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Taurine's Role in Mitigating Radar-Induced Oxidative Stress and Reproductive Toxicity in Male Rats: Antioxidant Defense Mechanism, Biochemical and Physiological Study

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Abstract
This study investigates the protective effects of taurine against infertility induced by radar electromagnetic radiation (EMR) in male rats. Exposure to radar EMR led to a significant decrease in reproductive hormone levels (e.g., testosterone), sperm quality (motility and count), and a marked increase in oxidative stress markers and reactive oxygen species (ROS) production. Taurine supplementation attenuated these effects by restoring the activities of key antioxidant enzymes [superoxide dismutase (SOD), catalase (CAT), and glutathione (GSH)]. The research utilized 30 male albino rats divided into a control group, an EMR-exposed group, and a taurine-treated group. EMR exposure (2.5 GHz for 4 weeks) caused an approximately 40% decrease in testosterone levels and a 30% reduction in sperm motility. Taurine supplementation (2% in drinking water) effectively restored antioxidant enzyme levels to near-control values, reduced ROS production, and prevented testicular atrophy. The results underscore taurine's potential as a therapeutic agent to combat EMR-associated infertility, particularly in occupational settings with prevalent radar exposure. This study emphasizes the need for antioxidant interventions to protect reproductive health in high-EMR environments, aligning with broader research on taurine's role in mitigating oxidative stress in tissues like the liver, heart, and testes.

Keywords: Taurine, Electromagnetic Radiation (EMR); Radar; Oxidative Stress; Reactive Oxygen Species (ROS); Male Infertility; Antioxidants; Rats.

1. Introduction

Radar and microwaves, a segment of the electromagnetic spectrum ranging from 300 MHz to 3000 GHz, are used in civilian and military sectors, including satellites, communications, networking, navigation, air traffic control, marine navigation, and meteorology. Consequently, many employees in these fields are directly exposed to these waves [1, 2]. The health risks, therefore, extend beyond direct thermal effects to biological consequences that may exceed the normal range of physiological adaptation, potentially harming health or well-being [3]. Previous research has indicated that radar frequency represents a health hazard. The adverse health effects of microwave radiation are divided into thermal and non-thermal effects. In thermal effects, absorbed energy is converted into thermal energy via Joule heating loss. Thermal effects become significant when the internal temperature rises by one degree Celsius or more. Microwaves produce thermal effects such as skin burns, lens cataracts, destruction of male reproductive glands, and increased temperature. In non-thermal effects, exposure is at a lower intensity than thermal effects, where electromagnetic fields have biological consequences; thus, human safety and health may be at risk, especially in epidemiological research [1, 2].

The non-thermal effects of microwaves are considered major causative factors for many human diseases, including hypersensitivity, cancer, heart and lung diseases, metabolic and genetic disorders, infectious diseases [4], and infertility [5]. A survey report investigating military naval mariners found a potential association between exposure to radiofrequency fields during the operation of radiofrequency equipment and radar and reduced fertility [6]. Other studies indicate that exposure to 0.9/1.8 GHz for one continuous hour daily for 28 days significantly reduces the percentage of motile sperm and leads to a marked increase in lipid peroxidation and a decrease in glutathione content in the epididymis and testis [7]. According to Goldsmith et al., exposure to radar frequencies may affect reproductive outcomes, particularly increasing spontaneous abortion [8]. This research has been reported by various investigations because the non-thermal effects of wide-band radar frequencies are somewhat extensive. Occupational health aims to promote health in the workplace [9].

The primary mechanism believed to underlie the non-thermal biological effects of EMR is the generation of oxidative stress. Oxidative stress occurs when there is an imbalance between the production of reactive oxygen species (ROS) and the biological system's ability to readily detoxify these reactive intermediates or repair the resulting damage. Exposure to EMR

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can lead to increased production of ROS such as superoxide anion ($^{-}O_2$), hydrogen peroxide (H_2O_2), and hydroxyl radicals (OH•). These highly reactive molecules can cause widespread damage to cellular biomolecules, including lipids, proteins, and nucleic acids. For instance, the interaction of ROS with lipids in cell membranes leads to lipid peroxidation, which can impair membrane integrity and function, leading to programmed cell death (apoptosis) or necrosis [10]. Recent studies have shown that chronic exposure to extremely low-frequency magnetic fields (ELF-MF) can impair antioxidant function and increase serum lipid peroxidation, confirming that EMR exposure is an environmental factor affecting biochemical parameters [11].

To counteract the effects of EMR, some studies are being conducted to find the best way to protect living tissues using various chemical methods, nanomaterials, and natural products such as amino acids, zinc oxide (ZnO), and graphene quantum dot (GQD) nanocomposites, which exhibit antioxidant activity by suppressing ROS, like hydroxyl radicals. The antioxidant role of zinc oxide reduces ROS levels, like superoxide anion. Graphene quantum dots may alleviate inflammation by inhibiting ROS. Taurine also exhibits anti-inflammatory effects by modulating various inflammatory pathways [12]. Furthermore, pyrazoline derivatives are potent antioxidants, analgesics, and anti-inflammatory agents. They inhibit nitric oxide (NO) production and ROS generation in models of inflammation and cancer [13].

