Archives of Razi Institute Journal
"Arch. Razi Inst."

Journal Homepage: https://archrazi.areeo.ac.ir/

Research Paper

Preparation of SSCs Recipients in Sheep; Effects of Anticancer Drugs

Mohammad Zandi[1*], Annahita Ghaedrahmati[2]

1. Iranian Research Organization for Science and Technology (IROST), Tehran, Iran.
2. Department of Animal Science, Agricultural Sciences and Natural Resources University of Khuzestan, Mollasani, Iran.

Use your device to scan and read the article online

How to cite this article Zandi M, Ghaedrahmati A. Preparation of SSCs Recipients in Sheep; Effects of Anticancer Drugs. Archives of Razi Institute Journal. 2026; 81(1):233-244. https://doi.org/10.32598/ARI.81.1.3321

https://doi.org/10.32598/ARI.81.1.3321

Article info:
Received: 21 Sep 2025
Accepted: 26 Nov 2025
Published: 01 Jan 2026

ABSTRACT

Introduction: This in vitro investigation aimed to assess the impact of taxol, carboplatin, vinblastine (VBL), and vincristine (VCR) on ovine spermatogonial stem cells (SSCs). SSCs can be extracted from the testes of an animal and cultured in a laboratory to increase their quantity for transplantation into a recipient. Upon transplantation, these cells maintain their population and initiate sperm production in the recipient animal.

Materials & Methods: Adequate preparation of the recipient is a crucial aspect of spermatogonial stem cell transplantation. Drawing upon the findings of in vitro investigations conducted on SSCs, a tripartite regimen comprising carboplatin, taxol, and VCR was administered to four-month-old male Shal lambs at varying concentrations. The in vivo experiments included the culture of SSCs, *GFRαl* and *c-myc* specific gene expression analysis, and histological analysis.

Results: The results demonstrated that injection of the aforementioned combination (at concentrations of 2.0632, 0.906, and 0.0072 mg, respectively) beneath the scrotums of each testicle of Shal lambs resulted in a significant reduction in the SSCs population. The expression of *GFRαl* and *c-myc* genes, as specific markers of stem cells, was reduced considerably in double and quadruple concentrations of carboplatin + taxol + vincristine compared to other treatments.

Conclusion: The findings suggest that a tripartite regimen consisting of carboplatin, taxol, and VCR may be suitable for preparing sheep recipients for SSCs transplantation, based on the results of this study, the use of a combination of carboplatin, taxol, and vincristine is recommended for the preparation of SSC transplant receptors in sheep. Injection of a combination of carboplatin, taxol, and vincristine, equivalent to twice the concentration recommended for cancer treatment by the drug manufacturer, under the Scrotum of each of the testicles of Shal lambs significantly reduces the cell population.

Keywords:
Expression, Ovine, Spermatogonial stem cells (SSCs), Transplantation, Vincristine

*** Corresponding Author:**
Mohammad Zandi, Associate Professor.
Address: *Iranian Research Organization for Science and Technology (IROST), Tehran, Iran.*
Tel: *+98 (912) 3115294*
E-mail: *mz1075@yahoo.com*

Copyright © 2026 The Author(s);
This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International license(https://creativecommons.org/licenses/by-nc/4.0/).
Noncommercial uses of the work are permitted, provided the original work is properly cited.

1. Introduction

Spermatogonial stem cells (SSCs) exhibit a unique capacity for self-renewal within the seminiferous tubules, thereby ensuring uninterrupted sustenance of spermatogenesis throughout the lifespan of male organisms [1]. In contemporary times, the transplantation of SSCs has proven to be an efficacious research tool for examining the interplay between Sertoli and germ cells in the process of spermatogenesis. Additionally, it has surfaced as a feasible approach for generating transgenic livestock [2]. The ovine sector encounters difficulties in the transportation and dissemination of genetics, primarily attributed to impediments concerning the cryopreservation of sperm, as well as insemination and embryo transfer procedures [3]. Although homologous transplantation has demonstrated efficacy in certain animals, its effectiveness in larger animals remains uncertain in the absence of suitable recipients. Therefore, alternative methods for transporting genetics would be advantageous for the sheep industry [4]. Preparation of the recipient for SSC transplantation necessitates the creation of space by eliminating the pre-existing germ cells [5]. Various techniques, including irradiation, heat shock, and chemical treatment, have been employed to achieve this objective. Nevertheless, the intraperitoneal (i.p.) administration of busulfan is the most frequently utilized approach owing to its ease of administration and accessibility [6].

