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Basic Study

GRK5 is an essential co-repressor of the cardiac mineralocorticoid receptor and is selectively induced by finerenone

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Abstract

BACKGROUND

In the heart, aldosterone (Aldo) binds the mineralocorticoid receptor (MR) to exert damaging, adverse remodeling-promoting effects. We recently showed that G protein-coupled receptor (GPCR)-kinase (GRK)-5 blocks the cardiac MR by directly phosphorylating it, thereby repressing its transcriptional activity. MR antagonist (MRA) drugs block the cardiac MR reducing morbidity and mortality of advanced human heart failure. Non-steroidal MRAs, such as finerenone, may provide better cardio-protection against Aldo than classic, steroidal MRAs, like spironolactone and eplerenone.

AIM

To investigate potential differences between finerenone and eplerenone at engaging GRK5-dependent cardiac MR phosphorylation and subsequent blockade.

METHODS

We used H9c2 cardiomyocytes, which endogenously express the MR and GRK5.

RESULTS

GRK5 phosphorylates the MR in H9c2 cardiomyocytes in response to finerenone but not to eplerenone. Unlike eplerenone, finerenone alone potently and efficiently suppresses cardiac MR transcriptional activity, thus displaying inverse agonism. GRK5 is necessary for finerenone`s inverse agonism, since GRK5 genetic deletion renders finerenone incapable of blocking cardiac MR transcriptional activity. Eplerenone alone does not fully suppress cardiac MR basal activity regardless of GRK5 expression levels. Finally, GRK5 is necessary for the anti-apoptotic, anti-oxidative, and anti-fibrotic effects of both finerenone and eplerenone against Aldo, as well as for the higher efficacy and potency of finerenone at blocking Aldo-induced apoptosis, oxidative stress, and fibrosis.

CONCLUSION

Finerenone, but not eplerenone, induces GRK5-dependent cardiac MR inhibition, which underlies, at least in part, its higher potency and efficacy, compared to eplerenone, as an MRA in the heart. GRK5 acts as a co-repressor of the cardiac MR and is essential for efficient MR antagonism in the myocardium

Key Words: aldosterone; cardiac myocyte; finerenone; G protein-coupled receptor kinase (GRK)-5; mineralocorticoid receptor antagonist (MRA); signal transduction.

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Core Tip: G protein-coupled receptor (GPCR)-kinase (GRK)-5 blocks the cardiac actions of aldosterone *via* phosphorylation of the mineralocorticoid receptor (MR). We show here that the non-steroidal MR antagonist (MRA) finerenone may provide better cardio-protection against aldosterone than classic, steroidal MRAs, like eplerenone, thanks to induction of GRK5`s phosphorylation and subsequent blockade of cardiac MR. GRK5 is

necessary for the anti-apoptotic, anti-oxidative, and anti-fibrotic effects of both finerenone and eplerenone against aldosterone but also for the higher efficacy/potency of the former drug at producing all these effects in cardiomyocytes. Thus, GRK5 acts as a co-repressor of the cardiac MR and is essential for efficient MR antagonism in the myocardium.

INTRODUCTION

Aldosterone (Aldo) is one of several cardio-toxic hormones, whose elevated circulating levels significantly confound and aggravate heart disease, including hypertension and chronic heart failure (CHF).[1-4] The mineralocorticoid receptor (MR), a cytosolic transcription factor that, upon activation, translocates to the nucleus to activate gene transcription, is the main receptor mediating Aldo`s adverse remodeling effects in the failing heart. [1-5] GRK2 and GRK5 are the most abundant cardiac G protein-coupled receptor (GPCR)-kinase (GRK) isoforms. Both phosphorylate GPCRs but also non-GPCR substrates.[6-10] We recently showed that GRK5 blocks the cardio-toxic MR-dependent effects of aldosterone in the heart by directly phosphorylating the cardiac MR and inhibiting its transcriptional activity.[11]

