAPI as a nuclear marker. For MR, some nuclear staining was observed in the control tissues with the 1D5 antibody (Fig. 2B,C). Counter to our expectation, nuclear MR staining was also found in the dexamethasone-treated tissue (Fig. 2A). Quantification of nuclear GR and MR expression in both the patient and controls clearly demonstrated more GR and MR positive nuclei in the dexamethasone-treated tissue (Fig. 2D). This is
not apparent for the MR 4G5 antibody, which showed a more cytosolic MR staining pattern (in line with earlier work [20]). In the dexamethasone-treated tissue and controls, this antibody showed both nuclear and cytosolic MR, suggesting that MR translocation was incomplete (Fig. 3). Overall, these data suggest that high dose dexamethasone exposure causes nuclear translocation for both GR and MR, although for MR translocation is not complete. This is in line with the in vitro data where higher concentrations of dexamethasone were able to activate MR, but at odds with binding studies in rodent brains [21].

**Gene expression levels in the human hippocampus: high variability between samples from the same subject**

In order to find evidence for the transcriptional effects of dexamethasone on GR and MR in human hippocampal tissue, we investigated the functionality of the receptors in the dexamethasone-treated tissue and 8 aged-matched control samples. To reduce the risk of chance findings in the tissue of the subject treated with dexamethasone, we determined mRNA expression in two separate blocks of hippocampal tissue and for each block we performed two independent rounds of cDNA synthesis. While cDNA from the same block of tissue resulted in reliable replication, there was a large variation between the different tissue blocks using β-Actin normalization, in particular for some of the (putative) target genes. Expression levels of *NR3C2* was in the range of average expression observed in the controls, while *NR3C1* was expressed at the lower range (Fig. 4A). Expression levels of the best-established putative MR target gene, *JDP2*, were consistently low in the dexamethasone-exposed brain relative to the control samples. However, mRNA of *SUPV3L1* showed low expression in the first processed dexamethasone-treated tissue (as defined by ranking 9 or 8 in the whole sample set), but expression levels were clearly higher in the second tissue block (Fig. 4B). On average, the expression of the putative MR genes had rank 6.7 +/- 3.2.

The expression of the classical mixed GR and MR target genes *FKBP5*, *GILZ*, *PER1* and *SGK1* was also highly variable between tissue blocks. In the first tissue block, *GILZ* and *SGK1* mRNA were expressed
at low levels, whereas in the second tissue block expression of FKBPS and PER1 was clearly in the higher range (Fig. 4C). Similarly, the expression of the putative selective GR target gene MT2A was high for second the dexamethasone-treated tissue sample (Fig. 4D). These high values are more in line with what may be expected from GR target genes after high dexamethasone, but the potential role of MR precludes a straightforward predication [18]. Average ranking of these genes that are GR sensitive was 3.2 +/- 1.9.

Altogether, these data demonstrate a rather disconcerting variation in hippocampal expression of target genes in the two tissue blocks from the same patient (see discussion). Although in the control tissue similar technical variation may have been present, the higher number of samples from different subjects should lead to a more reliable estimate in which technical and biological variation are both present. Of note, 18S normalization tended to show less extreme variation between the two tissue samples with respect to the extreme ‘batch effect’ that was observed for e.g. FKBPS. However, relative average expression levels between case and controls was essentially identical using 18S normalization (not shown).
Discussion

The aim of the current single case study was to evaluate the hypothesis that dexamethasone treatment leads to reduced MR activation in the human brain, in the context of the ‘MR refill’ concept to reduce psychiatric side effects of synthetic glucocorticoids treatment by add-on of cortisol. This was possible because of the availability of a unique hippocampal tissue from an 8-year-old brain tumor patient, who died during treatment with dexamethasone, only hours after the last administration. The boy had suffered from neuropsychiatric effects that accompanied the many dexamethasone treatments he had received. In this study, we confirm the ability of dexamethasone to activate MR\textit{ in vitro}, although with low potency and low efficacy. In human hippocampal tissue treated with dexamethasone we demonstrate nuclear translocation of GR and MR. Even if translocation was incomplete for MR, the data suggest that dexamethasone, hours after a very high dose, is able to bind to MR sufficiently to induce partial translocation. Although the pharmacokinetics\textit{ in vivo} are uncertain, the data is consistent with the known\textit{ in vitro} effects of dexamethasone that we also observed.