However, the use of busulfan has been associated with severe systemic toxicity resulting from the destruction of hematopoietic cells and germ cells [7]. As a result, alternative methods such as irradiation and heat shock have been explored. Nonetheless, these methods are limited by their requirement for specialized and expensive instruments, as well as a narrow transplantation window [2].

In light of the resemblance between stem cells and cancer cells, this investigation employed herbal remedies, including taxol, vinblastine (VBL), and vincristine (VCR), along with carboplatin, a platinum derivative utilized in cancer therapy, to establish recipients.

Taxol (paclitaxel) is a chemotherapeutic agent that is extensively used to treat various types of cancers, including lung, neck, and breast cancers [8]. Its mechanism of action involves binding specifically with tubulin β-subunits heterodimer, which promotes tubulin polymerization through its poly-oxygenated cyclic di-terpenoid with a characteristic taxane ring system [9]. This effect is particularly pronounced during the G2/M phase of the cell cycle, where taxol can halt cancer cell proliferation and trigger apoptosis [10].

The Vince alkaloids, procured from the Madagascar periwinkle plant, have demonstrated efficacy against a diverse range of cancer cell types. VCR and VBL were the pioneering agents in this class of chemotherapeutics. Their mechanism of action entails binding to a distinct site on the tubulin protein and impeding cellular division. This impediment is attributed to the hindrance of the protein's ability to form requisite structures within the cell [11]. Carboplatin is a platinum-based chemotherapeutic agent that shares a mechanistic similarity with cisplatin, albeit with distinct structural and toxicological features. It represents the second generation of platinum-based drugs following cisplatin. Both agents exert their antineoplastic effects by inducing DNA damage, which leads to the inhibition of DNA replication, transcription, and cellular division [12].

This study initially examined the effects of taxol, carboplatin, VBL, and VCR on ovine SSCs. Subsequently, a combination of carboplatin, taxol, and VCR was administered to four-month-old male Shal lambs at three concentrations based on the results of in vitro experiments.

2. Material and Methods

2.1. Chemicals

The procurement of chemicals was executed through Sigma (St. Louis, MO, USA), while the acquisition of plastics was conducted at Corning (USA).

2.2. Experiment

The procurement of the 4-month Shal male lambs was carried out from Rasouli Farm, located in Tehran, Iran. Furthermore, it is important to note that the protocol for animal usage in this study had received approval.

The present study is centered on an in vitro experiment conducted to assess the impact of various drug treatments. The drugs employed in the experiment included taxol, carboplatin, VBL, and VCR, which were tested at different concentrations ranging from 7.5 to 240 µg/mL using the MTT (methylthiazolyldiphenyl-tetrazolium bromide) test. Furthermore, the experiment investigated the combined effect of taxol and carboplatin, both individually and in combination with either VBL or VCR. Based on the results of the in vitro study, a combination of carboplatin, taxol, and VCR was administered to four-

month-old male Shal lambs. Three different concentrations of the drug combination were used to treat 12 lambs, with each treatment being replicated three times.

The effective concentrations (T1: 1.0316, 0.453, and 0.0036 mg of carboplatin, taxol, and VCR, respectively) were determined in accordance with the manufacturer's guidelines. In addition to administering the effective concentrations, double (T2) and quadruple (T3) concentrations were also administered to the left testis of the lambs included in the study. Accordingly, as pointed out by Lin et al., the studied treatments were performed by injection under the scrotum on both sides of the left testis once a week, repeated for four weeks [4]. The control group received 0 mg/kg (T0), and there was no difference regarding the injection volume between the experimental and control groups. The collection of the lambs' testes was performed four weeks after the treatment. Subsequently, the testes were transported to the laboratory for histological examination, isolation, and SSC culture.

2.3. Histology

Small sections of testicular tissue were preserved in modified Davidson's fluid overnight at a temperature of 4 ˚C. The specimens were first cleaned with 70% ethanol and then coated with paraffin wax. Afterward, they were sliced into thin 5 mm segments using typical procedures. These sections were then treated with xylene and ethanol. In the final phase, hematoxylin and eosin (H&E) were used for staining the sections in order to do histological analysis.

