**ACTH Induces Oxidative Stress and Decreases DNA Methylation of Fkbp5 in Suhuai Sow**

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**ABSTRACT**

Hypothalamic-pituitary-adrenal (HPA) axis plays an important role in stress response. However, in Suhuai sows, the relationship between glucocorticoid and oxidative stress is not yet understood. We found that malondialdehyde (MDA) level was increased, whereas the activity of antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GSH-Px), were decreased after ACTH treatment in Suhuai sow. Moreover, glutathione (GSH) level and total antioxidant capacity (T-AOC) were also decreased upon ACTH treatment. Moreover, we found that mRNA expression levels of antioxidant enzymes such as SOD, CAT, and GPX, were down-regulated in the ACTH group. We observed that the mRNA expression of glucocorticoid-responsive elements (GRE) such as CXCR4, DUSP1, IL7R, TXNIP, and Fkbp5 were upregulated, whereas DNA methylation in intron 6 of Fkbp5 was reduced by ACTH administration. Hence, our findings suggest that ACTH induces oxidative stress and increases the expression level of Fkbp5 by decreasing DNA methylation in the GRE region in Suhuai sow.

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**To Cite This Article:** Weng Q, Li B, Liu Z, Liu K, Wu W and Liu H, 2019. ACTH induces oxidative stress and decreases DNA methylation of Fkbp5 in suhuai sow. Pak Vet J, 39(3): 401-405. http://dx.doi.org/10.29261/pakvetj/2019.083

**INTRODUCTION**

The production and secretion adrenocorticotropic hormone (ACTH) from the anterior pituitary and that of the glucocorticoid hormones cortisol or corticosterone (CORT) from the adrenal gland are controlled by the HPA axis of the neuroendocrine system (Spencer and Deak, 2017). The HPA axis stimulates the release of glucocorticoid hormones from the adrenal cortex in response to stress (de Quervain et al., 2016). Glucocorticoid receptors (GRs), one of the widely expressed intracellular proteins, regulate cellular responses by binding to specific glucocorticoid response elements (GREs) in the DNA or by non-genomic mechanisms via protein interactions (Srinivasan and Lahiri, 2016). For example, the chaperones such as heat shock protein 70 and 90 interact with GR protein and influence its assembly and activity (Kirschke et al., 2014). Previous study has shown that glucocorticoid hormones can cause stress (Spiers et al., 2014). For example, dexamethasone (Dex), a synthetic glucocorticoid that mimics the effects of the natural steroid cortisol, induces oxidative stress (Min et al., 2016).

Oxidative stress, which arises from the imbalance of reactive oxygen species (ROS) production and elimination by antioxidant systems, exerts damaging effects on the cellular functions (Newsholme et al., 2016). Oxidative stress is associated with recurrent pregnancy loss, defective embryogenesis, molecular and structural damages in oocytes and granulosa cells, and accelerated oocyte aging (Agarwal et al., 2012). In addition, ROS influences folliculogenesis, oocyte maturation, and corpus luteum and uterine function (Agarwal et al., 2008). H2O2 concentrations and antioxidant enzymatic activity are reduced during follicle development in ovary (Basini et al., 2008).

Apart from hormones, several molecules are involved in the regulation of stress response. One such molecule is FK506 binding protein 51 (FKBP51 or FKBP5), a 51-kDa protein, which is a member of family of immunophilins or FK506 binding proteins (FKBPs) (LeMaster et al., 2015). Genetic variation of the gene Fkbp5 is considered to be associated with some diseases of glucocorticoid abnormalities, including post-traumatic stress disorder and mood disorders (Willour et al., 2009). Fkbp5 acts as a crucial determinant of the adaptive stress response and decreases the binding of cortisol to its receptor (Tatro et al., 2009).

**MATERIALS AND METHODS**

**Animals, treatment and blood samples:** All animal procedures were performed according to the guidelines of the Nanjing Agricultural University Animal Care and Ethics Committee. The experimental and control groups
RESULTS