MR antagonist (MRA) drugs are beneficial in human advanced CHF thanks to their blockade of the MR in various cardiovascular tissues, including in cardiomyocytes and cardiac fibroblasts. [3,12] Novel, non-steroidal MRAs, such as finerenone, may provide better cardio-protection against aldosterone`s cardio-toxic actions than the classic steroidal MRAs, such as sprironolactone and eplerenone.[13,14] Indeed, finerenone was recently shown to be a more potent and efficacious inverse agonist at the MR, compared to eplerenone, in terms of cardiac fibrosis/adverse remodeling attenuation.[15] This prompted us to investigate the effects of these two MRAs on GRK5-dependent cardiac MR phosphorylation and subsequent suppression, in an effort to delineate potential molecular mechanisms underlying their differences in cardiac MR blocking efficacy. Indeed, we found that finerenone, but not eplerenone, promotes the inhibitory action of GRK5 on cardiac MR, which may underlie finerenone`s significantly greater

efficacy/potency as an inverse agonist at this receptor. Moreover, GRK5 is necessary for both MRA drugs` cardioprotective actions against Aldo in cardiac myocytes.

MATERIALS AND METHODS

All methods were carried out in accordance with the **relevant guidelines and regulations.**

Materials. All drugs/chemicals were from Sigma-Aldrich (St. Louis, MO, USA), except for finerenone (BAY94-8862) which was purchased from MedKoo Biosciences, Inc. (Cat. #319698, Morrisville, NC, USA).

Cell Culture, Viruses, and Transfections. The H9c2 rat cardiomyoblast cell line was purchased from American Type Culture Collection (Manassas, VA, USA) and cultured as previously described.[11,16,17,18] Recombinant lentiviruses encoding for wild-type full-length GRK5 or for empty vector (control) (OriGene Technologies, Rockville, MD, USA) were propagated and purified *via* CsCl density gradient ultracentrifugation, as described previously.[11,19] For CRISPR/Cas9-mediated GRK5 gene deletion, a gRNA sequence was custom-synthesized by Sigma-Aldrich (target ID: RN0000391809, target sequence: 5′-GTGGTTTGAATTTATGCGG-3′) and incorporated into a lentiviral vector (Sigma-Aldrich). Along with negative control CRISPR lentiviral particles (CNCV, Cat #CRISPR12V-1EA, Sigma-Aldrich), this lentivirus was also propagated and purified through cesium chloride density gradient ultracentrifugation.

Immunoprecipitation (IP)/Western Blotting. Cell extracts were prepared, as described previously,[11,20] in a 20-mM Tris pH 7.4 buffer containing 137 mmol/L NaCl, 1% Nonidet P-40, 20% glycerol, 10 mmol/L phenylmethylsulfonylfluoride (PMSF), 1 mmol/L Na_3VO_4, 10 mmol/L NaF, 2.5 µg/mL aprotinin, and 2.5 µg/mL leupeptin. Protein concentration was determined (Pierce BCA Protein Assay Kit, Thermo Scientific, Waltham, MA, USA), and equal amounts of protein per sample were used for IP or western blotting. MR was immunoprecipitated by overnight incubation of extracts with an anti-MR antibody (#ab62532; Abcam, Cambridge, MA, USA), attached to Protein A/G-Sepharose beads (Sigma-Aldrich). The IPs were then subjected to

immunoblotting for GRK5 (#sc-565; Santa Cruz Biotechnology, Santa Cruz, CA, USA) or for phosphoserine (#AB1603; Millipore-Sigma, Burlington, MA, USA) to measure the pSer content of the immunoprecipitated MR. Finally, an anti-glyceraldehyde 3-phosphate dehydrogenase (GAPDH) antibody (#sc-25778; Santa Cruz Biotechnology) was used to control for protein loading. All immunoblots were revealed by enhanced chemiluminescence (ECL, Life Technologies, Grand Island, NY, USA) and visualized in the FluorChem E Digital Darkroom (Protein Simple, San Jose, CA, USA), as described previously.[21]

Luciferase Reporter Activity Assay. Luciferase reporter activity assay was performed, as described previously, by transfecting the cells with the LightSwitch™ luciferase reporter gene vector under the influence of the MR promoter (Active Motif, Inc., Carlsbad, CA, USA).[11] The measurements were done the next day with the manufacturer's assay kit and according to the manufacturer`s instructions.