Unfortunately, we observed highly variable mRNA expression levels of many MR and or GR target genes in dexamethasone-treated tissue, as compared to control tissue. The low expression of the characterized mouse MR target gene \textit{JDP2} is supportive for our hypothesis, but should be interpreted with caution given the highly variable expression of established GR targets. This argues that comparison of this single case does not permit a conclusion. Even with tight data, strong conclusions based on a single case would be challenging. The different results in the two samples from the same subject might be explained by differential presence of different hippocampal cell types and subregions. A recent single-cell transcriptome data analysis of mouse hippocampus showed that the expression of GR target genes are cell type specific (under basal conditions) [22]. For example, \textit{Fkbp5} seems to have highest expression in the glutamatergic neurons. However, if we would know the exact origin of the tissue – region and its cell types – we could get much better.
detail of the expression of the genes of interest. Normalization with 18S tended to show less extreme variation between the tissue samples, however, it yielded identical value average to be representative in the hippocampus as a whole.

Our assumption of MR underactivation after dexamethasone hinges on depletion of endogenous cortisol by dexamethasone. To our knowledge there are no reports of desensitisation of the negative feedback on the HPA axis as a consequence of chronic glucocorticoid exposure. Even if GR is known to suppress its own expression via a negative GRE [23], Cushing’s patients and e.g. AdKO ‘Cushings’ mice’ show sustained GR-mediated effects even after very long term (in this case: endogenous) glucocorticoid overexposure [24]. The dexamethasone-exposed tissue represents a context of high GR occupation. The lower expression range of GR mRNA would be in line with high GR activity in the dexamethasone exposed tissue.

Dexamethasone is used clinically in particular in oncology, neurosurgery and immunology, and has been studied in relation to brain corticosteroid receptors for almost 50 years [25]. While its potent suppressive effect on the HPA-axis primarily takes place at the level of the pituitary, dexamethasone at high doses penetrates the blood brain barrier [26]. When administered in low doses (in absence of a functional blood brain barrier) it clearly selectively binds brain GRs [27], and hence nuclear GR staining was expected in the hippocampus of the dexamethasone-treated subject. However, the nuclear presence of MR also suggests some level of activation. From kinetic experiments it is known that dexamethasone has a comparable association binding rate for MR as corticosterone, but has a very high dissociation rate [21]. As a result, an unstable binding complex is formed, which is probably why MR is not activated in vivo under non-steady state conditions. Our data under in vitro steady state conditions likely reflects these binding kinetics. Based on our current (translocation) data, we hypothesize that under conditions of intermittent dexamethasone treatment there may in fact be a partial temporary activation of MR. Another possibility is nuclear translocation of a heterodimer complex, which might consist of a GR activated by dexamethasone and a weakly/transiently bound
MR [28]. This complex could translocate to the nucleus, but whether the binding, in both cases, is strong enough to actually regulate gene transcription remains to be investigated (when brain tissue from more dexamethasone/glucocorticoid-treated subjects is available).

As discussed in detail elsewhere [16], psychological adverse effects of dexamethasone could be caused by GR overactivation, MR under activation or by a disbalance in MR:GR activity. It was already tentatively concluded that re-activating MR by cortisol add-on treatment may alleviate psychological adverse effects of dexamethasone in the subgroup of patients with childhood leukemia [17]. Re-activation of MR - in the context of high GR activation - seems to be an important goal for the improvement of glucocorticoid therapy by reducing psychiatric side effects.

The alternative explanation for a beneficial effect of cortisol would be that cortisol-activated GR exerts different effects from dexamethasone-activated GR. Given the strong suppression of the HPA-axis after dexamethasone, and the differences between cortisol-MR and dexamethasone-MR, we favor the option that MR mediates favorable effects of cortisol, but – again – the current data on human hippocampal gene expression do not allow us to differentiate between these options. It will be necessary to replicate our findings in samples from other individuals, to substantiate the lower MR activity in the human brain after synthetic glucocorticoid treatment, in relation to psychiatric side effects that is regularly observed with this treatment.