Taurine, a sulfur-containing beta-amino acid, plays vital roles in cell membrane stabilization, osmotic pressure regulation, and suppression of ROS [14]. It has been proven to alleviate oxidative stress-induced damage in various organs, including the testes [15]. Similar to the ability of GQDs and ZnO to suppress ROS, taurine is also known for its antioxidant properties, helping to neutralize harmful free radicals and reduce oxidative stress. A 2025 review titled "The Drug Reboot" highlights drug repurposing as a cost-effective strategy for discovering new treatments. This review specifically mentioned that drugs like taurine and selenium compounds are being repurposed for their antioxidant and anti-inflammatory effects [16]. The use of natural compounds with strong antioxidant properties, such as procyanidin found in many fruits and plants, has also shown great potential in protecting against chronic diseases associated with oxidative stress [17]. Therefore, investigating protective factors like taurine aligns with the broader trend of exploring natural and safe interventions to counter environmental stressors.

This study evaluates the protective effects of taurine on male reproductive health under the influence of radar EMR exposure, aiming to provide a scientific basis for a potential interventional strategy in occupational environments.

2. Materials and Methods

The experimental design included 30 male albino rats divided into three groups: a control group, a radar-exposed group (EMR), and a taurine-treated group (EMR + Taurine). Taurine was administered orally at a dose of 200 mg/kg/day for 28 consecutive days. Rats were exposed to radar EMR (2.5 GHz, peak power 2 W, average power density 0.02 mW/cm², specific absorption rate SAR ≈ 0.9 W/kg) for 60 minutes daily over 28 days. All experiments were conducted following the NIH Guide for the Care and Use of Laboratory Animals [18], with strict adherence to the principles for the care and use of laboratory animals, including providing suitable housing conditions and minimizing pain and suffering.

Biochemical indicators, including superoxide dismutase (SOD), glutathione (GSH), and catalase (CAT), were measured using ELISA kits and biochemical assays. Reproductive hormones [testosterone, follicle-stimulating hormone (FSH), luteinizing hormone (LH)] and sperm parameters [count, motility, abnormalities] were also measured. [19]. Data were analyzed using one-way analysis of variance (ANOVA), and differences were considered statistically significant at $p < 0.05$.

3. Results

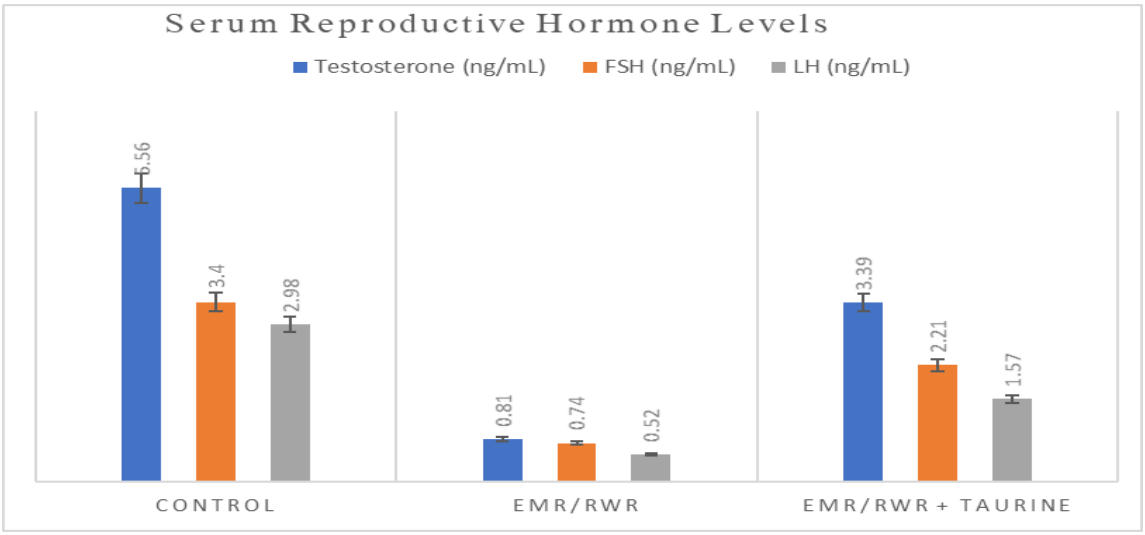
3.1 Effects of Radar EMR on Male Hormones, Sperm Parameters, and the Mitigating Role of Taurine:

Radar EMR exposure induced significant reproductive impairment, marked by a severe disruption of hormonal balance and spermatogenesis. Serum testosterone levels plummeted from 5.56 ± 0.48 ng/mL in controls to 0.81 ± 0.28 ng/mL in exposed rats ($p < 0.001$), with concomitant decreases in FSH and LH. This hormonal disruption was reflected in sperm quality, as evidenced by a drastic reduction in sperm count (from 86.55 ± 7.58 to 22.67 ± 4.48 million/mL) and motility (from 51.56 ± 4.65% to 21.28 ± 1.84%), alongside a sharp increase in morphological abnormalities (from 1.64 ± 0.48% to 11.04 ± 1.15%; $p < 0.001$ for all). However, supplementation with taurine conferred a significant protective effect, substantially mitigating these adverse outcomes. In the taurine-treated group, testosterone levels recovered to 3.39 ± 0.71 ng/mL, while sperm parameters showed marked improvement: count rose to 77.13 ± 3.61 million/mL, motility improved to 33.78 ± 3.2%, and the rate of abnormalities fell to 6.69 ± 0.80% ($p < 0.001$ for all comparisons versus the EMR-exposed group (Tables 1&2 and Figures1&2).

