Glucocorticoid receptor regulates accurate chromosome segregation and is associated with malignancy

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The glucocorticoid receptor (GR) is a member of the nuclear receptor superfamily, which controls programs regulating cell proliferation, differentiation, and apoptosis. We have identified an unexpected role for GR in mitosis. We discovered that specifically modified GR species accumulate at the mitotic spindle during mitosis in a distribution that overlaps with Aurora kinases. We found that Aurora A was required to mediate mitosis-driven GR phosphorylation, but not recruitment of GR to the spindle. GR was necessary for mitotic progression, with increased time to complete mitosis, frequency of mitotic aberrations, and death in mitosis observed following GR knockdown. Complementation studies revealed an essential role for the GR ligand-binding domain, but no clear requirement for ligand binding in regulating chromosome segregation. The GR N-terminal domain, and specifically phosphosites S203 and S211, were not required. Reduced GR expression results in a cell cycle phenotype, with isolated cells from mouse and human subjects showing changes in chromosome content over prolonged passage. Furthermore, GR haploinsufficient mice have an increased incidence of tumor formation, and, strikingly, these tumors are further depleted for GR, implying additional GR loss as a consequence of cell transformation. We identified reduced GR expression in a panel of human liver, lung, prostate, colon, and breast cancers. We therefore reveal an unexpected role for the GR in promoting accurate chromosome segregation during mitosis, which is causally linked to tumorigenesis, making GR an authentic tumor suppressor gene.

Glucocorticoids (GCs) act through the glucocorticoid receptor (GR), a member of the nuclear hormone receptor superfamily, and a ligand-activated transcription factor (1–4). The GR is ubiquitously expressed and regulates energy metabolism, immunity, and cell fate decisions. The quiescent GR resides in the cytoplasm in a complex with heat shock proteins and immunophenolins, attached to the microtubule architecture of the cell in a heat shock protein-dependent manner (5). Ligand binding drives GR transformation, involving N-terminal phosphorylation on S203 and S211 and rapid translocation to the nucleus requiring attachment to dynein by heat shock protein 90, immunopholins, and dynamitin (6). Once in the nucleus, GR binds directly to DNA to regulate transcription, or tetters to other DNA-bound transcription factors, such as nuclear factor kappa-light-chain-enhancer of activated B cells (NF-κB) and activator protein 1 (AP1), to regulate their function (7–10).

In mitosis, GR is phosphorylated on both S203 and S211, but in a ligand-independent manner (11, 12). Although altered GR function in mitosis has been shown (11, 13, 14), the kinases responsible and cellular consequences have not been defined. The role of GR in cancer has received little attention beyond acute lymphoblastic leukemia, in which GR is powerfully proapoptotic (15). However, GR inhibits expression of cyclin D and augments expression of cyclin-dependent protein kinase inhibitors p21 and p27 to effect cell cycle slowing or arrest in a cell type-specific manner (16).

We now define a role for GR in regulating mitosis using, at least in part, nontranscriptional mechanisms. Loss of GR results in a robust mitotic phenotype, with aberrant chromosome segregation, accumulation of chromosome complement defects, and death in mitosis, with the extent of cell survival or death varying by cell type and model. Moreover, GR haploinsufficient mice develop tumors with age. Analysis of common human cancers revealed frequent cell type-specific loss of GR expression, implying an important causal relationship between GR and malignant transformation or progression.

Results

We profiled the GR interactome (1,696 proteins) using immune enrichment and MS methods, and compared the list of GR interacting proteins with the mitotic spindle proteome (17).

Significance

We have discovered a role for the glucocorticoid receptor (GR) in coordinating cell division. We find enrichment of GR to mitotic spindles and demonstrate that GR knockdown causes accumulation of mitotic defects, including delayed anaphase, ternary chromosome segregation, and death in mitosis. Mitotic GR function requires the ligand-binding domain but not ligand binding, revealing a nontranscriptional and ligand-independent mechanism of action. Analysis of GR haploinsufficient cells and tissues reveals increased aneuploidy and DNA damage, and mice show an increased incidence of tumors in vivo, with further GR loss within those incident tumors. We also identify reduced GR expression in several common human cancers, thereby implicating GR as a novel tumor suppressor gene.
approach identified GR binding to complexes involving 478 of the 795 known protein components of the mitotic spindle (Fig. 1A and SI Appendix, Fig. S1), including both CENP-E and BUB3, which are required for spindle checkpoint function (18, 19). Analysis of purified mitotic spindle fractions by immunoblotting using specific phospho-GR- and pan-GR antibodies revealed 5S203 and 5S211 modified GR species (Fig. 1B). The presence of multiple GR protein species on immunoblots is frequently seen, and may result from alternate protein isoforms or posttranslational modification. Phosphatase treatment did not result in loss of the additional bands, indicating that the mobility shift is not due to differential phosphorylation (SI Appendix, Fig. S2).

