

# Electromagnetic Fields Ameliorate Hepatic Lipid Accumulation and Oxidative Stress by Activating the CaMKK $\beta$ /AMPK/SREBP-1c and Nrf2 Pathways in High-Fat Diet-Fed Mice

Mingming Zhai (✉ [zhaimingming@fmmu.edu.cn](mailto:zhaimingming@fmmu.edu.cn))

fourth military medical university <https://orcid.org/0000-0001-9793-2231>

Jinxu Cui

Fourth Military Medical University: Air Force Medical University

Chenxu Zhang

Fourth Military Medical University: Air Force Medical University

Juan Liu

Fourth Military Medical University: Air Force Medical University

Yuanzhe Li

Fourth Military Medical University: Air Force Medical University

Kangning Xie

Fourth Military Medical University: Air Force Medical University

Erping Luo

Fourth Military Medical University: Air Force Medical University

Chi Tang

Fourth Military Medical University: Air Force Medical University

---

## Research

**Keywords:** NAFLD, Electromagnetic fields, Lipid metabolism, AMPK, Oxidative stress, Nrf2

**Posted Date:** November 1st, 2021

**DOI:** <https://doi.org/10.21203/rs.3.rs-1018391/v1>

**License:**  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

---

# Abstract

**Background:** Nonalcoholic fatty liver disease (NAFLD) is the most common liver disease worldwide, and is related to disturbed lipid metabolism and redox homeostasis. However, a definitive drug treatment has not been approved for this disease. Studies have found that electromagnetic fields (EMFs) can ameliorate hepatic steatosis and oxidative stress. Nevertheless, the mechanism remains unclear.

**Methods:** NAFLD models were established by feeding mice a high-fat diet. Simultaneously, EMF exposure is performed. The effects of the EMF on hepatic lipid deposition and oxidative stress were investigated. Additionally, the AMPK and Nrf2 pathways were analysed to confirm whether they were activated by the EMF.

**Results:** Administration of the EMF decreased the body weight, liver weight and serum triglyceride (TG) levels and restrained the excessive hepatic lipid accumulation caused by feeding the HFD. This EMF function is achieved by boosting CaMKK $\beta$  protein expression, activating AMPK phosphorylation and suppressing mature SREBP-1c protein expression. Meanwhile, the activity of GSH-Px was enhanced following an increase in nuclear Nrf2 protein expression by EMF. However, no change was observed in the activities of SOD and CAT. Consequently, EMF reduced hepatic reactive oxygen species (ROS) and MDA levels, which means that EMF relieved liver damage by oxidative stress in HFD-fed mice.

**Conclusions:** EMF can activate the CaMKK $\beta$ /AMPK/SREBP-1c and Nrf2 pathways to control hepatic lipid deposition and oxidative stress. This investigation indicates that EMF may be a novel therapeutic method for NAFLD.

## 1. Background

Nonalcoholic fatty liver disease (NAFLD), also called metabolic associated fatty liver disease (MAFLD), is increasing worldwide and has a prevalence of one-fourth of the general population[1]. NAFLD ranges from simple hepatic steatosis to nonalcoholic steatohepatitis (NASH), liver fibrosis and cirrhosis, ultimately hepatocellular carcinoma[2]. Due to the unclear pathomechanism of NAFLD and unsatisfactory clinical drug experimental results, a specific therapy has not been approved for NAFLD[3]. The pathological condition of NAFLD is characterized by hepatic lipid accumulation (in more than 5% of hepatocytes) without alcohol consumption or viral infection[4]. Excessive lipid deposition can directly cause the overproduction of reactive oxygen species (ROS) in the liver that cannot be cleared by antioxidant pathways[5], which disrupts redox homeostasis and leads to oxidative stress. Oxidative stress activates cellular dysfunction, cell necrosis and apoptosis in hepatocytes, which contributes remarkably to the pathogenesis of NAFLD and progresses to NASH[4, 6].

AMP-activated protein kinase (AMPK) is critical for balancing cellular energy homeostasis and regulating lipid synthesis by restraining the cleavage of sterol regulatory element binding proteins (SREBPs), including the subtype of SREBP-1c[7, 8]. As a major subtype of SREBPs in the liver, SREBP-1c is a master

transcription factor of lipogenesis[9]. The benefit of the AMPK/SREBP-1c pathway in counteracting hepatic steatosis is widely recognized[8, 10, 11].

Excessive oxidative stress is the result of an imbalance between oxidant and antioxidant functions; thus, boosting the antioxidant capacity can antagonize oxidative stress. Nuclear factor erythroid 1-related Factor 2 (Nrf2) is a key transcription factor that plays an important role in regulating antioxidant enzymes. The activation of antioxidant enzymes can protect tissues against oxidative injury[12]. Based on clinical and experimental evidence, Nrf2 has been proposed as a therapeutic target in NAFLD[13], and the administration of lipid metabolism and redox homeostasis is an effective therapeutic in NAFLD[4, 6, 14, 15]. Our previous research demonstrated the positive effects of electromagnetic fields (EMFs) on hepatic steatosis and oxidative stress; however, the mechanism underlying the effect of EMFs on the liver has not been clarified[16]. In this study, we investigated the bioeffects of the EMF in mice fed a high-fat diet (HFD) and assessed the expression of AMPK/SREBP-1c and Nrf2 signalling pathways in the liver.

## **2. Methods And Materials**

### ***2.1 Animals and Study Design***

This experimental procedure was conducted on male C57BL/6 mice (eight mice in each group, 7 weeks old and 21-23 g of initial body weight) housed in approved animal facilities (21 ± 2°C and 12 h/day light and 12 h/day dark conditions, and ad libitum access to water and commercial chow). These mice were randomly divided into three groups, and the experiments were started at the same time: (1) the control group was fed a standard chow diet, (2) the HFD group received a commercial diet rich in fatty acids (BiotechHD Co. Ltd., Beijing, China), and (3) the HFD + EMF group was fed the same diet as the HFD group and continuously exposed to an EMF 2 hours per day. Five weeks later, the mice were sacrificed to collect samples. The animal experiments were approved by the Institutional Animal Care and Use Committee at the Fourth Military Medical University and carried out according to the Guide for the Care and Use of Laboratory Animals published by the National Institutes of Health (NIH).