Effect of ACTH on the oxidant levels and activity of antioxidant enzymes in plasma: In order to determine whether ACTH induces oxidative stress, we examined oxidant indicators such as MDA, GSH, and T-AOC, and antioxidant enzymes such as SOD, CAT, and GSH-Px levels in the plasma sample of Suhuai pigs. Plasma levels of SOD, CAT, GSH-Px, MDA, and T-AOC did not change significantly on day 1 of ACTH treatment. As shown in Fig. 1A, SOD activity was decreased on days 4, 5, and 7 in ACTH treated group compared with control group. CAT activity declined in the treatment group with time and decreased significantly on days 3, 6, and 7 (Fig. 1B). The activity of GSH-Px significantly decreased on days 3, 4, and 6 after ACTH treatment (Fig. 1C). Plasma MDA concentration increased significantly in the treatment group on several days, whereas the concentrations on days 1, 4 and 7 were not significantly different from that of control group (Fig. 1D). GSH level in ACTH group significantly decreased compared with that in the control group on days 2, 6 and 7 (Fig. 1E). A significant decrease of T-AOC activity was observed on days 2, 4, 5, 6 and 7 in the ACTH-treatment group compared to the control group (Fig. 1F).

ACTH down-regulated the mRNA level of antioxidant enzyme genes: To further understand the effect of ACTH on the expression of antioxidant enzymes, the mRNA expression level of the antioxidant enzyme genes in the blood was investigated. Quantitative real-time PCR analysis showed that the mRNA levels of SOD, CAT, and GSH-Px were lower in the blood decreased significantly after treatment with ACTH (Fig. 2A-C).

ACTH activated the expression of glucocorticoid-responsive genes: Five genes, namely CXCR4, DUSP1, IL7R, TXNIP, and Fkbp5, have been proposed as markers of differential regulation of glucocorticoid-responsive elements (Donn et al., 2007; Sautron et al., 2015). In order to study whether ACTH activates GR-related pathways and affects downstream gene expression, we examined the mRNA levels of these genes. The results showed that CXCR4, DUSP1, IL7R, TXNIP, and Fkbp5 mRNA levels were significantly increased upon ACTH treatment (Fig. 2A-E).

ACTH decreased the DNA methylation level in the intron 6 region of Fkbp: Lee et al. (2010) reported that corticosterone increases the expression of Fkbp5 and decreases the methylation level in intron 1 and 5 regions that contained GRE in mice. In the present study, we also used the website (http://alggen.lsi.upc.es/cgi-bin/promo_v3/promo/promominit.cgi?dirDB=TF_8.3) to predict GRE in Fkbp5 gene and found that a similar region contained GRE in intron 6 of pig Fkbp5 (Fig. 4A). To further investigate whether the intron 6 region of Fkbp6 undergoes demethylation after ACTH treatment, we used a pyrosequencing method to detect the methylation status in Fkbp5, which revealed that the methylation level of CpG2 site was significantly decreased in the ACTH treatment group compared with control group, while CpG1 site was not significantly different (Fig. 4B).
Fig. 1: Effect of ACTH injection for 7 days on contents of oxidant indicators in plasma. Sows were intravenously injected with ACTH (1 IU/Kg) for 7 days. (A, B, C, D, E and F) The effect of ACTH on SOD (U/mL), CAT (U/mL), GSH-Px (U/mL), MDA (nM), GSH (uM) and T-AOC (U/mL) in plasma, respectively. Data are expressed as the mean±SEM (n=4); **P<0.01; *P<0.05.

Fig. 2: Effect of ACTH injection on mRNA levels of oxidant enzyme genes in plasma. Relative expression levels of SOD (A), CAT (B) and GPX (C). The GAPDH gene is used to normalize these genes mRNA level. Data are expressed as the mean±SEM (n=4); *P<0.05.

Fig. 3: ACTH up-regulates expression of glucocorticoid-responsive sensitivity genes. Relative expression levels of CXCR4 (A), DUSP1 (B), IL7R (C), TXNIP (D), Fkbp5 (E). The GAPDH gene is used to normalize these genes mRNA level. Data are expressed as the mean±SEM (n=4); **P<0.01; *P<0.05.
Antioxidant enzymes play an important role in alleviating oxidative stress. In the present study, the expression of CuZnSOD, MnSOD, GSH-Px, and GPx4 was significantly decreased after ACTH treatment. These decreases in antioxidant enzyme activities suggest that ACTH treatment is associated with oxidative stress. Therefore, antioxidant enzyme activities were measured in piglets followed by ACTH treatment. The results of our study demonstrated that ACTH treatment significantly decreased the antioxidant enzyme activities. These findings are consistent with previous studies and suggest that ACTH treatment promotes oxidative stress in piglets.