TUNEL. Terminal deoxynucleotidyl transferase-mediated dUTP nick-end labeling (TUNEL) assay to measure apoptotic cell death was done as described.[22] Briefly, cells were fixed with 10% neutral buffered formalin, embedded in paraffin, and sectioned at 5-µm thickness. DNA fragmentation was detected in situ in deparaffinized sections using the ApopTag peroxidase in situ apoptosis detection Kit (Millipore-Sigma) and according to the manufacturer's instructions. The total number of nuclei was determined by manual counting of 4`,6`-diamidino-2-phenylindole (DAPI)-stained nuclei in six random fields per section. All terminal deoxynucleotidyl transferase-mediated dUTP nick end-labeling (TUNEL)-positive nuclei were counted in each section.

Real-Time PCR. Real-time PCR for rat plasminogen activator inhibitor (PAI)-1 and rat fibronectin mRNA levels in total RNA isolated from cells was done as described previously.[16] Briefly, quantitative real-time PCR was performed using a MyIQ Single-Color Real-Time PCR detection system (Bio-Rad Laboratories, Hercules, CA, USA) using SYBR Green Supermix (Bio-Rad) and 100 nM of gene-specific oligonucleotides. Quantification of mRNA included normalization to 18s rRNA levels. No bands were

seen in control reactions in the absence of reverse transcriptase. Primer pairs used were: 5′-TTCCTCCACAGCCATTCTAGTCT-3′ and 5′-GAAAGGATCGGTCTAAAACCATCTC-3′ for PAI-1; 5`-CGAGGTGACAGAGACCACAA-3` and 5`-CTGGAGTCAAGCCAGACACA-3` for fibronectin; and 5`-TCGATGCTCTTAGCTGAGTG-3` and 5`-TGATCGTCTTCGAACCTCC-3` for 18S rRNA.

Oxidative stress assay. To determine reactive oxygen species (ROS) production, the 2′,7′-dichlorofluorescein diacetate (DCFDA) dye-based assay kit from Molecular Probes (Cat. #C13293; Eugene, OR, USA) was used and the measurements were done according to manufacturer's instructions and as previously described.[11] Briefly, cell extracts were incubated with 2 μM DCFDA for 20 min and ROS production was monitored by determining the fluorescence intensity using a fluorescent plate reader in which excitation and emission wavelengths were set at 495 and 520 nm, respectively. The fluorescence OD values obtained were normalized with protein determination and expressed as % of the values obtained upon 100 nM Aldo treatment (1 mM DMSO was used as vehicle treatment).

Statistical Analyses. Student's t test and one- or two-way ANOVA with Bonferroni test were used for statistical comparisons, unless otherwise indicated. For multiple group analyses, Dunnett's test with SAS version 9 software (Cary, NC, USA) was also used. A p value of <0.05 indicated statistical significance.

RESULTS

Finerenone, but not eplerenone, induces GRK5-dependent cardiac MR phosphorylation. We recently reported that GRK5 selectively phosphorylates and inhibits the cardiac MR.[11] Based also on recent evidence suggesting greater potency for finerenone, compared to eplerenone, at inhibiting the cardiac MR and its downstream fibrosis,[15] we hypothesized, in the present study, that the higher efficacy/potency of finerenone over eplerenone might be due (at least in part) to differences in modulation of the GRK5 inhibitory action on the cardiac MR. Thus, in a first series of experiments,