Declaration of interest

The authors have nothing to disclose.

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References

1. Hockey B, Leslie K, and Williams D. Dexamethasone for intracranial neurosurgery and anaesthesia. *J Clin Neurosci* 2009;16(11):1389-93.
2. Ismail M F, Lavelle C, and Cassidy E M. Steroid-induced mental disorders in cancer patients: a systematic review. *Future Oncol* 2017;13(29):2719-2731.
3. Laugesen K, Jorgensen J O L, Petersen I, and Sorensen H T. Fifteen-year nationwide trends in systemic glucocorticoid drug use in Denmark. *Eur J Endocrinol* 2019;181(3):267-273.
4. Judd L L, Schettler P J, Brown E S, Wolkowitz O M, Sternberg E M, Bender B G, Bulloch K, Cidlowski J A, de Kloet E R, Fardet L, et al. Adverse consequences of glucocorticoid medication: psychological, cognitive, and behavioral effects. *Am J Psychiatry* 2014;171(10):1045-51.
5. Fardet L, Petersen I, and Nazareth I. Suicidal behavior and severe neuropsychiatric disorders following glucocorticoid therapy in primary care. *Am J Psychiatry* 2012;169(5):491-7.
6. de Kloet E R, Joels M, and Holsboer F. Stress and the brain: from adaptation to disease. *Nat Rev Neurosci* 2005;6(6):463-75.
7. Grossmann C, Scholz T, Rochel M, Bumke-Vogt C, Oelkers W, Pfeiffer A F, Diederich S, and Bahr V. Transactivation via the human glucocorticoid and mineralocorticoid receptor by therapeutically used steroids in CV-1 cells: a comparison of their glucocorticoid and mineralocorticoid properties. *Eur J Endocrinol* 2004;151(3):397-406.
8. Meijer O C, Buurstedt J C, and Schaaf M J M. Corticosteroid Receptors in the Brain: Transcriptional Mechanisms for Specificity and Context-Dependent Effects. *Cell Mol Neurobiol* 2018;39(4):539-549.
9. van Weert L, Buurstedt J C, Mahfouz A, Braakhuis P S M, Polman J A E, Sips H C M, Roozenendaal B, Balog J, de Kloet E R, Datson N A, et al. NeuroD Factors Discriminate Mineralocorticoid From Glucocorticoid Receptor DNA Binding in the Male Rat Brain. *Endocrinology* 2017;158(5):1511-1522.
10. Joels M, Hesen W, and de Kloet E R. Mineralocorticoid hormones suppress serotonin-induced hyperpolarization of rat hippocampal CA1 neurons. *J Neurosci* 1991;11(8):2288-94.
11. Otte C, Wingenfeld K, Kuehl L K, Kaczmarczyk M, Richter S, Quante A, Regen F, Bajbouj M, Zimmermann-Viehoff F, Wiedemann K, et al. Mineralocorticoid receptor stimulation improves cognitive function and decreases cortisol secretion in depressed patients and healthy individuals. *Neuropsychopharmacology* 2015;40(2):386-93.
12. Klok M D, Giltay E J, Van der Does A J, Geleijnse J M, Antypa N, Penninx B W, de Geus E J, Willemsen G, Boomsma D I, van Leeuwen N, et al. A common and functional mineralocorticoid receptor haplotype enhances optimism and protects against depression in females. *Transl Psychiatry* 2011;1:e62.
13. Otte C, Hinkelmann K, Moritz S, Yassouridis A, Jahn H, Wiedemann K, and Kellner M. Modulation of the mineralocorticoid receptor as add-on treatment in depression: a randomized, double-blind, placebo-controlled proof-of-concept study. *J Psychiatr Res* 2010;44(6):339-46.
14. Sapolsky R M, Romero L M, and Munck A U. How do glucocorticoids influence stress responses? Integrating permissive, suppressive, stimulatory, and preparative actions. *Endocrine Reviews* 2000;21(1):55-89.
15. Spencer R L and Deak T. A users guide to HPA axis research. *Physiol Behav* 2017;178:43-65.
16. Meijer O C and de Kloet E R. A Refill for the Brain Mineralocorticoid Receptor: The Benefit of Cortisol Add-On to Dexamethasone Therapy. *Endocrinology* 2017;158(3):448-454.
17. Warris L T, van den Heuvel-Eibrink M M, Aarsen F K, Pluim J M, Bierings M B, van den Bos C, Zwaan C M, Thygesen H H, Tissing W J, Veening M A, et al. Hydrocortisone as an Intervention for Dexamethasone-Induced Adverse Effects in Pediatric Patients With Acute Lymphoblastic
Leukemia: Results of a Double-Blind, Randomized Controlled Trial. *J Clin Oncol* 2016;34(19):2287-93.