2.4. Isolating and culturing SSCs

Four weeks post-busulfan treatment, the researchers obtained the left testis from the male sheep. To isolate SSCs, a two-step enzymatic digestion process was employed, following a modified version of the method described by Rasouli et al [13]. In the initial enzymatic digestion step, the tunica albuginea was removed. Subsequently, approximately 50 g of tissue was finely cut into small fragments using fine scissors. These minced seminiferous tissue fragments were then suspended in Dulbecco's modified eagle medium (DMEM) obtained from Inoclon, Iran. The tissue was incubated in a shaker incubator at 37 ˚C for 45 minutes, resulting in separation. The supernatant above the tissue was collected, and the remaining solid material was washed with DMEM. To undergo a second round of enzymatic digestion, the solid material was combined with DMEM containing hyaluronidase type II, collagenase, and DNase. This mixture was also incubated in a shaker incubator at 200 cycles/min for 30 minutes. The suspension was then centrifuged at 1000 rpm for 2 minutes.

2.5. Enriching SSCs

To increase the number of SSCs, the liquid above the original sample was passed through two filters: first, an 80 µm filter and then a 60 µm filter made of nylon net. The cells that passed through the filters were then placed in 60 mm Petri dishes coated with a mixture of lectin and bovine serum albumin (BSA), using a technique previously explained by Jafarnejad et al [14]. To make the lectin-BSA coated dishes, the Datura stramonium agglutinin lectin was mixed with DPBS at a concentration of 5 µg/mL. The mixture was left at room temperature for 2 hours, and then the dishes were washed with DPBS containing 0.6% BSA. After that, the dishes were coated with BSA and left at room temperature for another 2 hours.

The cells were put onto dishes that had been covered with lectin and left to sit for roughly 5-6 hours at 37 ˚C in a CO_2 incubator with 5% CO_2 in the air. This procedure helped to ensure that any extraneous cells would attach to the lectin-BSA. Following the incubation period, the liquid containing the stem cells was transferred to a 15 mL tube and spun at 1000 rpm for 5 minutes. The liquid above the cells was then disposed of, and the solid material was mixed with DMEM.

2.6. Feeder layers preparation and culturing SSC

Fresh DMEM mixed with 10% fetal bovine serum (FBS) (Gibco, USA) was used for the preparation of feeder layers and SSC culture to revive the remaining cells in lectin-coated dishes. The cells were then placed in a CO_2 incubator with 5% CO_2 in air at 37 ˚C for 2-3 days. The purpose of incubation was to encourage the growth of these cells, which were mainly Sertoli cells, until they formed a confluent monolayer. To grow the cells, they were moved to a 50 mL cell culture flask after being treated with 0.25% trypsin-EDTA. A layer of feeder cells was created by deactivating Sertoli cells with 10 µg/mL of mitomycin-C for three hours. The cells were then rinsed five times with DPBS and finally washed with DMEM containing 10% FBS. The isolated SSCs were grown in a culture flask containing DMEM medium with 10% FBS, on top of a Sertoli cell feeder layer. The flask was then placed in a CO_2 incubator with a 5% CO_2 and 37 ˚C temperature. After 10 days, the primary culture hosted SSC colonies.

2.7. Characterizing and analyzing SSCs

The researchers employed alkaline phosphatase staining and measured the presence of GFRa1 and c-myc genes to characterize SSCs. To carry out the alkaline phosphatase staining, the SSC colonies were washed twice with DPBS, and staining was done using a kit from Sigma (Catalogue No. 86C) following the provided guidelines. The colonies were then counted using an inverted microscope.

2.8. The reduction assay of MTT

To create the feeder layer, 96-well dishes were coated with Sertoli cells treated with mytomycin. Then, SSCs were added to the layer after one day. The cells were then cultured for 48 hours in 96-well dishes with different concentrations of taxol, carboplatin, VBL and VCR (7.5 to 240 µg/mL of each drug) at a density of 5000 cells per well. To assess the cell viability, a Thermo Fisher Scientific kit was utilized following the manufacturer's guidelines.