we overexpressed or knocked out (via CRISPR) GRK5 in H9c2 cardiac myocytes (Figure 1A), which endogenously express both GRK5 and MR,[11,23] and checked for the effects of the two MRA drugs on MR serine phosphorylation. GRK5, being a Ser/Thr kinase, likely phosphorylates multiple Ser and Thr residues of the MR protein, with phosphorylations of Ser601 and Ser843 (in the human orthologue sequence), in particular, resulting in significant functional inhibition of the MR, courtesy of cytosolic retention and transcriptional activity suppression, respectively.[24,25] After preliminary concentration-response experiments (not shown), and based on the associated literature, we chose a 10 mmol/L concentration for both drugs throughout the experiments of our study, as this concentration (10 mmol/L) is quite close to both drugs` effective IC_{50} values.[12,15] As shown in Figures 1B & 1C, finerenone led to much higher phosphorylation (pSer content) of the MR than eplerenone did in control H9c2 cardiomyocytes (mock virus-EV lanes). This finerenone-induced MR phosphorylation was significantly enhanced upon GRK5 overexpression but essentially abrogated in GRK5-depleted H9c2 cardiomyocytes (Figures 1B & 1C). Notably, eplerenone essentially failed to elicit any appreciable MR Ser phosphorylation in H9c2 cardiomyocytes (Figures 1B & 1C), irrespective of GRK5 expression levels [eplerenone-induced phosphorylation: 1.2±0.25-fold of vehicle in EV cells; 1.23±0.27-fold of vehicle in GRK5-OE cells; 0.6±0.55-fold of vehicle in GRK5-KO cells; i.e. non-significant vs. vehicle, in all three clones at $P = 0.05$ ($n = 3$); Figure 1C]. Although we cannot account for the potential of some extent of Thr phosphorylation of the MR induced by the two drugs, these results strongly suggest that only finerenone (not eplerenone) induces GRK5-mediated phosphorylation of the MR in H9c2 cardiac myocytes.

GRK5 is essential for finerenone`s inverse agonism at the cardiac MR. Since GRK5-induced phosphorylation translates into transcriptional repression of the cardiac MR,[11] we next examined the impact of the finerenone-induced, GRK5-mediated MR phosphorylation on the transcriptional activity of the receptor. In contrast with eplerenone, finerenone lacks agonist activity at the MR in control (CNCV) H9c2 cardiomyocytes, i.e. no increase in MR basal transcriptional activity (in the absence of

Aldo) is observed with finerenone (Figure 2). In the absence of GRK5 however, finerenone loses the ability to keep the MR transcriptionally inactive, i.e. the MR displays significant basal activity in GRK5-KO H9c2 cardiomyocytes (Figure 2). Upon GRK5 overexpression, this picture is reversed, i.e. finerenone acts as potent inverse agonist at the MR, markedly suppressing MR basal transcriptional activity in GRK5-overexpressing (GRK5-OE) cardiomyocytes (Figure 2). In contrast, eplerenone allows for substantial MR basal transcriptional activity, regardless of GRK5 expression levels (Figure 2). Taken together, these results indicate that GRK5 is essential for finerenone`s inverse agonism at the cardiac MR, while eplerenone is essentially a partial agonist (mixed agonist/antagonist) at this receptor in the heart, a finding consistent with the literature.[12,15] GRK5 is unable to affect eplerenone`s actions on the cardiac MR, probably because this MRA agent cannot induce the inhibitory phosphorylation of this receptor by GRK5 in cardiac myocytes (see above, Figure 1).

GRK5 is essential for MRA-dependent antagonism of Aldo-induced cardiac apoptosis and oxidative stress and underlies finerenone`s advantage over eplerenone toward these effects. Next, we compared the cardio-protective efficacies of the two MRA drugs against the deleterious actions of Aldo. Finerenone was much more effective than eplerenone at suppressing Aldo-induced apoptosis (Figure 3A) and oxidative stress (Figure 3B), in control myocytes. However, upon GRK5 genetic deletion, both MRAs failed completely to block these two cardiac adverse remodeling-promoting Aldo effects (Figures 3A & 3B). This strongly suggests that GRK5 is essential for the anti-apoptotic and anti-oxidative effects of MRAs against Aldo in the heart, as well as for the better cardioprotective efficacy of finerenone vs. eplerenone against Aldo.