18. van Weert L, Buurstede J C, Sips H C M, Vettorazzi S, Mol I M, Hartmann J, Prekovic S, Zwart W, Schmidt M V, Roozendaal B, *et al.* Identification of mineralocorticoid receptor target genes in the mouse hippocampus. *J Neuroendocrinol* 2019;31:e12735.

19. Liu W H, Wang J, Yu G Q, and Pearce D. Steroid receptor transcriptional synergy is potentiared by disruption of the DNA-binding domain dimer interface. *Molecular Endocrinology* 1996;10(11):1399-1406.

20. Gomez-Sanchez C E, de Rodriguez A F, Romero D G, Estess J, Warden M P, Gomez-Sanchez M T, and Gomez-Sanchez E P. Development of a panel of monoclonal antibodies against the mineralocorticoid receptor. *Endocrinology* 2006;147(3):1343-8.

21. Reul J M, Gesing A, Droste S, Stec I S, Weber A, Bachmann C, Bilang-Bleuel A, Holsboer F, and Linthorst A C. The brain mineralocorticoid receptor: greedy for ligand, mysterious in function. *Eur J Pharmacol* 2000;405(1-3):235-49.

22. Buurstede J C, van Weert L, Colucci P, Gentenaar M, Viho E M G, Koorneef L L, Schoonderwoerd R A, Lanooij S D, Moustakas I, Balog J, *et al.* Hippocampal glucocorticoid target genes associated with enhancement of memory consolidation. *Eur J Neurosci* 2021.

23. Ramamoorthy S and Cidlowski J A. Ligand-induced repression of the glucocorticoid receptor gene is mediated by an NCoR1 repression complex formed by long-range chromatin interactions with intragenic glucocorticoid response elements. *Mol Cell Biol* 2013;33(9):1711-22.

24. Amaya J M, Suidgeest E, Sahut-Barnola I, Dumontet T, Montanier N, Pages G, Keller C, van der Weerd L, Pereira A M, Martinez A, *et al.* Effects of Long-Term Endogenous Corticosteroid Exposure on Brain Volume and Glial Cells in the AdKO Mouse. *Frontiers in Neuroscience* 2021;15.

25. de Kloet E R, van der Vies J, and de Wied D. The site of the suppressive action of dexamethasone on pituitary-adrenal activity. *Endocrinology* 1974;94(1):61-73.

26. Karssen A M, Meijer O C, Berry A, Sanjuan Pinol R, and de Kloet E R. Low doses of dexamethasone can produce a hypocorticosteroid state in the brain. *Endocrinology* 2005;146(12):5587-95.

27. Meijer O C, de Lange E C M, Breimer D D, de Boer A G, Workel J O, and de Kloet E R. Penetration of dexamethasone into brain glucocorticoid targets is enhanced in mdr1A P-glycoprotein knockout mice. *Endocrinology* 1998;139(4):1789-1793.

28. Koning A, Buurstede J C, van Weert L, and Meijer O C. Glucocorticoid and Mineralocorticoid Receptors in the Brain: A Transcriptional Perspective. *J Endocr Soc* 2019;3(10):1917-1930.
Figure legends

Figure 1. **The effect of aldosterone, cortisol and dexamethasone on MR activity in vitro.** Nonlinear fit model for the concentration-effect in HEK293T cells transfected with a TAT1-luciferase reporter. Transactivation via hMR for aldosterone, cortisol and dexamethasone at different concentrations for 24 hours.