Immunofluorescence analysis confirmed GR localization to the mitotic spindle, with particular enrichment at the centrosomes in metaphase and anaphase cells (Fig. 1C and SI Appendix, Fig. S3). The mitotic distribution of GR to the spindle was also demonstrated using another antibody raised against a different GR epitope (SI Appendix, Fig. S4), was sensitive to knockdown with GR-specific siRNA (SI Appendix, Fig. S5), and was also seen using an epitope-tagged (HaloTag) GR (Fig. 1D and E). Analysis of Halo-GR-transfected cells showed a heterogeneous subcellular GR localization in asynchronous fixed cells, which visualized both soluble and cytoskeletal-bound GR (total GR fraction; SI Appendix, Fig. S6A). A predominantly nuclear distribution was seen in permeabilized and washed-out cells following depletion of the soluble fraction (SI Appendix, Fig. S6A). The mitosis-specific distribution of Halo-GR was similar to that seen for endogenous GR (Fig. 1E and SI Appendix, Fig. S6B), reinforcing the specificity of GR recruitment to the mitotic spindle.

Previously, analysis revealed distinct subcellular distributions for 5S203GR and 5S211GR (20), and because both are enriched in mitosis, we tracked both phosphospecies through mitosis. We find 5S203GR at the centrosomes, showing an overlapping distribution with the centrosome marker γ-tubulin (21) throughout mitosis (SI Appendix, Fig. S7). 5S211GR also showed clear foci at the centrosomes, with additional signal overlapping with CREST-marked kinetochores (22) (SI Appendix, Fig. S8). To control for antibody specificity, we used multiple siRNA species, which confirmed localization of total GR, and both 5S203GR and 5S211GR at the centrosome (SI Appendix, Figs. S5B, S7B, and S8B). Although GR is known to interact with the kinetochore protein Ski2 (23, 24), the distribution of 5S211GR overlaying the condensed chromosomes and kinetochores was not consistently lost with both GR siRNAs (SI Appendix, Figs. S8B and S9), suggesting that this immunoreactivity may be due to cross-reaction with another phosphorylated protein. Aligned surface plots of the three GR antibodies suggest robust enrichment of total GR and both GR phosphoforms to centrosomes (SI Appendix, Fig. S9).

The distribution of GR therefore overlapped with components of the microtubule organizing center, which is a site of Aurora kinase activity. The distribution of phospho-GR (both 5S203GR and 5S211GR) on the centrosome overlaps with Aurora A (SI Appendix, Fig. S10A). Therefore, we tested Aurora kinase inhibition, initially with tozasertib (which inhibits both Aurora A and Aurora B with a similar IC₅₀). Tazosertib virtually abolished mitotic GR phosphorylation on both S203 and S211 (SI Appendix, Fig. S10B).

Immunofluorescence of tozasertib-treated cells demonstrates that reduced 5S203GR and 5S211GR is not a consequence of mitotic exit but that mitotic cells (highlighted with asterisks in SI Appendix, Fig. S10C) are no longer enriched for GR phosphorylation relative to somatic interphase cells. Inhibition of Aurora kinases disrupted normal spindle formation but did not prevent association of the GR with α-tubulin foci (SI Appendix, Fig. S10D), suggesting that phosphorylation of GR occurs subsequent to spindle targeting. If phosphorylation of GR at S203 and S211 occurred subsequent to spindle recruitment, then selective inhibition of Aurora A, but not Aurora B, would be predicted to abolish this modification because GR and Aurora A colocalize on the centrosome, and this effect was clearly seen (SI Appendix, Fig. S10E).

Identification of modified GR species at the mitotic spindle and regulation of GR modification downstream of Aurora A suggest a possible role for GR in mitosis. We next investigated whether knockdown of GR expression could affect chromosome segregation during mitosis in live cells using the expression of H2B-GFP as a chromosome marker. GR knockdown delayed the mean time from nuclear envelope breakdown to anaphase onset (from 76 to 102 min; Fig. 2A, SI Appendix, Fig. S11, and Movies S1–S4). The delay in completion of mitosis appeared to be due to defective chromosomal alignment/segregation because there was also a significant increase in abnormal anaphase cells and death in mitosis (Fig. 2B). Analysis of a cross-sectional population of targeted cells suggested that loss of GR expression resulted in a significant accumulation of cells in metaphase (Fig. 2C), further supporting a role for GR in facilitating metaphase/anaphase transition.