GRK5 is essential for MRA-dependent anti-fibrotic effects in the heart and for finerenone`s advantage over eplerenone towards this effect. In addition to apoptosis and oxidative stress, we compared the two MRAs in terms of Aldo-induced fibrosis inhibition in cardiac myocytes. Assessment of Aldo-dependent mRNA induction of two major pro-fibrotic stimuli, PAI-1 and fibronectin, both of which are immediate/early

MR-responsive genes,[1,3,16] revealed that finerenone was more effective than eplerenone at suppressing both PAI-1 (Figure 4A) and fibronectin (Figure 4B) mRNA inductions by Aldo in control cells. Again however, neither drug was effective at all when GRK5 was absent (Figures 4A & 4B, compare with GRK5-KO bars). Thus, GRK5 is essential also for the anti-fibrotic effects of MRAs in cardiac myocytes.

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The MR has long been established as an important molecular culprit in heart disease progression,[1-5] including a recent study in transgenic mice showing that, unlike its closely related glucocorticoid receptor, the MR promotes cardiac dysfunction even in the absence of a cardiac insult or injury.[26] Indeed, the well-documented deleterious effects of the cardiac MR have provided the pharmacological basis for the use of MRA drugs in advanced stage human CHF and other heart diseases.[1-5,27,28] The MRA drug class, which began with the approval and marketing of spironolactone more than 60 years ago, now encompasses several agents, with some already in clinical use and some in clinical trials. The MRAs are broadly divided to traditional, steroidal MRAs, like spironolactone and eplerenone currently in clinical use, and later generation, non-steroidal agents. Among the latter is finerenone (formerly BAY 94-8862), a third generation, non-steroidal, dihydropyridine-derived MRA currently in phase III clinical trials.[3,12]

Despite being very potent and effective aldosterone antagonists with salutary effects in the heart and kidneys, the currently available steroidal MRAs are hampered by several limiting side effects, most prominent of which are hyperkalemia, renal function deterioration, and gynecomastia. These are generally thought to be due to their binding to other types of steroid receptors (e.g. estrogen receptor, glucocorticoid receptor, *etc.*) exactly because of their steroidal structure.[3,12,29] Thus, non-steroidal MRAs have been developed, currently headlined by finerenone. Finerenone has shown advantageous pharmacological and therapeutic profiles, compared to the steroidal MRAs. It has demonstrated improved therapeutic properties in heart failure animal models in head-to-head comparisons with eplerenone[12,15] and leads to bigger improvements in HFrEF (heart failure with reduced ejection fraction) confounded by diabetes or chronic kidney

disease.[12,14] In addition to its much higher selectivity for the MR over other steroid receptors, finerenone is also at least one log scale more potent at MR antagonism than eplerenone and spironolactone, both of which are competitive MR antagonists.[3] Furthermore, finerenone displays inverse agonist activity at the MR, whereas the steroidal MRAs are only partial MR antagonists.[3,12] This means that, depending on the activity status of the MR, spironolactone and eplerenone may actually promote the activity of the MR rather than inhibiting it.[12,14,15] In other words, eplerenone inhibits the MR when the receptor is activated by Aldo but it may actually promote the activity of the MR when bound alone to the receptor (in the absence of Aldo). Finerenone, thanks to the non-steroidal nature of its structure, appears to be devoid of any agonist activity at the MR and thus, has strong potential to provide better cardiovascular and renal outcomes, especially in diseases severely affected by hyperaldosteronism.

One of the most important parameters affecting the selectivity of a particular MRA for the MR *vs* other steroid receptors, as well as tissue specificity for MR antagonism (inhibition of the cardiac MR *vs* inhibition of the MR in other tissues), is the identity/identities of the receptor`s co-factors activated or repressed by the MRA agent, which ultimately affects the MRA drug`s potency & efficacy.[1,3,15,25] In other words, how good a particular MRA is at blocking the cardiac MR depends strongly on which co-activators of the MR the drug inhibits and/or which co-repressors of the MR it activates inside the cardiac myocyte.[3] Indeed, a recent study in mice reported much higher potency and inverse agonism of finerenone, relative to eplerenone, in terms of cardiac fibrosis suppression and suggested that the pharmacological difference between these two MRAs was probably due to differential cardiac MR co-factor regulation/engagement.[15] We recently uncovered that GRK5 is an important co-repressor of the cardiac MR, *via* its direct binding to, and phosphorylation of the MR that results in cytosolic retention of the phosphorylated receptor and thus, MR transcriptional repression.[11] Our present data strongly suggest that finerenone selectively activates this kinase in cardiac myocytes to potently inhibit/repress the