Table 1: Serum Reproductive Hormone Levels (Testosterone, FSH, and LH)

Group	Testosterone (ng/mL)	FSH (ng/mL)	LH (ng/mL)
Control	5.56 ± 0.48	3.4 ± 0.31	2.98 ± 0.27
EMR/RWR	0.81 ± 0.28 ***a	0.74 ± 0.25 ***a	0.52 ± 0.14 ***a
EMR/RWR + Taurine	3.39 ± 0.71 ***a, **b	2.21 ± 0.46 ***a, ns b	1.57 ± 0.21 ***a, **b

Data expressed as mean ± SD, n = 10. a: Comparison with the Control group; b: Comparison with the EMR/RWR group. ns: not significant ($p > 0.05$); (*) statistically significant ($p < 0.05$); (**) statistically highly significant ($p < 0.01$); (***) statistically very highly significant ($p < 0.001$).



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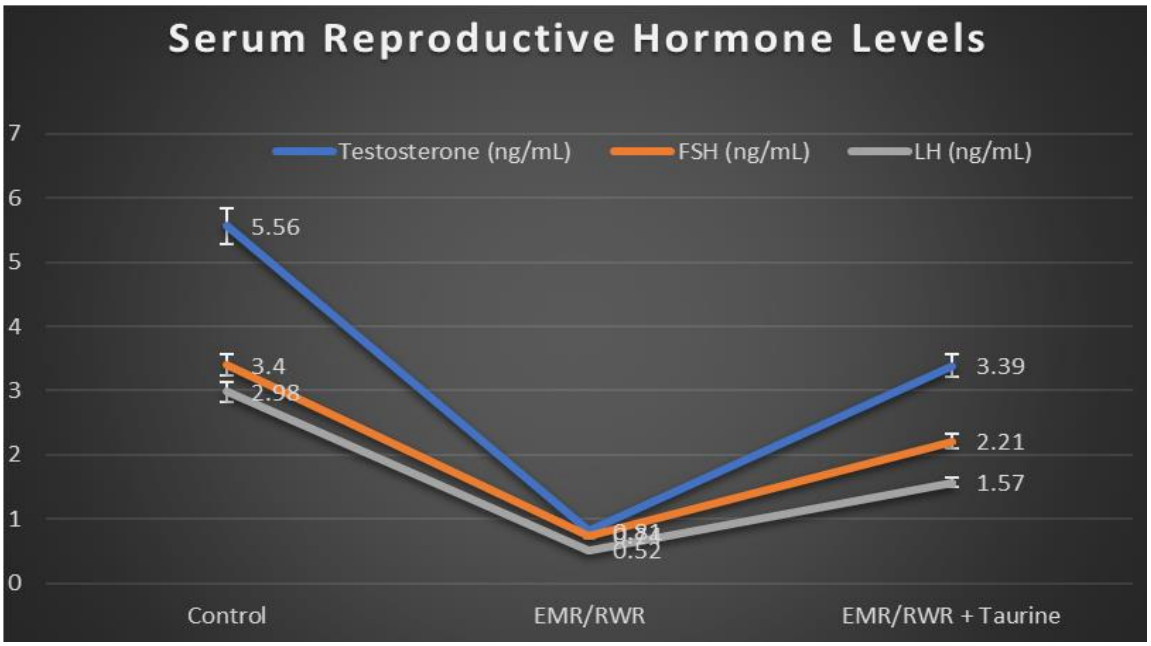

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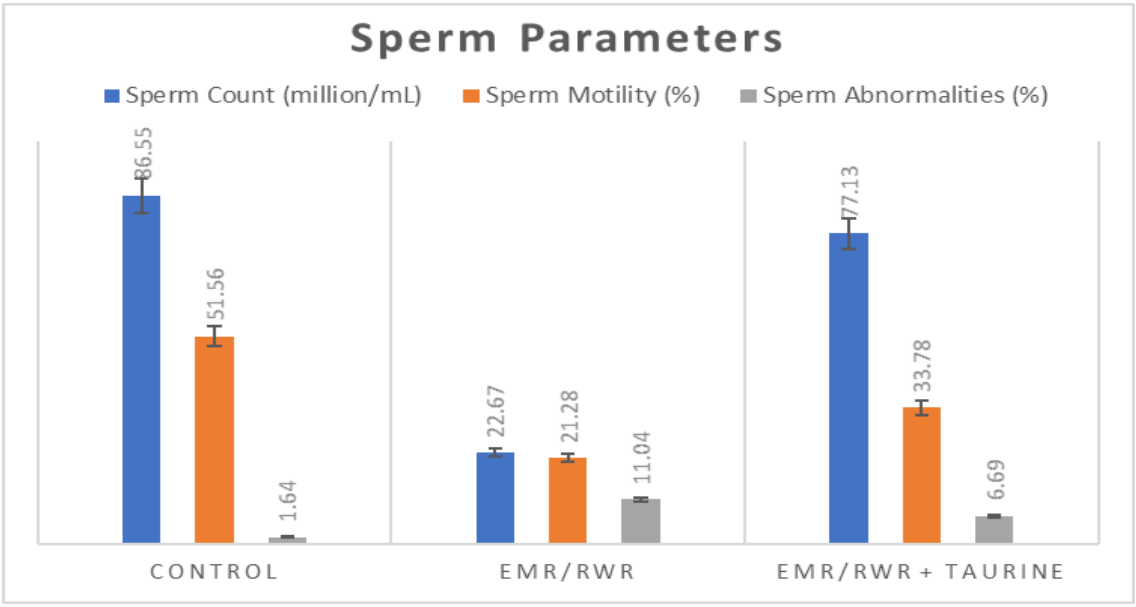
Figure 1: Comparison of reproductive hormone levels (Testosterone, LH, FSH) between groups.