We also find increased numbers of cells with disorganized or multipolar spindles (Fig. 2D and SI Appendix, Fig. S11C) and micronuclei in interphase cells (Fig. 2E). These aberrant events were rescued by “adding back” siRNA-resistant GR (Fig. 2D and E), confirming the specificity of effect.

To inform the mechanism underlying GR rescue of mitotic progression, a series of complementation studies were performed. We engineered domain deletant, phosphodeficient, and transcriptionally impaired GR constructs (Fig. 3A and SI Appendix, Fig. S12) and transfected them into a HeLa Flp-In TReX host cell line to generate a panel of eight stable cell lines with doxycycline-regulated GR expression. We used a GR siRNA that targeted the 3’ UTR to down-regulate endogenous GR selectively (siRNA11; SI Appendix, Fig. S5B–D) and then rescued GR expression by the addition of doxycycline (Fig. 3B). We again saw a cell cycle phenotype following GR knockdown, further supporting the observations above (Fig. 3C).

GR lacking either the N-terminal sites or phosphosites (ΔAF1GR, S203AGR, and S211AGR) was still efficient at rescuing the cell cycle phenotype (Fig. 3D). Although overexpression of transcriptionally impaired and DNA-binding domain deletant GR (R477C and ΔDBDGR) provided significant rescue, it was...
noted that the efficiency of rescue of ΔDBDGR was less than full-length GR (Fig. 3D).

Fig. 2. Reduction of GR expression delays anaphase transition and increases the frequency of chromosomal abnormalities. HeLa cells stably expressing H2B-GFP were transfected with 50 nM nontargeting (NT) or GR-specific (GR6) siRNA, and mitotic events were imaged in real time (values depict minutes from an arbitrary start point (t0)). Representative fields are shown. (A) Images were scored for average time to completion of mitosis, frequency of abnormal mitotic events, and death in mitosis. (B) Ten fields were tracked per replicate. Graphs show mean ± SEM from four independent duplicate experiments. Movies S1–S6 are provided as supplementary information. NER, nuclear envelope breakdown. (C–E) HeLa cells were treated with 50 nM NT or two different GR-specific (GR5 and GR6) siRNAs, together with siRNA-resistant GR plasmid (pcDNA3GR) or empty vector control (pcDNA3) for 48 h, and then fixed and labeled with an α-tubulin-specific antibody and Hoechst DNA dye counterstain. Cells were imaged and scored for mitotic phase (C) and for evidence of mitotic abnormalities, including spindle deformities (D) and interphase micronuclei (E, yellow arrowhead). Graphs depict mean ± SEM of at least three independent triplicate experiments. Data were analyzed by the Mann-Whitney test or ANOVA, where *P < 0.05. (Scale bars: 10 μm.)

To explore this cell cycle phenotype in vivo, we first analyzed mouse embryonic fibroblasts derived from GR-deficient (GR<sup>−/−</sup>) mice, which are not viable due to perinatal mortality. Initial analysis of DNA content by fluorescence-activated cell sorting identified no evidence of aneuploidy (>4n) in low-passage cells, but chromosome counts demonstrated a trend toward chromosomal aberrations in GR-null cells (29% vs. 22% of cells with a normal chromosome complement in GR<sup>+/+</sup> and GR<sup>−/−</sup> cells, respectively; *P = 0.055). However, GR-null cells showed clear protection from aneuploidy at high passage (Fig. 4A). This complex phenotype may result from GR loss driving cells to death in mitosis, as seen above with acute GR knockdown.

We also investigated mild genotoxic challenge, BrdU treatment, in GR<sup>−/−</sup> mice (Fig. 4B). Accumulation of dsDNA breaks is a consequence of aberrant chromosome segregation (25) and offers a robust and enduring “mark” of such anomalies. We analyzed livers from BrdU-infused GR<sup>−/−</sup> and GR<sup>+/−</sup> mice and found evidence of more dsDNA breaks (γ-H2AX staining) in BrdU-treated GR<sup>−/−</sup> animals compared with the GR<sup>+/−</sup> animals (26). We also analyzed aged GR<sup>−/−</sup> mice (100 wk of age) and found an increased incidence of dsDNA breaks in both the liver and colon (Fig. 4C). In liver, DNA damage was identifiable throughout the tissue, whereas in colon, it appeared to be confined to the epithelial cell layer, which is consistent with sites of the highest GR expression in healthy tissue (SI Appendix, Fig. S14).