### ***2.2 Electromagnetic Field***

The electromagnetic exposure system used in this research was described in our previous articles. The EMF pulsed burst consists of a 5 ms burst width, 0.2 μs pulse rise, 0.02 ms pulse wait, 60 ms burst wait, 0.3 μs pulse rise and 0.2 μs pulse fall, and it is repeated at 15 Hz[16, 17]. The peak value of the EMF was approximately 1.6 mT, as measured by a Gaussmeter (Lake Shore Cryotronics, Westerville, OH). A schematic representation of the EMF system is shown in Figure 1A.

### ***2.3 Analysis of the General Parameters***

Five weeks after the intervention, the body weight was measured, and the animals were sacrificed. Following overnight fasting, blood was sampled from the eyes to obtain serum according to a previous study[18]. The liver of each mouse was collected immediately on ice after sacrifice, rinsed with 0.9%

saline, dried with filter paper and weighed. Liver samples were stored at  $-80^{\circ}\text{C}$  before evaluation. The procedures applied to the liver tissues were consistent with our previous report[16, 19].

## ***2.4 Analysis of Biochemical Parameters***

Hepatic superoxide dismutase (SOD), catalase (CAT), glutathione peroxidase (GSH-Px) and serum triglyceride (TG) were analysed with commercial assay kits purchased from the Nanjing Jiancheng Bioengineering Institute (product numbers: A001-3-2, A007-2-1, A005-1-1 and F001-1-1). These experimental processes were performed following the manufacturer's instructions as described in our earlier report[16, 19].

## ***2.5 Histological Analysis***

Frozen liver slices were used to detect reactive oxygen species (ROS) activation and lipid deposition. Fresh liver samples were stored at  $-80^{\circ}\text{C}$  and sliced into  $10\ \mu\text{m}$  thick tissue sections. The hepatic cryosections were incubated with a  $10\ \mu\text{M}$  dihydroethidium (DHE) fluorescence probe (S0063, Beyotime, Beyotime Biotechnology., Shanghai, China) for 1 h in the dark. After rinsing with PBS, Hoechst 33258 (C0003, Beyotime, Beyotime Biotechnology., Shanghai, China) was used to stain the cell nucleus. A modified Oil Red O staining kit (C0158S, Beyotime, Beyotime Biotechnology., Shanghai, China) was applied to examine lipid accumulation in the hepatocytes. The liver slice was stained with oil-saturated O liquid for 10 minutes in the dark and then washed in distilled water. Next, haematoxylin and eosin (HE) was applied to stain the nucleus and cytoplasm. We used Image-Pro Plus 6.0 software to analyse the histology results.

## ***2.6 Western Blotting***

Fresh liver tissues were homogenized on ice. Total and nuclear proteins were extracted separately in accordance with the manufacturer's instructions. Equal amounts of protein were loaded on 10% SDS-PAGE gels to separate the targets. After electrotransfer onto PVDF membranes following a standard procedure, the target proteins were incubated with primary antibodies. CaMKK $\beta$  (#16810, 1:1000, Cell Signaling Technology., USA), AMPK (#2532, 1:1000, Cell Signaling Technology Inc., USA), *p*-AMPK (#2535, 1:1000, Cell Signaling Technology., USA), Nrf2 (ab62352, 1:1000, Abcam, UK) and SREBP-1c (ab28481, 1:1000, Abcam, UK) were individually supplemented at  $4^{\circ}\text{C}$  overnight. Histone H3 (GB11102, 1:1000, Servicebio, Wuhan, China) was used as the nuclear protein internal reference, and  $\beta$ -actin (GB12001, 1:3000, Servicebio, Wuhan, China) was used as the total protein housekeeping gene. Furthermore, HRP-labelled goat anti-rabbit IgG (ab6721, 1:5000, Abcam, UK) was used for reprobating at  $37^{\circ}\text{C}$  for 1 h. Quantity One software v4.6.6 was applied to analyse the protein bands[20].

## ***2.7 Statistical Analysis***

All data are expressed as the mean  $\pm$  standard deviation (SD). One-way ANOVA with LSD *t*-test was used to evaluate the significant intergroup differences. Statistical analysis of data was managed with SPSS 16.0 at a significance level of  $P < 0.05$ .

## 3. Results

### ***3.1 EMF attenuates HFD-induced elevation of body weight, liver weight, serum TG and hepatic lipid deposition***

The mouse model was induced by a HFD for five weeks. To assess the positive effects of the EMF, we evaluated the body and liver weights. Both the body and liver weights in the EMF group were significantly lower than those in the HFD group ( $P < 0.05$ , Figure 1B and 1C). The serum TG level was reduced in the EMF group compared with the HFD group ( $P < 0.05$ , Figure 1D). Moreover, hepatic lipid accumulation had the same result ( $P < 0.05$ , Figure 1E and 1F). These findings imply that the EMF could improve hepatic lipid metabolism.

### ***3.2 EMF reduces HFD-induced lipid accumulation by activating the CaMKK $\beta$ /AMPK signalling pathway in the liver***

To determine the potential mechanism by which EMF improves hepatic lipid metabolism, we investigated the protein expression of the CaMKK $\beta$ /AMPK/SREBP-1c signalling pathway. Figure 2 confirms the significant suppression of CaMKK $\beta$  and AMPK activation by HFD ( $P < 0.05$ ). In addition, HFD induced an increase in mature SREBP-1c compared with the control group ( $P < 0.05$ ). Nevertheless, the EMF inhibited the damage of HFD according to the western blot results, based on the alterations of target band intensity in the HFD group when compared with the EMF group ( $P < 0.05$ ). The western blot results demonstrated that the EMF activates the CaMKK $\beta$ /AMPK/SREBP-1c signalling pathway to improve lipid deposition.