Table 2: Sperm Parameters - Sperm Count, Motility, and Abnormalities

Group	Sperm Count (million/mL)	Sperm Motility (%)	Sperm Abnormalities (%)
Control	86.55 ± 7.58	51.56 ± 4.65	1.64 ± 0.48
EMR/RWR	22.67 ± 4.48 ***a	21.28 ± 1.84 ***a	11.04 ± 1.15 ***a
EMR/RWR + Taurine	77.13 ± 3.61 ***a, ***b	33.78 ± 3.2 ***a, *b	6.69 ± 0.80 ***a, ***b

Data expressed as mean ± SD, n = 10. a: Comparison with the Control group; b: Comparison with the EMR/RWR group. ns: not significant ($p > 0.05$); (*) statistically significant ($p < 0.05$); (**) statistically highly significant ($p < 0.01$); (***) statistically very highly significant ($p < 0.001$).



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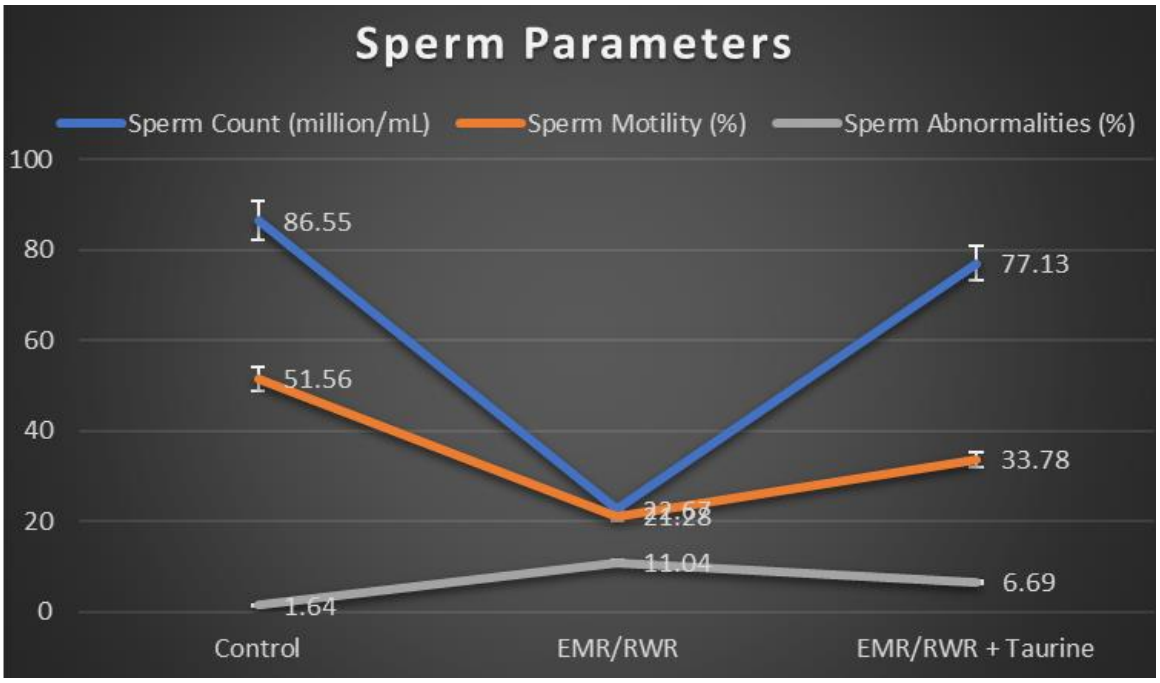

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Figure 2: Comparison of sperm parameters (Count, Motility, Abnormalities) between groups

3.2 Effects of Radar EMR on Oxidative Stress and the Role of Taurine

Taurine supplementation significantly ameliorated radar-induced oxidative stress, as evidenced by the marked restoration of key antioxidant markers to levels approaching those of the control group. Specifically, the activity of superoxide dismutase (SOD) increased from 40.26 ± 3.36 U/mL to 67.97 ± 3.36 U/mL, while catalase (CAT) activity rose from 15.08 ± 3.44 U/mL to 32.02 ± 3.52 U/mL. Furthermore, glutathione (GSH) content was substantially replenished, increasing from 15.68 ± 2.52 µmol/mL to 43.97 ± 5.67 µmol/mL. These results demonstrate that taurine effectively counteracts oxidative damage by enhancing the body's endogenous antioxidant defense system (Table 3 and Figure 3).