Initially, 5 mg of MTT was combined with 1 mL of sterile PBS to produce a stock solution containing 12 mM MTT. Then, each well received 10 µL of the stock solution. Furthermore, a negative control was prepared with 100 µL of medium. The incubation of wells was conducted with the presence of 5% CO_2 at 37 ˚C for 4 hours. In the next phase, each well was provided with 100 µL of Sodium dodecyl sulfate-hydrochloric acid (SDS-HCl) solution. The small plate was kept in a damp chamber at 37 ˚C overnight. The concentration of formazan was measured using optical density at 570 nm. To eliminate the influence of Sertoli cells, 96-well dishes without SSCs were coated for each treatment. The toxic effects on cell viability were expressed as a percentage of the control's cell viability. The viability of untreated cells is considered 100% in all studies related to cell toxicity. LC_{50} values were estimated using a nonlinear regression method.

2.9. Isolation of RNA, reverse transcription and real time PCR

The process of isolating total RNA from a sample has been a significant procedure. Trizol reagent was used for the isolation, followed by DNase treatment to prevent DNA contamination. The RNA concentration was measured by detecting its absorbance at 260 nm. To create the first-strand complementary DNA, 0.5 mg of the total RNA was utilized, along with MMLV enzyme and oligo dT primers for reverse transcription.

The researchers employed real-time PCR to investigate the expression of certain markers. The PCR was formed with a final volume of 10 µL. To begin the real-time PCR process, the polymerase was activated by exposing it to a temperature of 94 ˚C for 15 minutes. This was followed by 40 amplification cycles, each consisting of denaturation at 95 ˚C for 10 s, annealing of specific primers at 60 ˚C for 15 seconds, and extension at 72 ˚C for 20 seconds. The process concluded with a final extension at 72 ˚C for 5 minutes.

Custom primers sequences employed for analyzing gene expression through real-time PCR were as follows:

β actin [5' ACCCAGCACGATGAAGATCA 3' (forward) and 5' GTAACGCAGCTAACAGTCCG 3' (reverse)]; gfra1 [5' CCACCAGCATGTCCAATGAC 3' (forward) and 5' GAGCATCCCATAGCTGTGCTT 3' (reverse) c-myc [5' AGAATGACAAGAGGCGGACA 3' (forward) and 5' CAACTGTTCTCGCCTCTTC 3' (reverse)].

The comparative threshold cycle (ΔΔCT) method was the analytical approach used for analyzing the data, and β actin was adopted as the endogenous control.

2.10. Statistical analysis

The data collected for the study were analyzed using SPSS software, version 16 (IBM, USA). Duncan's multiple-range test and one-way analysis of variance (ANOVA) were the inferential measures to compare multiple numeric datasets.

3. Results

In this study, the effect of different concentrations of taxol, carboplatin, VBL and VCR, both separately and in combination, on the survival of SSCs in vitro were studied. Based on these results, the most effective combination of the studied drugs was evaluated in an in vivo study regarding the survival of testicular spermatogonia in lambs.

3.1. The effects of each of the compounds of taxol, carboplatin, VBL and VCR on the viability of SSCs

In this experiment, the effects of toxicity and inhibitory concentration of 50% of each of the drugs taxol, carboplatin, VBL and VCR on SSCs were investigated. For this purpose, concentrations ranging from 7.5 to 240 µg/mL of each drug were applied to the cells for 72 hours