### ***3.3 EMF alleviates HFD-induced oxidative stress in liver***

A HFD can induce oxidative stress in the liver. To clarify the effects of the EMF on hepatic redox homeostasis, we measured oxidative stress indices. Figure 3A shows that DHE fluorescence intensity, an indicator of ROS, was higher in the HFD group than in the EMF group. The mean IOD data in Figure 3B also support this finding ( $P < 0.05$ ). The level of hepatic MDA as a redox status marker was measured. The hepatic MDA content increased significantly due to HFD administration compared to the control group ( $P < 0.05$ ). However, the EMF downregulated the MDA level, and a significant effect was seen in the EMF group compared with the HFD group ( $P < 0.05$ , Figure 3C). These results hint that the EMF rebalances redox homeostasis.

### ***3.4 EMF improves hepatic antioxidant via the Nrf2 pathway***

To verify whether the EMF regulated liver redox through antioxidant enzyme activation, we determined the hepatic nuclear Nrf2 protein expression and downstream antioxidant enzyme levels. Figure 4 shows that the nuclear Nrf2 protein expression levels were lower in the HFD group than the control group but were remarkably upregulated following EMF exposure ( $P < 0.05$ , Figure 4A). Compared to the HFD-fed animals,

the hepatic SOD and CAT levels were not changed after EMF exposure (Figure 4B and 4C). However, the GSH-Px level was notably increased by the EMF ( $P < 0.05$ , Figure 4D). These results verify that applying an EMF ameliorates hepatic oxidative stress in HFD-induced mice by strengthening antioxidants through Nrf2 activation.

## 4. Discussion

NAFLD is currently a globally common liver disease, and it is predicted to affect up to one quarter of the population[14]. NAFLD is indicated by hepatic steatosis and associated with multiple detrimental effects and even increased mortality[21]. Therefore, the most globally pressing challenges are developing prevention and therapy strategies for NAFLD. Although the underlying mechanism is not well understood, applying an EMF can regulate lipid metabolism, insulin resistance, inflammation and redox homeostasis, which are related to the pathological mechanisms in NAFLD[16, 22–25]. Accordingly, the present research confirmed the bioeffects and explored the potential mechanism of action of EMFs on hepatic lipid deposition and oxidative stress in an HFD-induced animal model. The results showed that the EMF enhanced the expression of the CaMKK $\beta$ /AMPK/SREBP-1c and Nrf2 signalling pathways in the liver.

In modern societies, people have shifted away from healthy lifestyles towards sedentariness (lacking physical activity), and excessive energy intake (particularly food rich in fat) is considered one of the main factors that cause metabolic disorders, including NAFLD. Long-term and overconsumption of dietary fat can change lipid metabolism. In this study, we demonstrated that a HFD induced massive weight gain in the body and liver and abnormal blood TG levels. Interestingly, the EMF effectively weakened these changes. TG is mainly assembled and secreted in the endoplasmic reticulum of the liver. As an essential organ in regulating lipid metabolism, the liver is responsible for orchestrating the synthesis of fatty acids. When matured, TG is subsequently released into the blood and then redistributed to other tissues[26]. The abnormally increased serum TG level implies the disruption of lipid metabolism in the liver. To prove this hypothesis, we histologically determined the amount and size of lipid droplets in hepatocytes. The HFD treatment led to visible changes in hepatic lipid accumulation at five weeks. This result is consistent with earlier reports[27]. At the same time, we found that the EMF significantly inhibited lipid deposition. It is possible that the EMF may control hepatic lipid homeostasis to influence blood TG levels and liver weight. Additionally, the EMF regulates lipid production to diminish body weight gain.

Lipogenesis and lipid catabolism are involved in lipid metabolism; however, this study is focused on lipid synthesis. The process of lipogenesis is regulated by complex interactions with transcription factors, such as SREBP-1c[14]. SREBP-1c is expressed in the majority of tissues in mice and humans, with an especially high level in the liver[28]. A high-fat diet markedly increases SREBP-1c transcription, which increases *de novo* lipogenesis. Data from hepatocytes and animals showed that the transcription of mature SREBP-1c is inhibited by AMPK[21, 29]. AMPK is an essential intracellular energy regulator that has been verified to be closely linked to hepatic steatosis and insulin resistance[30]. Phosphorylation activation of AMPK reduces *de novo* lipogenesis and augments fatty acid oxidation in NAFLD by downstream factors covering SREBP-1c, ACC1 and FAS[21, 31]. Hence, we analysed whether the EMF

functions in lipogenesis by modulating the AMPK/SREBP-1c pathway. In this investigation, we found a decrease in *p*-AMPK/AMPK levels and high mature SREBP-1c levels in NAFLD, which was reversed by EMF exposure. Simultaneously, we discovered that the EMF inverted the HFD-induced suppression of CaMKK $\beta$  protein expression. Both CaMKK $\beta$  and liver kinase B1 (LKB1) can phosphorylate and activate AMPK, and CaMKK $\beta$  plays a critical role in AMPK phosphorylation in LKB1-deficient cells[32, 33]. Therefore, the EMF likely activates CaMKK $\beta$  to phosphorylate and activate AMPK. Similar to previous reports, nanosecond-pulsed electric fields activated AMPK by CaMKK $\beta$ [33]. However, a limitation of this study was that we did not inquire about whether the EMF requires CaMKK $\beta$  to act on AMPK. Therefore, we can only speculate that the hepatic CaMKK $\beta$ /AMPK/SREBP-1c pathway is activated by EMF exposure in HFD-fed mice.

To fully explore the potential of EMFs as an effective method of improving fatty liver, we also focused on oxidative stress, which is vital for the development of NAFLD. This consequence is consistent with our early report that EMF attenuated oxidative stress[16]. The hepatic DHE staining and MDA levels in the present research revealed that EMFs likely eliminate the excess ROS induced by HFD feeding to prevent oxidative stress damage. Altering ROS homeostasis, especially O<sub>2</sub><sup>-</sup> products, has been identified as a signal for enhancing the antioxidant capacity to fight against the harmful consequences of oxidative distress[34]. In addition, EMFs have previously been shown to improve antioxidant capacity in the liver in db/db mice and combined static magnetic and electric fields have been shown to scavenge overproduced superoxide by modulating the reduced glutathione (GSH)/oxidized glutathione (GSSG) redox environment[16, 23]. Similar results were observed in this study. The EMF increased the protein expression of Nrf2 and the activation of GSH-Px but not SOD or CAT. Nrf2 plays a key role in cellular resistance to oxidative stress. Although Nrf2 is present in the cytoplasm in a steady state, it will enter the nucleus to initiate antioxidant response elements when activated[35]. GSH-Px, as a downstream target of Nrf2, can metabolize lipid hydroperoxides and hydrogen peroxide into inoffensive compounds trading on GSH as a cosubstrate into GSSG[19]. A previous study reported that strengthening the activities of GSH-Px and paraoxonase (PON) enzymes provide protection against oxidative injury in rat liver[36]. In summary, the EMF activated Nrf2 to boost GSH-Px rather than SOD and CAT, which resulted in enhanced antioxidant ability and ameliorated hepatic oxidative stress induced by HFD. Furthermore, the expression of GSH-Px, GSH and GSSG proteins needs to be analysed, which is a limitation of this study.