cardiac MR. In contrast, eplerenone is incapable of this action (GRK5 activation) and thus, is a much weaker MR antagonist in the myocardium.

There are a few very important questions emanating from our present work that await delineation in future studies. First, does finerenone activate GRK5 to suppress MR activity only in the heart or in other tissues, as well (e.g., kidneys)? Another critical question is whether this property is shared by other non-steroidal MRAs or it is specific to finerenone. Finally, there is also the obvious mechanistic question of how exactly finerenone, not known to be a GPCR agonist, induces GRK5, normally activated by a GPCR, such as the b_2-adrenergic receptor (Figure 5),[8,11] to phosphorylate and inhibit the MR in the cytosol of a cardiac myocyte. Nevertheless, these salient questions will be the focus of our future investigations, along with our already ongoing efforts to map the specific phosphorylation sites of GRK5 on the human MR protein and to characterize the functional impact for the receptor of each one of them.

In summary, our present study reinforces the emerging and therapeutically very intriguing notion that GRK5, acting as a cardiac MR co-repressor in this instance, may actually be beneficial in the myocardium,[11,31-33] contrary to its counterpart GRK2 that is generally considered deleterious in the heart.[7,10] Importantly, we have identified GRK5 as a potential co-factor of the cardiac MR that is differentially regulated by finerenone and eplerenone, which may underlie the higher potency/efficacy (and inverse agonism) of finerenone at the MR. To our knowledge, cardiac GRK5 is the first such MR co-factor to be shown as differentially modulated/stimulated among different individual MRA drugs. Finally, from the therapeutic standpoint, we provide evidence that GRK5 is indispensable for MRAs` cardioprotective actions against Aldo (e.g. anti-apoptosis, anti-oxidant action, anti-fibrosis) and, importantly, this applies to both steroidal (eplerenone) and non-steroidal (finerenone) MRA agents alike.

DISCUSSION

In the present study, we report that finerenone is a more potent and efficacious cardiac MR blocker than eplerenone, thanks, at least in part, to stimulation of GRK5-dependent

cardiac MR phosphorylation, which eplerenone is incapable of inducing (Figure 5). This non-canonical effect of GRK5 on the cardiac MR is essential for efficient blockade of Aldo`s deleterious actions in the heart, such as apoptosis, oxidative stress, fibrosis, and probably other adverse remodeling-associated effects (Figure 5). Therefore, GRK5-dependent inhibitory phosphorylation is a key molecular mechanism for cardiac MR inverse agonism and needs to be considered in the design & development of novel, more effective MRA drugs for heart disease (e.g. CHF, hypertension, renal insufficiency, *etc.*) treatment.

CONCLUSION

Cardiac GRK5 is an essential mediator of the general cardio-protection afforded by MRA drugs against the cardio-toxic effects of excess Aldo, *e.g.* during CHF and other chronic cardiac diseases. This is due to the inhibitory phosphorylation GRK5 performs on the cardiac MR. This non-canonical (given the substrate is not a GPCR), co-repressor effect of GRK5 on cardiac MR is also (at least partly) responsible for the inverse agonism properties of finerenone at this receptor that bestow this non-steroidal MRA with superior potency and efficacy, compared to eplerenone, at protecting the heart against the damaging effects of Aldo. Finally, since GRK5 is a co-repressor of the MR, at least in the myocardium, its stimulation (or potentiation) should be a desired property of every novel MRA drug designed and developed for improved cardiovascular pharmacotherapy.

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