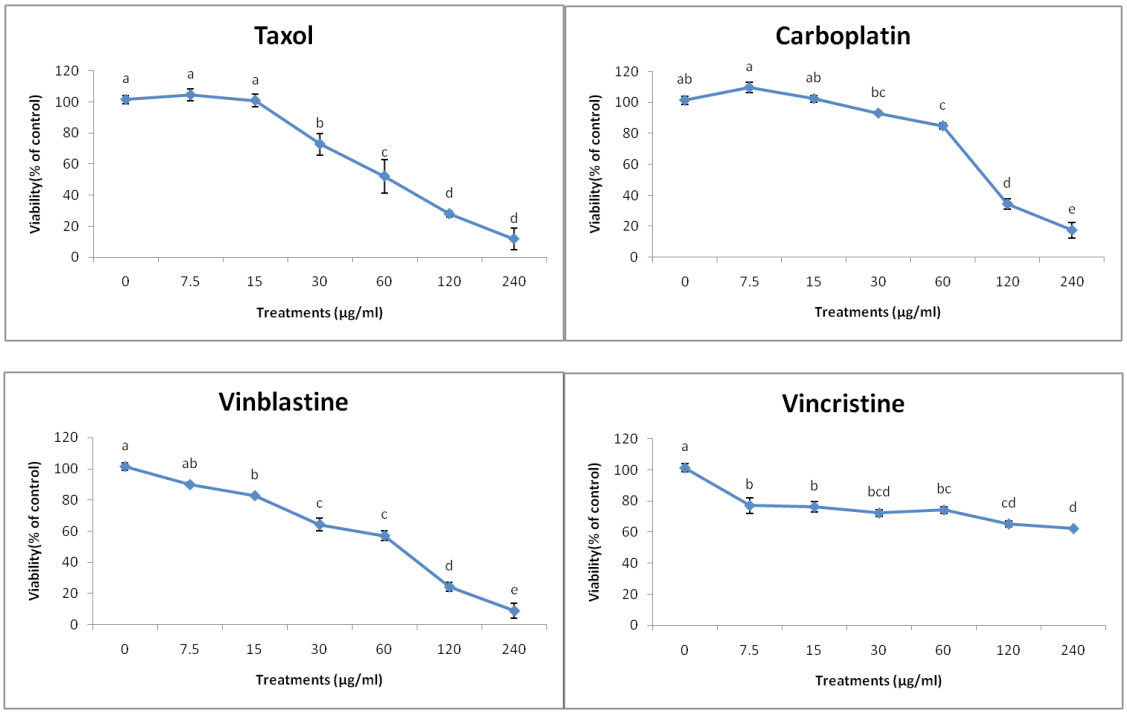

Figure 1 Viability of SSCs treated for 72 h with taxol, carboplatin, VBL, or VCR in a concentration range of 7.5–240 µg/mL

(Figure 1). The results showed that the survival of SSCs at concentrations equal to or greater than 30 µg/mL was significantly reduced compared to the control (P<0.05). Carboplatin at a concentration of 7.5 µg/mL increased survival, while at concentrations equal to or greater than 30 µg/mL, it significantly reduced SSC viability (P<0.05). In contrast, cell viability was significantly reduced by VBL and VCR at concentrations equal to or greater than 15 and 7.5 µg/mL, respectively.

3.2. Combination effect of taxol with VBL or VCR on the viability of SSCs

Figure 2 illustrates the impact of the combination of Taxol with VBL and VCR on the survival of SSC. The combination of Taxol and VBL at equal concentrations exceeding 60 µg/mL resulted in a significant reduction of SSC viability. Similarly, the combination of taxol and VCR at equal concentrations exceeding 15 µg/mL significantly decreased the viability of these cells (P<0.05).

3.3. Combination effects of carboplatin with taxol, VBL, or VCR on the viability of SSCs

Figure 3 displays the findings of treating SSCs with a mixture of carboplatin and taxol, VBL, or VCR. When used in equal concentrations of more than 30, 7.5, and 7.5 µg/mL, respectively, these combinations considerably reduced the viability of stem cells (P<0.05). carboplatin + taxol + VBL and carboplatin + taxol + VCR treatments at equal concentrations exceeding 30 µg/mL significantly reduced the viability of these cells (P<0.05).

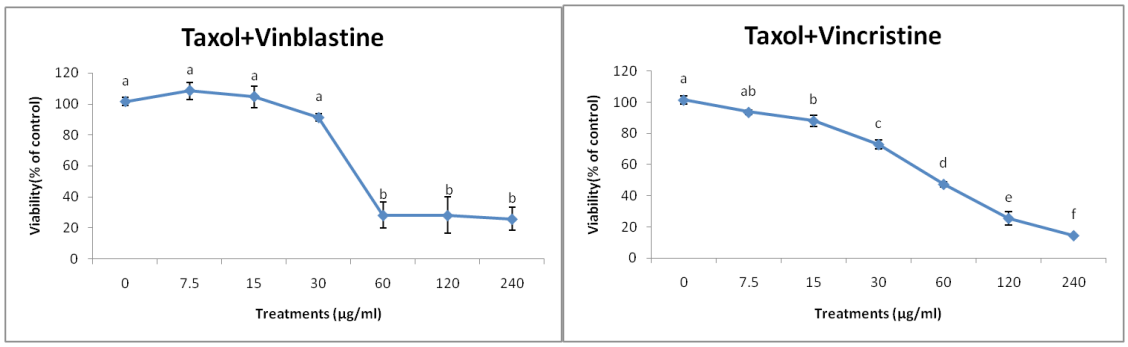

Figure 2. The combination of taxol with VCR and VBL within different concentrations of 7.5–240 µg/mL was used for SSCs viability treatment for 72 h