According to the findings presented here, we found that the EMF can regulate the CaMKK $\beta$ /AMPK/SREBP-1c and Nrf2 pathways to attenuate hepatic lipid accumulation and oxidative stress. The findings of the present study suggest a promising physical therapeutic strategy for improving NAFLD.

## 5. Conclusions

In conclusion, the use of an EMF as a noninvasive physical intervention method had very desirable bioeffects on lipogenesis and the redox rebalance in fatty liver. This study provides new insights into

treating NFALD by a single therapy or a combination of therapy and medication. Further research is expected to overcome the current dilemma of the lack of drugs approved for NAFLD.

## 6. List Of Abbreviations

<b>NAFLD</b>	Nonalcoholic fatty liver disease
<b>MAFLD</b>	Metabolic associated fatty liver disease
<b>NASH</b>	Nonalcoholic steatohepatitis
<b>EMFs</b>	Electromagnetic fields
<b>AMPK</b>	Adenosine Monophosphate Activated Protein Kinase
<b>Nrf2</b>	Nuclear factor erythroid 1-related Factor 2
<b>TG</b>	Triglyceride
<b>HFD</b>	High fat diet
<b>CaMKK<math>\beta</math></b>	Calcium/calmodulin dependent protein kinase kinase 2
<b>ROS</b>	Reactive oxygen species
<b>GSH-Px</b>	Glutathione peroxidase
<b>SREBP-1c</b>	Sterol regulatory element binding transcription factor 1
<b>MDA</b>	Malondialdehyde
<b>SOD</b>	Superoxide dismutase
<b>CAT</b>	Catalase

## Declarations

### *Ethics approval and consent to participate*

The animal experiments were approved by the Institutional Animal Care and Use Committee at the Fourth Military Medical University and carried out according to the Guide for the Care and Use of Laboratory Animals published by the National Institutes of Health (NIH).

### *Consent for publication*

Not available.

### *Availability of data and materials*

Not available.

### *Competing interests*

The authors declare that they have no competing interests.

### *Funding*

Not available.

### *Authors' contributions*

Zhai Mingming: Conceptualization, Investigation, Formal analysis, Methodology, Visualization, Writing - original draft.

Cui Jinxiu: Data curation, Investigation, Methodology, Software, Writing - original draft.

Zhang Chenxu: Data curation, Investigation, Visualization, Writing - review & editing.

Liu Juan: Investigation, Methodology.

Li Yuanzhe: Investigation.

Xie Kangning: Software.

Luo Erping: Project administration, Resources.

Tang Chi: Project administration, Resources, Supervision, Validation.

### *Acknowledgments*

This work was supported by Natural Science Foundation of Shaanxi Province youth Project (Acceptance number: S2022-JC-QN-1231) and National Natural Science Foundation of China (No. 51907197).

## References

1. Huang DQ, El-Serag HB, Loomba R: **Global epidemiology of NAFLD-related HCC: trends, predictions, risk factors and prevention.** *Nat Rev Gastroenterol Hepatol* 2021, **18**(4):223–238.
2. Mashek DG: **Hepatic lipid droplets: A balancing act between energy storage and metabolic dysfunction in NAFLD.** *MOL METAB* 2021, **50**:101115.
3. Faheem SA, Saeed NM, El-Naga RN, Ayoub IM, Azab SS: **Hepatoprotective Effect of Cranberry Nutraceutical Extract in Non-alcoholic Fatty Liver Model in Rats: Impact on Insulin Resistance and Nrf-2 Expression.** *FRONT PHARMACOL* 2020, **11**.
4. Arroyave-Ospina JC, Wu Z, Geng Y, Moshage H: **Role of Oxidative Stress in the Pathogenesis of Non-Alcoholic Fatty Liver Disease: Implications for Prevention and Therapy.** *Antioxidants* 2021,