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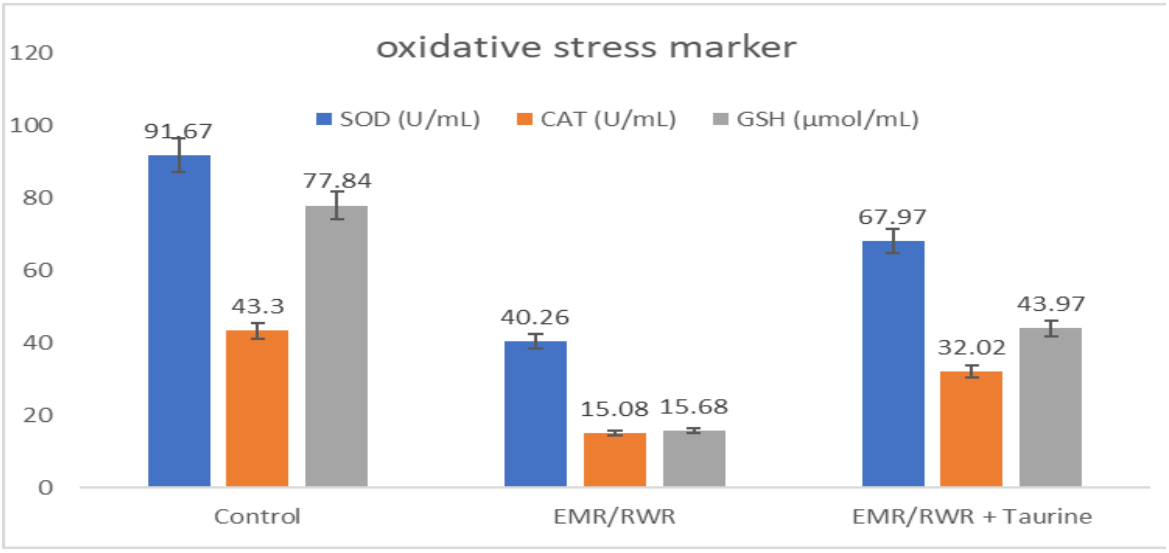
Table 3: Oxidative Stress Markers

Group	SOD (U/mL)	CAT (U/mL)	GSH (µmol/mL)
Control	91.67 ± 4.31	43.3 ± 2.94	77.84 ± 7.87
EMR/RWR	40.26 ± 3.36 ***a	15.08 ± 3.44 ***a	15.68 ± 2.52 ***a
EMR/RWR + Taurine	67.97 ± 3.36 ***a, ***b	32.02 ± 3.52 ***a, **b	43.97 ± 5.67 ***a, ***b

* Data expressed as mean ± SD, n = 10. a: Comparison with the Control group; b: Comparison with the EMR/RWR group. ns: not significant ($p > 0.05$); (*) statistically significant ($p < 0.05$); (**) statistically highly significant ($p < 0.01$); (***) statistically very highly significant ($p < 0.001$).



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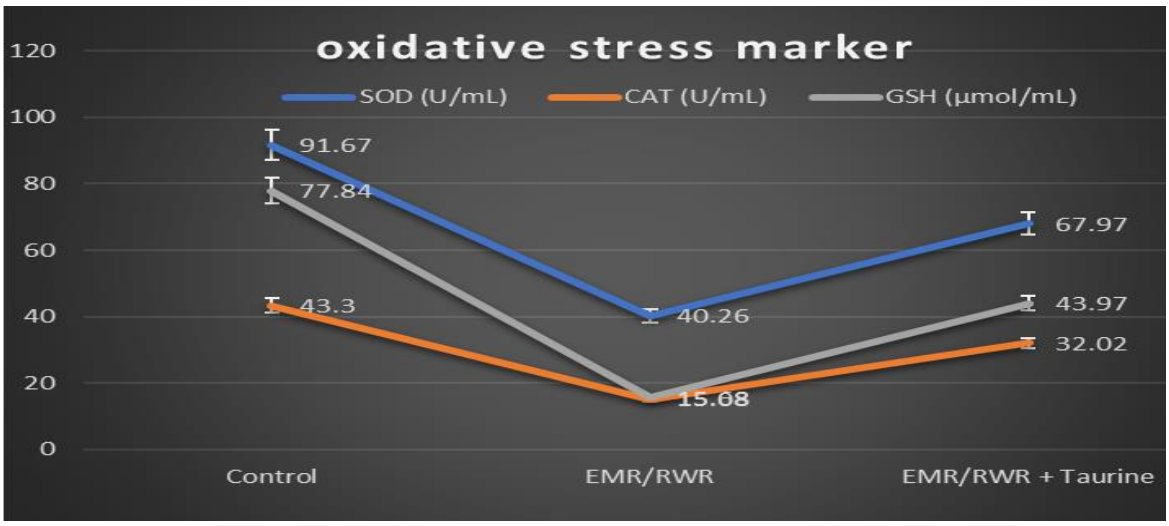

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Figure 3: Comparison of oxidative stress marker levels (SOD, CAT, GSH) between groups.