discussion

Superoxide is first dismutated by SOD to H$_2$O$_2$ and then catalyzed by two enzymes, CAT and GSH-Px, into H$_2$O and O$_2$ (Sun et al., 2014). Therefore, antioxidant systems play an important role in alleviating oxidative stress. It has been demonstrated that administration of a certain dose of carbon disulfide (CS$_2$) significantly reduces GSH, SOD, CAT, and GSH-Px contents in the rat hippocampus (Wang et al., 2017). Moreover, early weaning in piglets disrupts oxidative balance and causes oxidative injury in piglets, resulting in decreased expression of CuZnSOD, MnSOD, GSH-Px, and GPx4 (Yin et al., 2014). In the present study, SOD, CAT, GSH-Px, CAT, and T-AOC activity were significantly decreased after ACTH treatment. We further found that SOD, CAT, and GPX mRNA levels were also decreased in ACTH-induced group. These results suggest that elevated ACTH concentration in sow's suppresses the antioxidant enzyme expression level, resulting in oxidative stress in Suhuai sow.

Increasing evidence suggests that ACTH affects ovulation, reduces estrogen secretion and delays onset of estrus and shortens the duration of estrus (Brandt et al., 2006). Studies have shown that CAT and SOD activities are high in the human (Sugino et al., 2000) and bovine (Rueda et al., 1995) corpus luteum during early pregnancy. Furthermore, oxidative stress can lead to meiosis, fertilization and embryo development defects, and cause infertility (Keefe and Liu, 2009). Oxidative stress has been linked to endometriosis and polycystic ovarian syndrome (Menezes et al., 2016). In our study, ACTH increased the oxidative damage and decreased the activity of antioxidant enzymes. Hence, it is possible that excessive ACTH will induce oxidative stress and play a critical role during estrous cycle in the Suhuai sow.

Glucocorticoid production is induced by stress and it regulates gene expression by binding to its intracellular receptor (Hapgood et al., 2016). It has been demonstrated that glucocorticoids increase the transcription of DUSP1 gene by binding to GRE region in A549 human lung adenocarcinoma cells (Shipp et al., 2010). CXCR4, IL7R, and TXNIP genes were differentially expressed in response to ACTH in pigs (Sautron et al., 2015). Fkbp5 is identified as glucocorticoid-responsive genes and is regulated by the binding GR to the sequences corresponding to the GRE in Fkbp5 gene region (U et al., 2004). In the present study, we demonstrated that mRNA expression level of CXCR4, DUSP1, IL7R, TXNIP, and Fkbp5 were increased after ACTH treatment, which are consistent with previous study. These results showed that ACTH promoted transcription of glucocorticoid sensitive genes.

Fkbp5 protein acts an important co-chaperone in the formation of GR-complex (LeMaster et al., 2015). When Fkbp5 binds to GR-complex, the formation of GR-complex has a lower affinity for glucocorticoid (Wochnik et al., 2005). However, GR activation can promote the transcription of Fkbp5 via activation at GR elements (Kitraki et al., 2015). Therefore, in response to stress, Fkbp5 can inhibit GR affinity for glucocorticoid via negative feedback. It has been shown that the DNA methylation of GRE region is decreased after treatment with corticosterone in mice hypothalamus and
hippocampus (U et al., 2004; Lee et al., 2010). A previous study also showed that Dexamethasone treatment induced demethylation in intron 7 in the human hippocampal progenitor cell line (Klengel et al., 2013). In the present study, we found that ACTH induces Fkbp5 gene expression and decreases the methylation level in GRE region of intron 6 in Fkbp5 gene. Therefore, it appears that ACTH treatment induces DNA demethylation in Fkbp5 gene, resulting in increased transcription of Fkbp5.

Conclusions: In summary, ACTH treatment induces oxidative stress in Suhuai sow and increases the expression of glucocorticoid-responsive genes. ACTH also regulates Fkbp5 expression via demethylation in the GRE region. Hence, this study provides novel insights into the regulatory mechanisms between glucocorticoids and oxidative stress in Suhuai sow.

Acknowledgements: We thank Richard S. Lee (Johns Hopkins School of Medicine, Baltimore, MD 21287, USA) for helping to analyze the GRE of Fkbp5 gene. This project was supported by the 973 Program (2014CB138502), the National Natural Science Foundation of China (31472073), the State Key Program of National Natural Science Foundation of China (31630072), the National Natural Science Foundation of China (31501920) and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

Authors contribution: QW carried out the study and drafted the manuscript. BL and ZL helped to perform the study. KL analyzed the data. WW and HL designed the study and revised the manuscript. All authors interpreted the data, critically revised the manuscript for important intellectual contents and approved the final version.

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