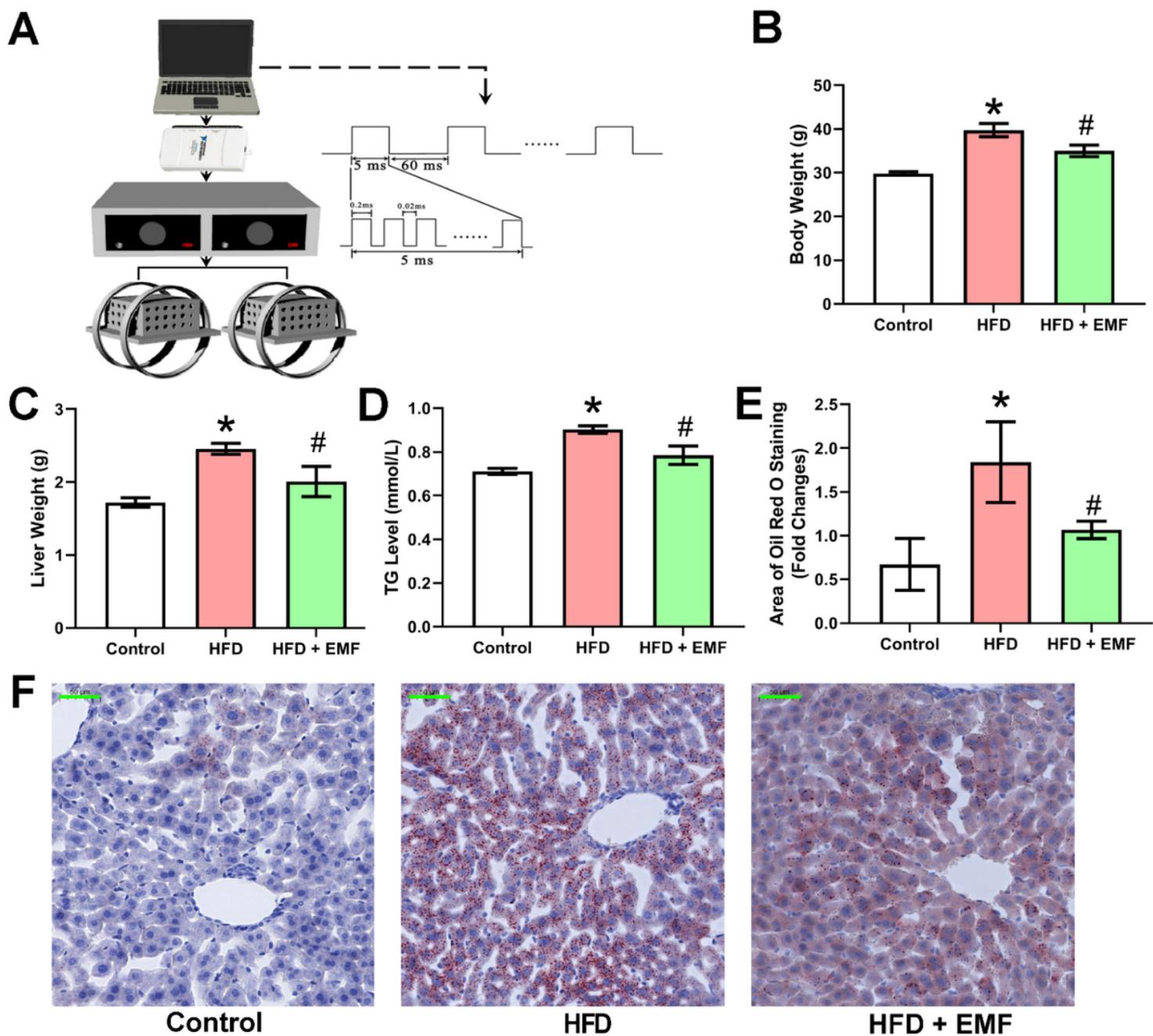
10(2):174.

5. Manne V, Handa P, Kowdley KV: **Pathophysiology of Nonalcoholic Fatty Liver Disease/Nonalcoholic Steatohepatitis.** *CLIN LIVER DIS* 2018, **22**(1):23–37.
6. Pafili K, Roden M: **Nonalcoholic fatty liver disease (NAFLD) from pathogenesis to treatment concepts in humans.** *MOL METAB* 2021, **50**:101122.
7. Guo S, Gong L, Shen Q, Xing D: **Photobiomodulation reduces hepatic lipogenesis and enhances insulin sensitivity through activation of CaMKK $\beta$ /AMPK signaling pathway.** *Journal of photochemistry and photobiology. B, Biology* 2020, **213**:112075.
8. Wei Q, Zhou B, Yang G, Hu W, Zhang L, Liu R, Li M, Wang K, Gu HF, Guan Y *et al*: **JAZF1 ameliorates age and diet-associated hepatic steatosis through SREBP-1c -dependent mechanism.** *CELL DEATH DIS* 2018, **9**(9):859.
9. Shao W, Espenshade PJ: **Expanding roles for SREBP in metabolism.** *CELL METAB* 2012, **16**(4):414–419.
10. Li J, Liu M, Yu H, Wang W, Han L, Chen Q, Ruan J, Wen S, Zhang Y, Wang T: **Mangiferin Improves Hepatic Lipid Metabolism Mainly Through Its Metabolite-Norathyriol by Modulating SIRT-1/AMPK/SREBP-1c Signaling.** *FRONT PHARMACOL* 2018, **9**:201.
11. Zhu X, Bian H, Wang L, Sun X, Xu X, Yan H, Xia M, Chang X, Lu Y, Li Y *et al*: **Berberine attenuates nonalcoholic hepatic steatosis through the AMPK-SREBP-1c-SCD1 pathway.** *Free Radic Biol Med* 2019, **141**:192–204.
12. Shimozono R, Asaoka Y, Yoshizawa Y, Aoki T, Noda H, Yamada M, Kaino M, Mochizuki H: **Nrf2 activators attenuate the progression of nonalcoholic steatohepatitis-related fibrosis in a dietary rat model.** *MOL PHARMACOL* 2013, **84**(1):62–70.
13. Masarone M, Rosato V, Dallio M, Gravina AG, Aglitti A, Loguercio C, Federico A, Persico M: **Role of Oxidative Stress in Pathophysiology of Nonalcoholic Fatty Liver Disease.** *OXID MED CELL LONGEV* 2018, **2018**:9547613.
14. Ipsen DH, Lykkesfeldt J, Tveden-Nyborg P: **Molecular mechanisms of hepatic lipid accumulation in non-alcoholic fatty liver disease.** *CELL MOL LIFE SCI* 2018, **75**(18):3313–3327.
15. Abenavoli L, Greco M, Milic N, Accattato F, Foti D, Gulletta E, Luzzza F: **Effect of Mediterranean Diet and Antioxidant Formulation in Non-Alcoholic Fatty Liver Disease: A Randomized Study.** *NUTRIENTS* 2017, **9**(8).
16. Zhai M, Yan X, Liu J, Long Z, Zhao S, Li W, Liu Y, Hai C: **Electromagnetic Fields Ameliorate Insulin Resistance and Hepatic Steatosis by Modulating Redox Homeostasis and SREBP-1c Expression in db/db Mice.** *Diabetes, Metabolic Syndrome and Obesity: Targets and Therapy* 2021, **Volume 14**:1035–1042.
17. Lei T, Liang Z, Li F, Tang C, Xie K, Wang P, Dong X, Shan S, Jiang M, Xu Q *et al*: **Pulsed electromagnetic fields (PEMF) attenuate changes in vertebral bone mass, architecture and strength in ovariectomized mice.** *BONE* 2018, **108**:10-19.