Figure 2. **Cell nuclear localization of GR and MR in human hippocampal dentate gyrus (DG) region.** Immunofluorescence staining of cell nuclei (blue), GR (green) and MR with the 1D5 antibody (red) in (A) tissue of the dexamethasone-treated patient and in (B) tissue from the 5-year-old control patient and (C) tissue from the 11-year-old control patient. (D) The percentage of GR and MR positive cell nuclei in the different tissues. White arrows show nuclear MR staining and yellow dotted arrows show cytosolic MR staining. In the left corner a magnification is shown and the dotted line represents the region of interest.

Figure 3. **Cytosolic and nuclear MR staining in human hippocampal dentate gyrus (DG) and Cornu Ammonis 4 (CA4) region.** Immunofluorescence staining of cell nuclei (blue) and MR with the 4G5 antibody (red) in the DG (A,C,E) and CA4 (B,D,F) in tissue of the dexamethasone-treated patient (A,B) and tissue from the 5-year-old control patient (C,D) and tissue from the 11-year-old control patient (E,F). White arrows show nuclear MR staining and yellow dotted arrows show cytosolic MR staining.

Figure 4. **Expression of glucocorticoid target genes in human hippocampal tissue.** Hippocampal mRNA levels of glucocorticoid target genes assessed in dexamethasone-treated tissue and controls with β-Actin normalization. Gene expression of (A) NR3C2 (MR) and NR3C1 (GR), (B) putative MR-specific targets, (C) classical mixed GR/MR targets and (D) putative GR-specific targets in n=1 dexamethasone-treated patient versus n=8 controls. Two tissue samples were independently processed with each having two independent cDNA samples (illustrated as squares and diamonds).
### Table 1

| Subject | Age (yr) | Gender | PMI (hrs) | Cause of death         |
|---------|----------|--------|-----------|------------------------|
| # 1     | 8        | M      | 12        | Drowning               |
| # 2     | 6        | F      | 22        | Smoke inhalation       |
| # 3     | 6        | M      | 16        | Drowning               |
| # 4     | 11       | F      | 12        | Asthma                 |
| # 5     | 12       | M      | 22        | Cardiac Arrhythmia     |
| # 6     | 12       | M      | 13        | Drowning               |
| # 7     | 12       | M      | 15        | Hanging                |
| # 8     | 13       | F      | 17        | Asthma                 |

PMI: Post mortem interval
Table 2

| Gene     | Forward and reverse sequence                      |
|----------|--------------------------------------------------|
| FKBPS    | Forward TGGAAAGAAGTTTGATTCCAGTCAT Reverse CATGGTAGCCACCCCCCATGT |
| GILZ     | Forward CCAGCGTGGTGCCATAGA Reverse CACGCTCTAGCTGGGAGTTC |
| PER1     | Forward CACTCTGCAGCCAGGGTAGA Reverse TAGGGGGCACACTCATGCTT |
| SGK1     | Forward ACTCTATGCATGCAAACACCC Reverse AGAAGGACTTGGGAGGAGAA |
| NR3C1    | Forward TGCCCTGTTGCTCTGATGA Reverse CACATAGGTAATTGTGCTGCTT |
| NR3C2    | Forward GGGCAAAGGTACTTCCAGGATT Reverse GTGCATCCCCTGGCATAGTT |
| JDP2     | Forward PROPRIETARY (Qiagen) Reverse |
| SUPV3L1  | Forward TGTGCCATGTGACTTGGTGA Reverse CACATGGTAATTGTGCTGCTT |
| NOS1AP   | Forward ACATGCTCCAGCACATCTCC Reverse GAGCCCATGGCAGTGTCTT |
| MTA2     | Forward GCACCTCTGCAAAGAAAAGCTG Reverse CGGCACGGTCAGGGTTGTA |
Figure 1. *The effect of aldosterone, cortisol and dexamethasone on MR activity in vitro.*

149x90mm (600 x 600 DPI)
Figure 2

A

B

C

D

GR

MR

% Green positive nuclei

% Red positive nuclei

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Figure 3
Figure 4. **Expression of glucocorticoid target genes in human hippocampal tissue.**

198x87mm (300 x 300 DPI)