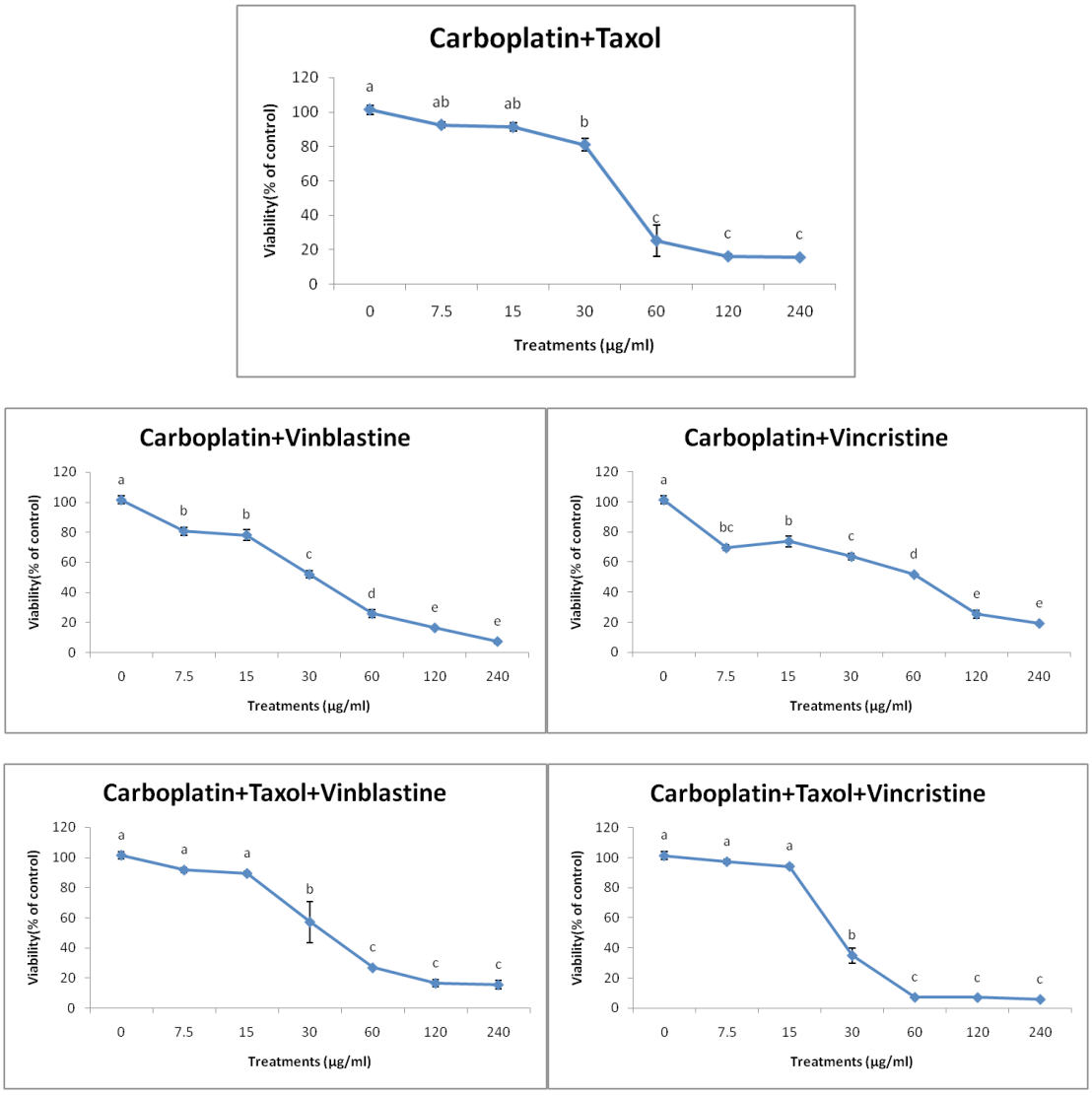

Figure 3. Description of an experiment where a type of cells called SSCs were treated with a combination of drugs for 72 h

Note: The drugs used were carboplatin, taxol, VBL and VCR, at different concentrations of 7.5–240 µg/mL.