18. Vanani AR, Kalantari H, Mahdavinia M, Rashno M, Khorsandi L, Khodayar MJ: **Dimethyl fumarate reduces oxidative stress, inflammation and fat deposition by modulation of Nrf2, SREBP-1c and NF- $\kappa$ B signaling in HFD fed mice.** *LIFE SCI* 2021, **283**:119852.
19. Liu Y, Zhai M, Guo F, Shi T, Liu J, Wang X, Zhang X, Jing D, Hai C: **Whole Body Vibration Improves Insulin Resistance in db/db Mice: Amelioration of Lipid Accumulation and Oxidative Stress.** *Appl Biochem Biotechnol* 2016, **179**(5):819–829.
20. Yao M, Cui B, Zhang W, Ma W, Zhao G, Xing L: **Exosomal miR-21 secreted by IL-1 $\beta$ -primed-mesenchymal stem cells induces macrophage M2 polarization and ameliorates sepsis.** *LIFE SCI* 2021, **264**:118658.
21. Xiao Z, Chu Y, Qin W: **IGFBP5 modulates lipid metabolism and insulin sensitivity through activating AMPK pathway in non-alcoholic fatty liver disease.** *LIFE SCI* 2020, **256**:117997.
22. Patruno A, Tabrez S, Pesce M, Shakil S, Kamal MA, Reale M: **Effects of extremely low frequency electromagnetic field (ELF-EMF) on catalase, cytochrome P450 and nitric oxide synthase in erythro-leukemic cells.** *LIFE SCI* 2015, **121**:117–123.
23. Carter CS, Huang SC, Searby CC, Cassaidy B, Miller MJ, Grzesik WJ, Piorczynski TB, Pak TK, Walsh SA, Acevedo M *et al*: **Exposure to Static Magnetic and Electric Fields Treats Type 2 Diabetes.** *CELL METAB* 2020, **32**(4):561–574.
24. Gualdi G, Costantini E, Reale M, Amerio P: **Wound Repair and Extremely Low Frequency-Electromagnetic Field: Insight from In Vitro Study and Potential Clinical Application.** *INT J MOL SCI* 2021, **22**(9):5037.
25. Ross CL, Ang DC, Almeida-Porada G: **Targeting Mesenchymal Stromal Cells/Pericytes (MSCs) With Pulsed Electromagnetic Field (PEMF) Has the Potential to Treat Rheumatoid Arthritis.** *FRONT IMMUNOL* 2019, **10**.
26. Koo SH: **Nonalcoholic fatty liver disease: molecular mechanisms for the hepatic steatosis.** *Clin Mol Hepatol* 2013, **19**(3):210–215.
27. Konstantynowicz-Nowicka K, Berk K, Chabowski A, Kasacka I, Bielawiec P, Łukaszuk B, Harasim-Symbor E: **High-Fat Feeding in Time-Dependent Manner Affects Metabolic Routes Leading to Nervonic Acid Synthesis in NAFLD.** *INT J MOL SCI* 2019, **20**(15):3829.
28. MUSSO G, GAMBINO R, CASSADER M: **Recent insights into hepatic lipid metabolism in non-alcoholic fatty liver disease (NAFLD).** *PROG LIPID RES* 2009, **48**(1):1–26.
29. Li J, Liu M, Yu H, Wang W, Han L, Chen Q, Ruan J, Wen S, Zhang Y, Wang T: **Mangiferin Improves Hepatic Lipid Metabolism Mainly Through Its Metabolite-Norathyriol by Modulating SIRT-1/AMPK/SREBP-1c Signaling.** *FRONT PHARMACOL* 2018, **9**.
30. Long YC, Zierath JR: **AMP-activated protein kinase signaling in metabolic regulation.** *The Journal of clinical investigation* 2006, **116**(7):1776–1783.
31. Li Y, Xu S, Mihaylova MM, Zheng B, Hou X, Jiang B, Park O, Luo Z, Lefai E, Shyy JY *et al*: **AMPK phosphorylates and inhibits SREBP activity to attenuate hepatic steatosis and atherosclerosis in diet-induced insulin-resistant mice.** *CELL METAB* 2011, **13**(4):376–388.

32. Green MF, Anderson KA, Means AR: **Characterization of the CaMKK $\beta$ –AMPK signaling complex.** *CELL SIGNAL* 2011, **23**(12):2005–2012.
33. Morotomi-Yano K, Akiyama H, Yano K: **Nanosecond pulsed electric fields activate AMP-activated protein kinase: Implications for calcium-mediated activation of cellular signaling.** *BIOCHEM BIOPH RES CO* 2012, **428**(3):371–375.
34. Cox CS, McKay SE, Holmbeck MA, Christian BE, Scortea AC, Tsay AJ, Newman LE, Shadel GS: **Mitohormesis in Mice via Sustained Basal Activation of Mitochondrial and Antioxidant Signaling.** *CELL METAB* 2018, **28**(5):776.
35. Park SM, Kim JK, Kim EO, Jegal KH, Jung DH, Lee SG, Cho IJ, Kim S, Byun SH, Ku S *et al*: **Hepatoprotective Effect of Pericarpium zanthoxyli Extract Is Mediated via Antagonism of Oxidative Stress.** *EVID-BASED COMPL ALT* 2020, **2020**:1–15.
36. Demirtas CY, Pasaoglu OT, Bircan FS, Kantar S, Turkozkan N: **The investigation of melatonin effect on liver antioxidant and oxidant levels in fructose-mediated metabolic syndrome model.** *Eur Rev Med Pharmacol Sci* 2015, **19**(10):1915–1921.

## Figures



**Figure 1**

Schematic representation of EMF generator with Helmholtz coil and effects of EMF on the weight of body and liver, serum TG level and hepatic lipid deposition. A) The EMF pulsed burst consists of 5 ms burst width, 0.2  $\mu$ s pulse rise, 0.02 ms pulse wait, 60 ms burst wait, 0.3  $\mu$ s pulse rise and 0.2  $\mu$ s pulse fall and repeated at 15 Hz. B) Data of body weight (n = 5). C) Data of liver weight (n = 5). D) Data of serum TG level (n = 5). E) Statistical analysis of hepatic Oil Red O staining dyeing area. F) Representative images of hepatic Oil Red O staining. Values are all expressed as mean  $\pm$  SD. Scale bar is 50  $\mu$ m. \*  $P < 0.05$ , compared with control. #  $P < 0.05$ , compared with HFD.