3.4 Effects of Radar EMR on testis tissue and the Role of Taurine

Histopathological examination of the testis shows structural changes. Figure 4 -A) The control group shows normal architecture. Figure 4 -B) The EMR/RWR group shows atrophy and degenerative changes. Figure 4 -C) EMR/RWR + Taurine-treated group shows marked improvement in histological structure.

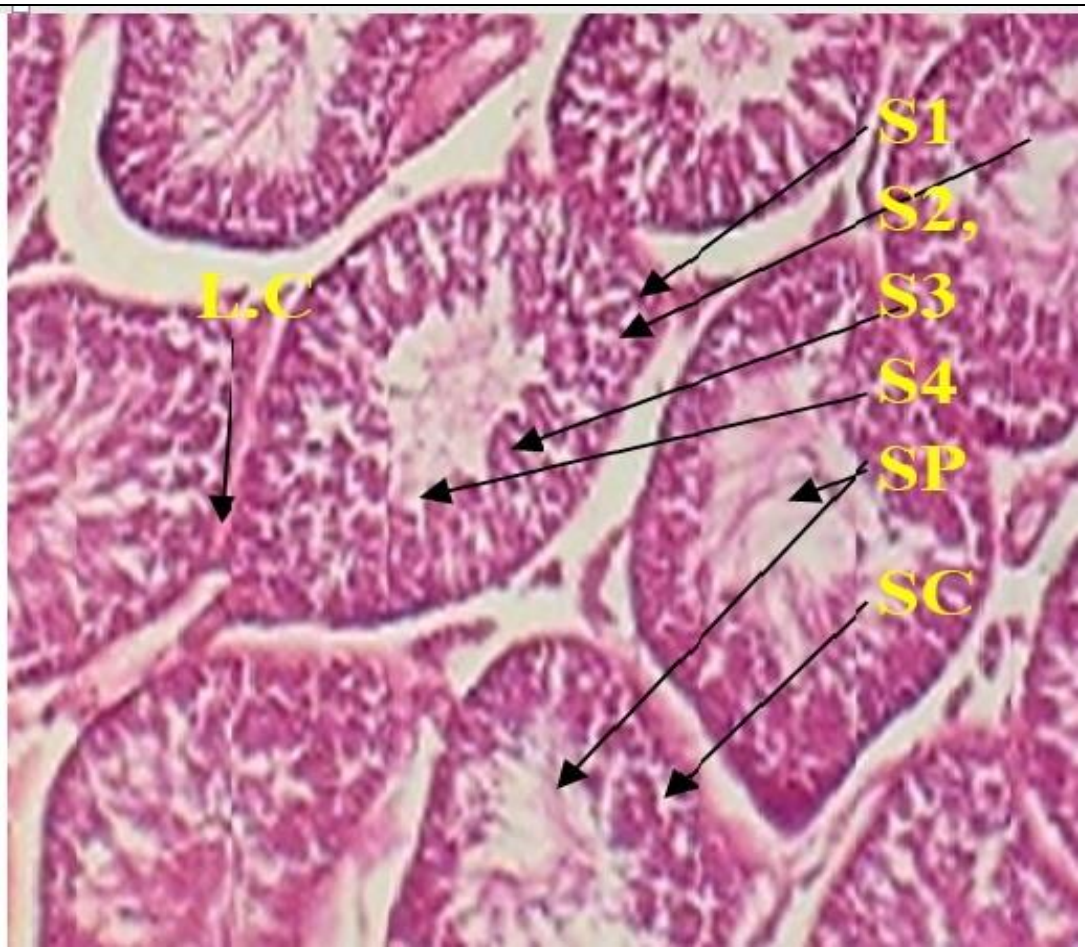

Figure 4- A Control group× 400

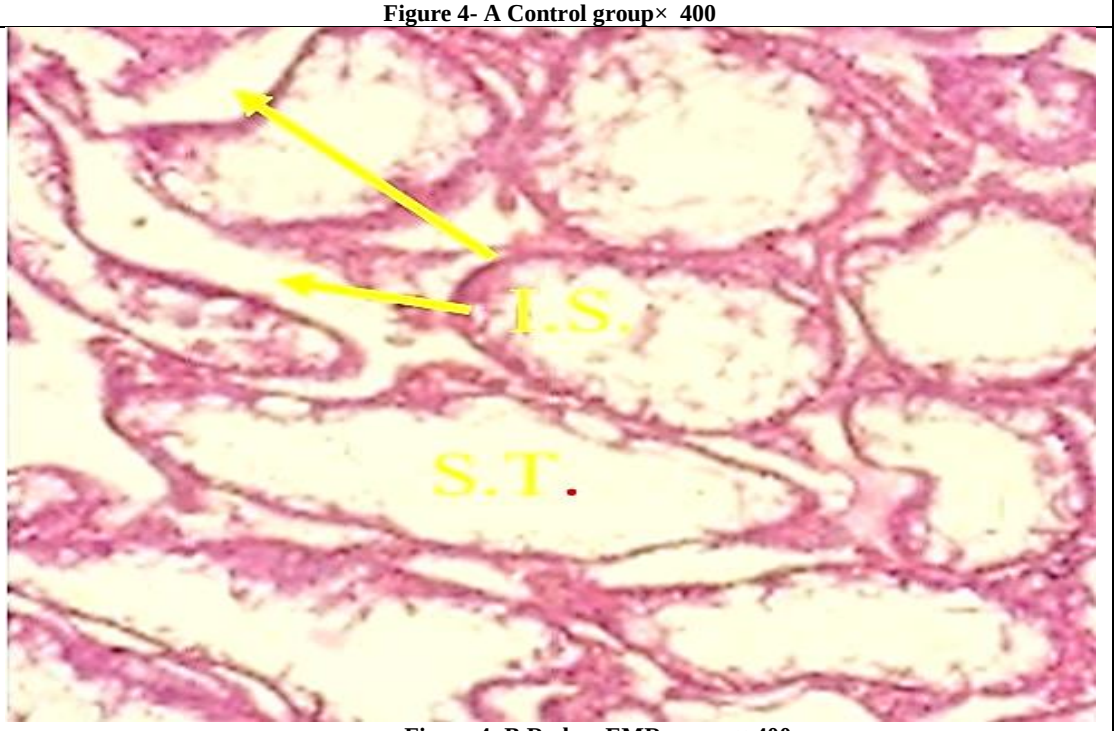

Figure 4 -B Radar- EMR group × 400

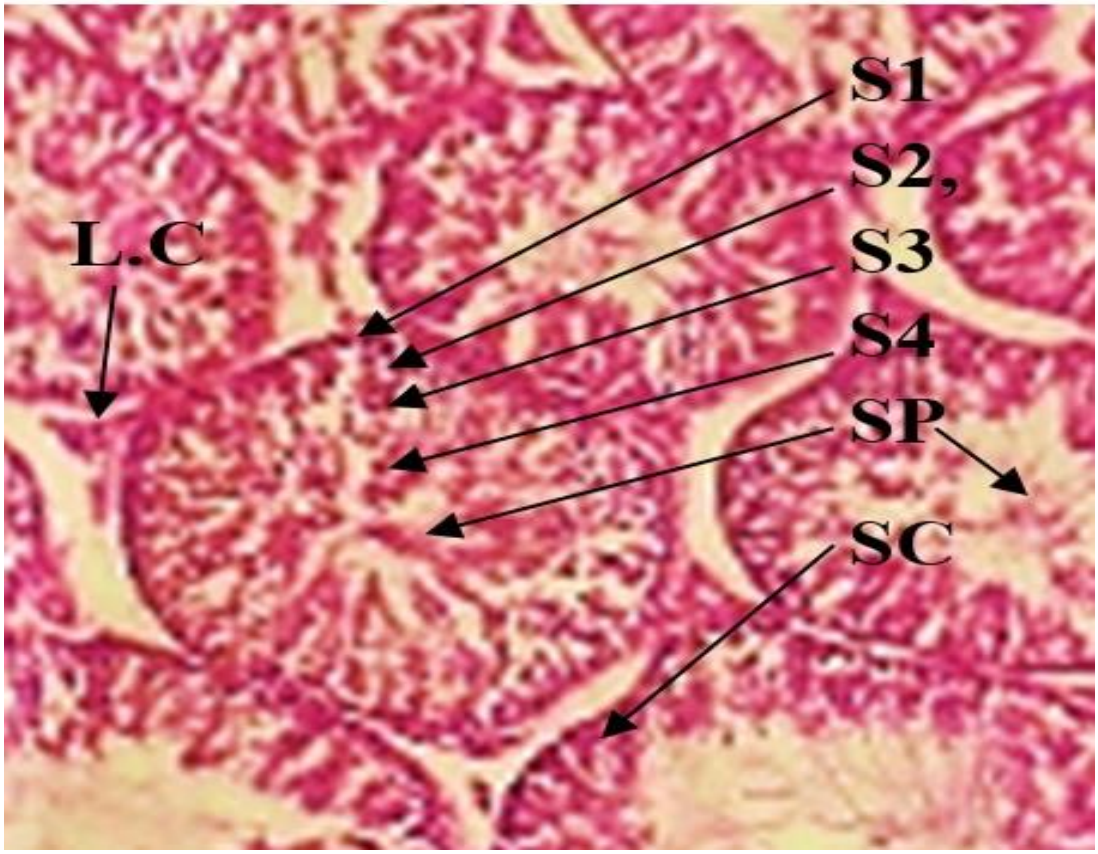

Figure 4 -C Taurine-treated group × 400

Figure 4: Histopathological examination of the testis tissue

Figure 4 presents a histopathological examination of testicular tissue, illustrating the structural impact of electromagnetic radiation (EMR) and the protective effect of taurine. The control group (A) displays normal testicular architecture, characterized by well-defined seminiferous tubules (S.T.) exhibiting all stages of spermatogenesis, including spermatogonia (S1), spermatocytes (S2), spermatids (S3), and mature spermatozoa (S4, SP), supported by Sertoli cells (SC) and Leydig cells (L.C.). In stark contrast, the EMR-exposed group (B) shows severe degenerative changes, with atrophic, distorted, and irregular seminiferous tubules, a loss of tissue structure, and the presence of inflammatory infiltrate. The taurine-treated group (C), however, demonstrates a marked improvement, with seminiferous tubules, spermatocytes, and spermatids appearing near normal, indicating a significant recovery of testicular histology.