3.4. The effects of taxol, carboplatin, VBL and VCR, both Individually and in combination, on the viability of SSCs by assessing their cytotoxicity

The results of the experiment show that the combination of carboplatin, taxol, and VCR at a concentration of 26 µg/mL had the highest inhibitory effect on the SSCs. The details of the results can be found in Table 1.

3.5. Effect of carboplatin + taxol + VCR on SSCs in vivo

Based on the results of the effects of taxol, carboplatin, VBL and VCR treatments on the survival of SSCs under in vitro conditions, the combination of carboplatin + taxol + VCR was selected for in vivo study. The effective concentration (T1: 1.0316, 0.453 and 0.0036 mg of carboplatin, taxol, and VCR, respectively) was calculated based on the manufacturer's recommendation. In addition to injecting the effective concentrations, double (T2) and quadruple (T3) concentrations were also studied on the left testis of the lambs.

3.6. Testicular weights after carboplatin + taxol + VCR treatment

The results of injecting three levels of carboplatin + taxol + VBL into the left testis of the lambs showed that injecting double (T2) and quadruple (T3) concentrations significantly decreased the mean testicular weight compared

Table 1. Cytotoxicity of carboplatin, taxol, VCR, or VBL or against the SSCs

IC_{50}	Treatments
59.92	Taxol
99.17	Carboplatin
52.81	VBL
98.75	VCR
56.41	Taxol + VCR
57.36	Taxol + VCR
47.24	Carboplatin + taxol
30.96	Carboplatin + VBL
48.32	Carboplatin + VCR
36.68	Carboplatin + taxol + VBL
25.99	Carboplatin + taxol + VCR

to other treatments and control. The largest decrease was related to the T3 treatment (P<0.05) (Figure 4).

3.7. Histological analysis

The testicular histological results of the studied lambs four weeks after the application of three levels of carboplatin + taxol + VBL are shown in Figure 5. As the concentration of the treatments increased, the number of spermatocytes decreased. The lowest cell count was observed at the highest concentration, which was four times the baseline level (T3).

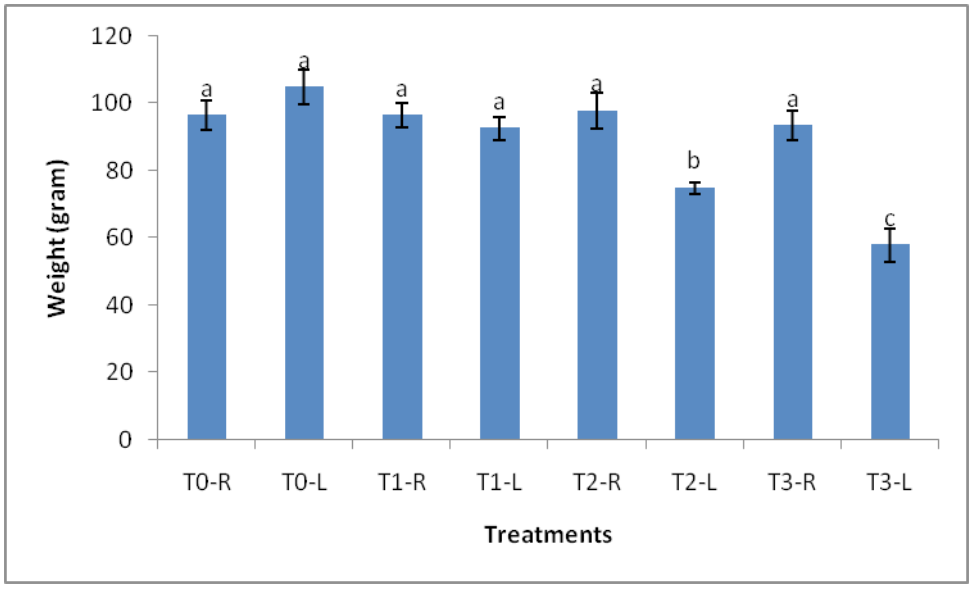

Figure 4. Mean testicular weight in controls (T0-R and T0-L) and different treatments

R: Right testis; L: Left testis.