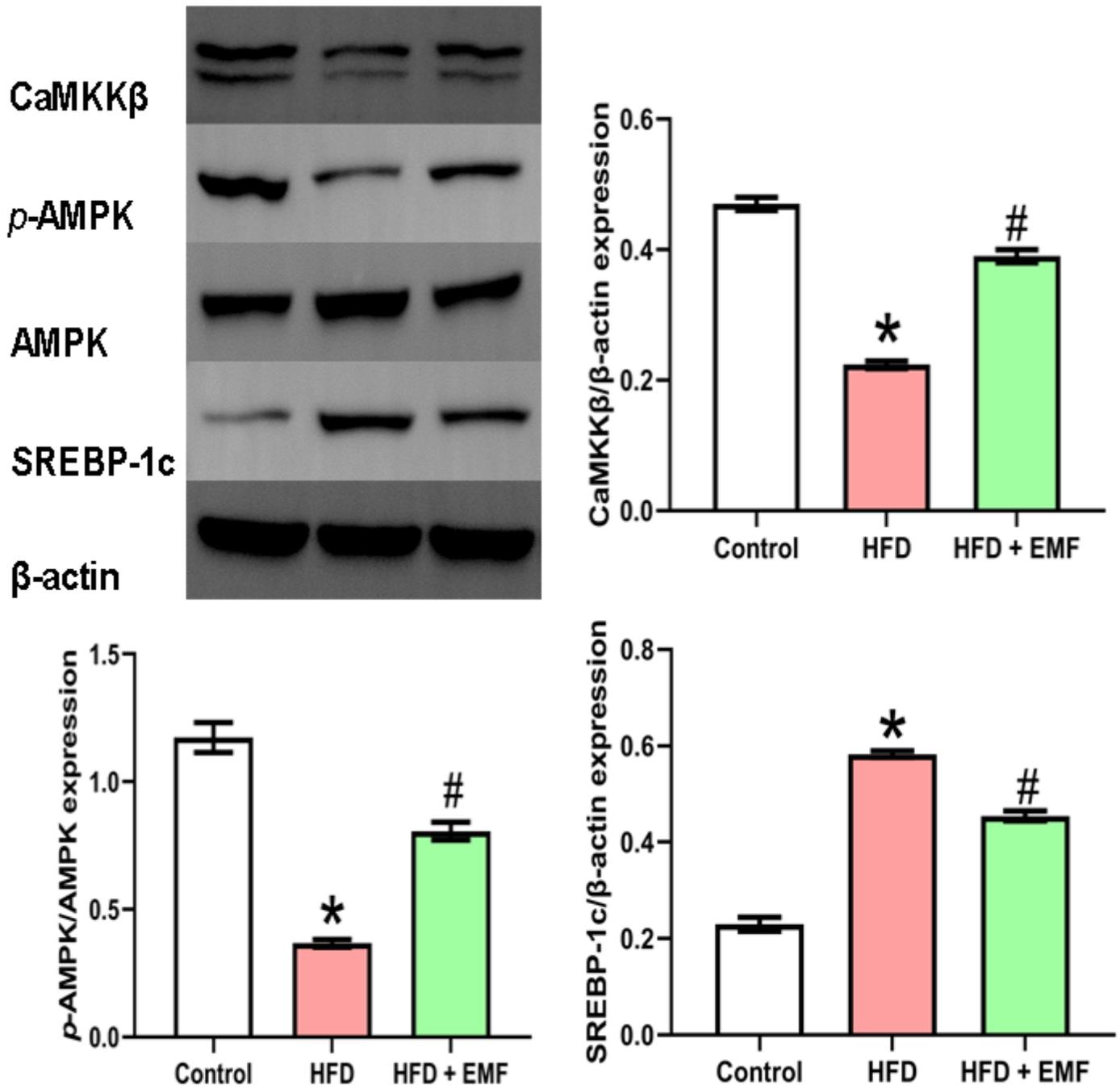
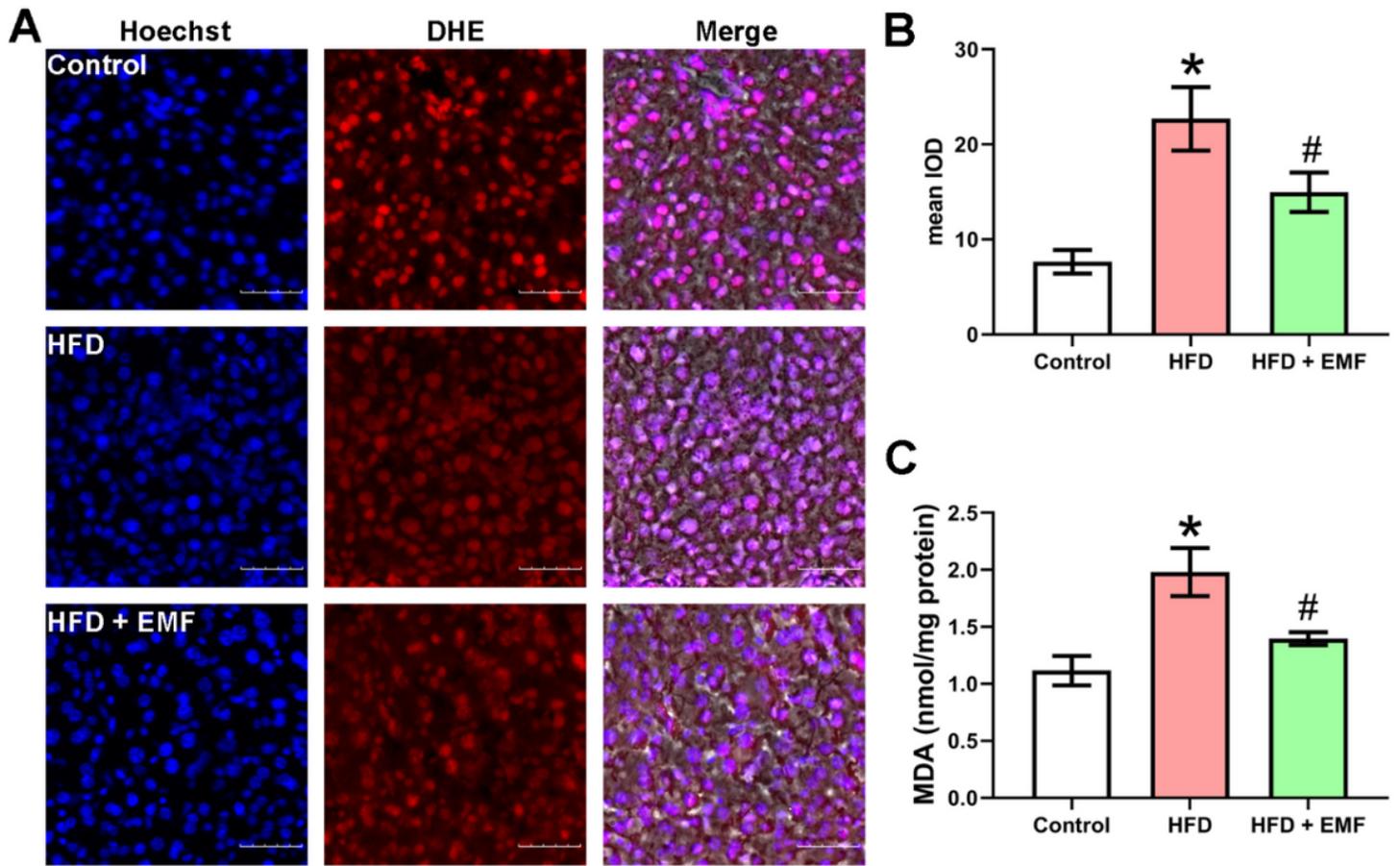