4. Discussion

The results of this study agree with previous studies showing that radar EMR causes significant oxidative stress, disrupting the hypothalamic-pituitary-gonadal (HPG) axis and impairing spermatogenesis [20, 21, 22]. The current results confirm and extend these observations by demonstrating the strong protective effect of taurine against this reproductive toxicity.

4.1 Non-Thermal Effects of EMR and Reproductive Dysfunction

Our findings confirm previous studies indicating that exposure to radar EMR can lead to oxidative stress and reproductive dysfunction [6, 7, 20-22]. The sharp decline in testosterone, FSH, and LH levels observed in the exposed group indicates a central disruption of the HPG axis. The testes are highly sensitive to oxidative stress due to high cell division rates and high polyunsaturated fatty acid content in sperm membranes. The EMR-induced overproduction of ROS damages Leydig cells (responsible for testosterone production) and Sertoli cells (which support spermatogenesis), leading to decreased hormone production and impaired sperm quality. This aligns with research published in Biointerface Research in Applied Chemistry, which showed that exposure to electromagnetic fields can cause structural changes in biomolecules like lipids and proteins, leading to increased lipid peroxidation and impaired antioxidant function [11].

4.2 Antioxidant Protective Mechanism of Taurine

Taurine supplements effectively mitigated these harmful effects by enhancing antioxidant defenses and preserving testicular structure. The increase in the activities of the antioxidant enzymes SOD, CAT, and GSH indicates their role in quenching ROS and preventing lipid peroxidation [7]. SOD is the first line of defense, catalyzing the conversion of superoxide anions to

hydrogen peroxide, which is then detoxified by CAT and GPx. GSH, a non-enzymatic antioxidant, is essential for regenerating other antioxidants and providing direct protection against ROS. The restoration of these enzyme levels by taurine protected testicular tissue from oxidative damage, as evident from the improvement in histological parameters.

The protective mechanisms of taurine include stabilization of mitochondrial membranes, reduction of apoptosis, and restoration of hormonal balance [23]. For example, Mailankot et al. reported a significant decrease in sperm motility and glutathione content after radar exposure, which was reversed by taurine treatment .Similarly, Türkoglu et al. found that taurine supplements improved sperm morphology and motility in men with fertility issues [7, 24]. These results are consistent with previous studies showing taurine's ability to protect against oxidative stress-induced damage in various tissues; its multi-functional properties, including osmotic regulation, membrane stabilization, and anti-inflammatory actions, contribute to its protective effects on male fertility [15]. The efficacy of taurine can be compared to other natural antioxidants like procyanidins, which have been shown to possess antioxidant capacity stronger than vitamins C and E and act as a preventive mechanism against oxidative stress [17].

4.3 Clinical and Occupational Significance and Future Directions

This study highlights the significant potential of taurine as a protective agent for workers occupationally exposed to high levels of EMR, such as military personnel, communication workers, and air traffic controllers. Taurine is a naturally occurring, readily available compound with an excellent safety record, making it an ideal candidate for dietary intervention.

However, there are some limitations to this study. It was conducted on an animal model, and human responses may differ. The duration of exposure and treatment was relatively short (28 days). Further research is needed to assess long-term effects and optimal dosages for human applications. Future studies should explore the precise molecular pathways mediated by taurine, such as the Nrf2/HO-1 signaling pathway, which plays a key role in regulating the antioxidant response [22]. Furthermore, computational approaches, such as Density Functional Theory (DFT) and molecular docking, as illustrated in recent research, could be used to elucidate interaction indicators and the electronic properties of taurine, providing a deeper understanding of its antioxidant potential [25].

5. Conclusion

In conclusion, taurine supplementation effectively protects against radar EMR-induced infertility in male rats by enhancing antioxidant defenses and preserving testicular structure and function. The results show that EMR exposure causes acute oxidative stress, leading to a significant decline in reproductive hormones and sperm quality. Taurine successfully reversed these adverse effects, restoring biochemical and physiological parameters to near-normal levels. These findings highlight the therapeutic potential of taurine as a simple and cost-effective protective agent for workers exposed to radar waves, particularly military personnel and communication workers. Further studies are warranted to explore long-term effects and optimal dosages for human applications, paving the way for evidence-based occupational health strategies.

Conflicts of interest

There are no conflicts to declare.

6. Recommendations

Periodic Monitoring: Workers exposed to radar EMR should undergo periodic monitoring for oxidative stress markers (e.g., SOD, CAT, GSH) and reproductive hormone levels (testosterone, LH, FSH) to detect early signs of physiological damage.

Dietary Supplement Protocols: Employers should consider providing taurine supplements for workers in radar-dense environments to mitigate oxidative stress and preserve fertility, following further clinical research to determine effective and safe dosages.

Further Research: Longitudinal studies are needed to evaluate the efficacy of taurine supplements in humans and to refine dosages for maximum protection. Future research should also focus on the molecular mechanisms underlying taurine's protective effects and explore potential synergistic antioxidants.

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