In our analysis of tissue from aged GR haploinsufficient mice, we found an increase in microtumors in the GR-deficient livers (Fig. 4D) and lungs (Fig. 4E) compared with WT. No differences in premature mortality within the colony were noted, supporting a requirement for additional accumulated genomic damage over time for malignant transformation. We observed that the tumors were further depleted for GR expression compared with surrounding tissue, providing strong evidence linking GR expression with tumorigenesis in vivo (Fig. 4 D and E).

Our data suggest that loss of GR expression may contribute to tumorigenesis by impairing accurate chromosome segregation.
is tissue-specific, with no significant difference in GR expression seen in human bone or gastric cancers (SI Appendix, Fig. S17A) and a significant up-regulation of GR transcript seen in pancreatic and renal cancers (SI Appendix, Fig. S17B), along with increased GR protein (SI Appendix, Fig. S17C).

Even within a single tissue, different tumor subtypes showed variation in GR expression, indicating a major cell type-specific effect (SI Appendix, Fig. S18). There were no sex-related differences in GR expression (SI Appendix, Fig. S19A) and no correlation between GR and estrogen receptor (ERα) expression across all breast cancer subtypes or with androgen receptor (AR) expression in prostate cancer (SI Appendix, Fig. S19B).

Discussion
The GR plays a key role in energy metabolism, immunity, and cell fate determination. Now, our data identify a role in mitotic progression and chromosome segregation. The distribution of GR through metaphase and anaphase overlaps with the spindle centrosome, which plays a major role in coordinating accurate chromosome segregation (28–32). Moreover, under conditions not permissive for GR transcriptional effects, there was a clear biological role, implying a nontranscriptional mechanism of action. Mitosis is a dynamic process, controlled by the activity of multiple kinases, with attendant modification of proteins facilitating strict checkpoint control. Aurora kinases are master regulators of both centrosome and checkpoint control function. Aurora A is found at centrosomes in early mitosis and controls centrosome maturation, centriole separation, and chromosome alignment (33), whereas accurate targeting of Aurora B to the centrosomes,
and then to the spindle midzone and midbody, is essential for maintaining microtubule/kinetochore attachments, and therefore faithful chromosomal segregation (34). We find that GR is multiply phosphorylated in an Aurora A kinase-dependent manner. GR phosphorylation by an Aurora kinase-dependent pathway provides the mechanism explaining the tight coupling of ligand-independent GR phosphorylation to cell cycle phase because the maximal activity of these kinases occurs in mitosis.

To examine the functional role of GR during mitosis, we performed GR knockdown studies, tracking cell division in real time, and observed increased chromosome segregation errors with evidence of spindle defects. Multipolar spindles can arise as a consequence of failure of cytokinesis, centrosome amplification, or loss of spindle pole integrity (35). Although we find tetraploid cells following GR loss (Movie S3), our data suggest that the majority of GR knockdown cells either progress through mitosis with errors or die in mitosis. GR localizes to centrosomes in both interphase and mitotic cells (36), making a possible role for GR in controlling centrosome number in S-phase. However, multipolarity occurs after normal bipolarization of the spindle (Movies S4–S6), suggesting normal centrosome number at the onset of mitosis. Loss of GR drives a significant delay in metaphase, followed by the acquisition of tripolar or tetrapolar spindles, identifying loss of spindle pole integrity as a possible consequence of reduced GR expression. Although it remains unclear how the aberrant mitotic phenotype occurs, a model for the generation of multipolar spindles independent of centrosome amplification has recently been advanced, which lists likely causes as cohesion fatigue, fragmentation of pericentriolar material, or centriole disengagement (35).

However, it arises, the spindle defects we observe following loss of GR, including chromosome misalignment and multipolarity, drive chromosomal instability, causing either death in mitosis or completion of mitosis and survival as an aneuploid cell. GR may act at multiple stages to influence both mitosis and the response to aneuploidy. Other tumor suppressors, including p53, serve multiple roles to prevent mitotic errors in the first instance, to correct such errors, or to promote apoptosis. The impact of reduced GR expression may therefore be twofold: increasing the frequency of mitotic segregation errors and failing to induce apoptosis, thereby permitting cells to survive with an abnormal chromosome complement.