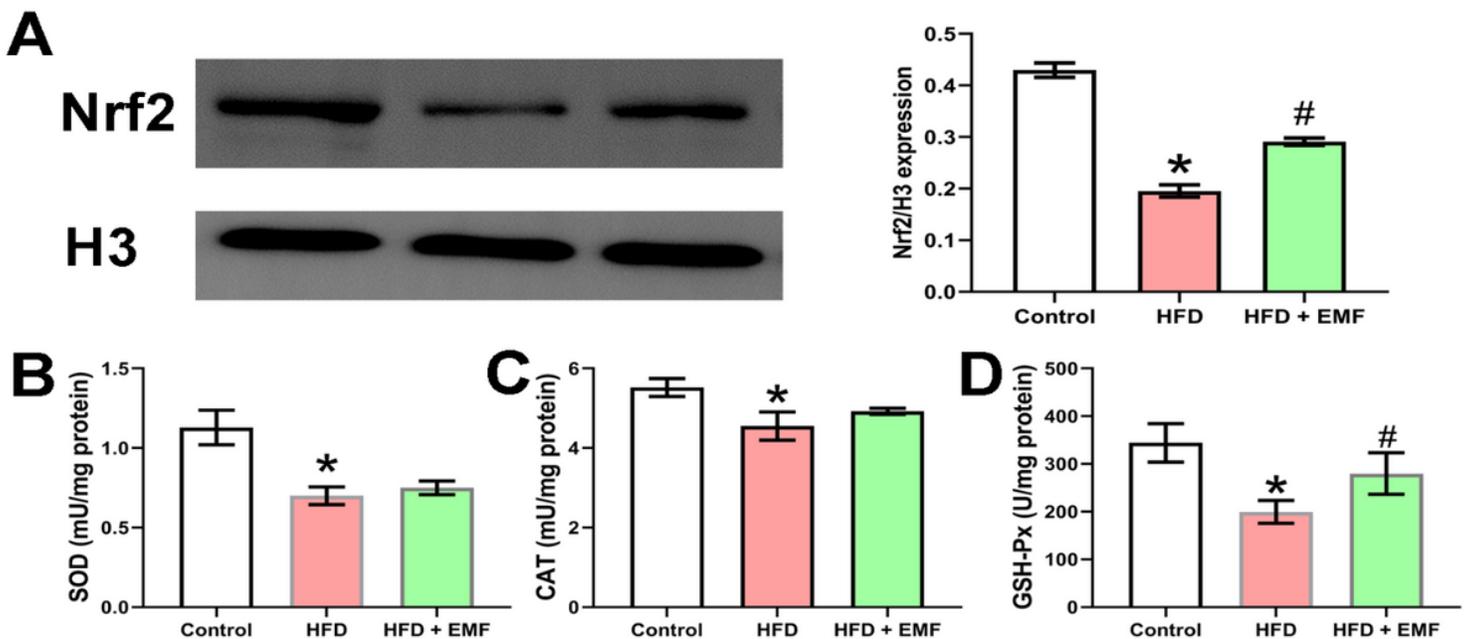
Figure 2

Representative western blotting of hepatic CaMKKβ/AMPK/SREBP-1c signalling pathway. Values are all expressed as mean ± SD, n = 3. \* P < 0.05, compared with control. # P < 0.05, compared with HFD.



**Figure 3**

Representative images of hepatic ROS and MDA levels. A) Hepatic DHE staining. B) Analysis of fluorescence intensity. C) Hepatic MDA levels. Scale bar is 50  $\mu$ m. Values are all expressed as mean  $\pm$  SD, n = 3. \*  $P < 0.05$ , compared with control. #  $P < 0.05$ , compared with HFD.



## Figure 4

Effects of EMF on hepatic Nrf2 pathway. A) Western blotting of hepatic Nrf2 and statistical analysis. B) Activity of hepatic SOD. C) Activity of hepatic CAT. D) Activity of hepatic GSH-Px. Values are all expressed as mean  $\pm$  SD, n = 3. \*  $P < 0.05$ , compared with control. #  $P < 0.05$ , compared with HFD.