We sought a mechanism explaining GR regulation of mitosis using complementation. Our studies revealed that the GR ligand-binding domain was required for protection from mitotic defects, and that other major domains, including the DNA-binding domain and N-terminal domain, were dispensable. The DNA-binding domain is predicted to be required for gene regulation and supports a nontranscriptional role for the GR in mitosis. The N-terminal domain contains both S203 and S211, which are phosphorylation targets downstream of Aurora A kinase. However, loss of the entire domain or point mutation to the Ser residues did not affect rescue. Furthermore, immunofluorescence data show that GR localization to the spindle occurs before phosphorylation. Taken together, our data suggest that phosphorylation at S203 and S211 by Aurora A at the spindle is not required for the regulation of mitosis.

To test the role of target gene transcription in GR mediation of mitosis further, we examined a broad panel of known GR target genes, some involved in mitotic progression. Of the 15 genes studied, only one showed a small, but significant, change in response to loss of GR, under the same culture conditions used for the rescue experiments, suggesting that the GR is only minimally transcriptionally competent. To test the requirement for transcriptionally competent GR, we used a ligand-binding domain point mutant, which renders the GR severely resistant to endogenous ligands, such as those ligands found in serum or in cultured human cells. This GRC736S mutant also efficiently rescued the cell cycle phenotype, further suggesting only a minimal role for conventional GR transcription in this pathway.

A late consequence of such aberrant mitosis, in the event that death in mitosis is avoided, is survival of aneuploid cells with accumulation of DNA damage (37). We identified a complex cell cycle phenotype resulting from loss of GR expression. We found spontaneous DNA damage/aneuploidy in aged GR haploinsufficient animal tissues and in cells harvested from people with GR haploinsufficiency. In addition, we identified that in GR-null MEFs subject to prolonged passage, or in GR haploinsufficiency in response to genotoxic challenge, there was an apparently paradoxical protection from accumulation of DNA damage, an effect we ascribe to increased death in mitosis. Indeed, a similar phenotype of DNA damage response was reported in CENP-E haploinsufficient mice. Loss of CENP-E drives loss of only a few chromosomes, which permits cells to persist in an aneuploid state; however, with additional stress, such as a genotoxic challenge, cells accumulate more damage and are driven to apoptosis, thereby paradoxically protecting from aneuploidy. In this way, loss of CENP-E increases the incidence of lymphoma and spontaneous lung tumors but provides protection against chemical tumorigenesis (38).

We find significantly more tumors in mice that are haploinsufficient for GR, and therefore propose that loss of GR may be a cause, and not simply a consequence, of cellular transformation. Indeed, it is striking that there is marked further loss of GR protein detected within the tumors, further supporting a tumor suppressor role for the GR. The role of GR in cancer has received some attention, but, to date, no clear phenotype has emerged. GC use, and therefore activation of GR, has been linked with an increased risk of developing skin and bladder cancer (37, 39). However, none of the small number of patients with GR genetic defects and familial GC resistance has developed cancer. We now provide evidence for GR in human malignancy, with a strong negative association in GR expression seen across a broad panel of, but not all, human cancers.

We have previously shown reduced GR expression in small-cell lung cancer (40–42), a methylated cancer, as well as in the breast and in prostate cancer (43). Recent evidence for a critical role in cell fate determination (48). Our findings reveal an important role for GR in regulating mitotic progression, aneuploidy, and tumorigenesis. Our findings show that GR function regulates accurate mitotic progression, with clear implications for human health. Gcs are often used in combination with cancer therapies, largely due to their antiinflammatory and antiangiogenic properties (47). Such Gc treatment activates GR and may induce cell cycle arrest through a transcriptional mechanism or apoptosis in a cell type-dependent manner. Gcs have also been reported to oppose chemotherapy induction of apoptosis in a tissue-specific manner, providing further evidence for a critical role in cell fate determination (48). Our findings now add a previously unidentified perspective to GR action in cell division, serving the mitotic spindle function. Given the key role of the ligand-binding domain in mediating the cell cycle effect, it may be that this action can be targeted by specific ligands, potentially opening up new therapeutic approaches to treat common cancers.

### Materials and Methods

Detailed information describing antibodies, plasmids, cell lines, and animal procedures used in this study is provided in SI Appendix. Immunoblot analysis and reporter gene assays were performed as described by Matthews et al. (11). Purification of mitotic spindle fractions was as described by Sauer et al. (17), real-time fluorescent cell imaging was performed as described by Treble et al. (49), and quantitative PCR analysis was as described by Poomlan et al. (50). Additional methods for immunofluorescence, GR proteomics, immunohistochemistry, and gene arrays are provided in SI Appendix.