Note: T1: 1.0316, 0.453, and 0.0036 mg of carboplatin, taxol, and VCR, respectively; T2: 2.0632, 0.906, and 0.0072 mg of carboplatin, taxol, and VCR, respectively; and T3: 4.1264, 1.812 and 0.0144 mg of carboplatin, taxol, and VCR, respectively.

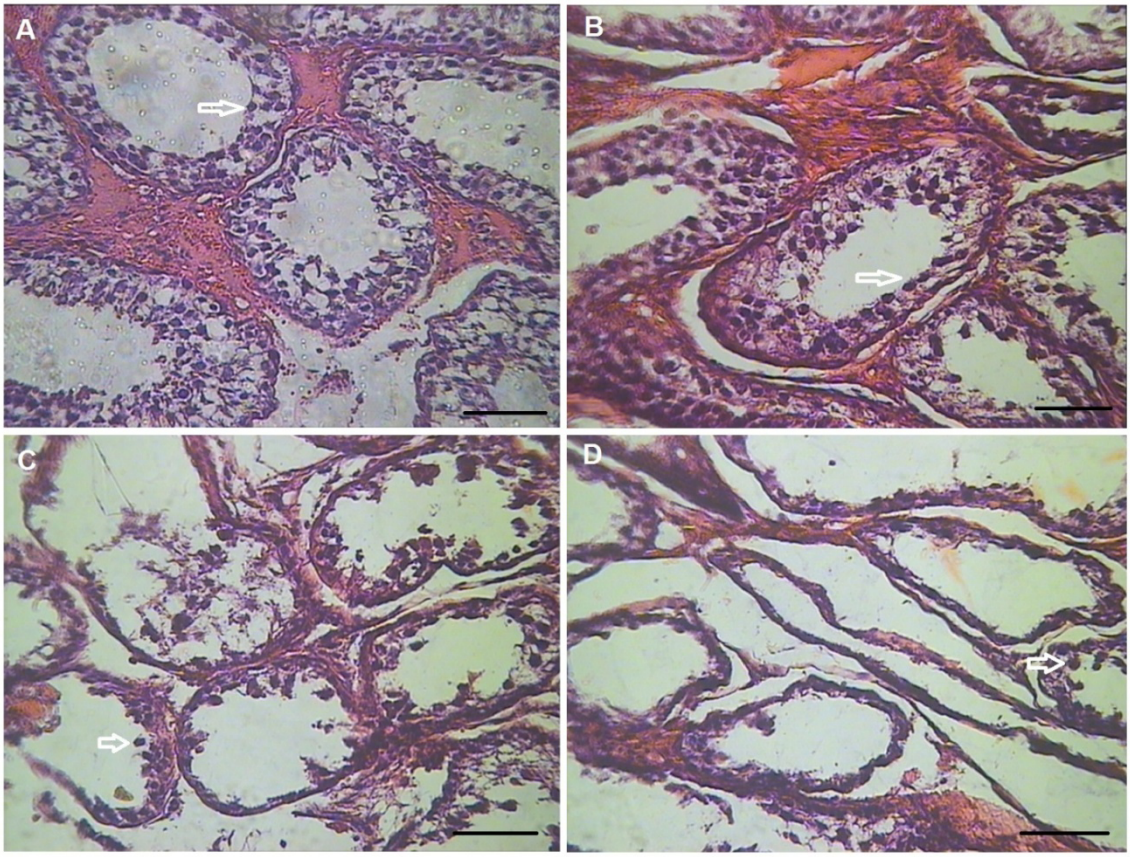

Figure 5. A section of tissue from ram testes under a microscope. Hematoxylin and eosin were used for staining the tissue

Note: Spermatogenesis is not fully developed, and the most advanced germ cell type seen is spermatocytes, which are indicated by arrows. The treatments are (A) control; (B) T1: 1.0316, 0.453, and 0.0036 mg of carboplatin, taxol, and VCR, respectively; (C) T2: 2.0632, 0.906, and 0.0072 mg of carboplatin, taxol, and VCR, respectively; and (D) T3: 4.1264, 1.812 and 0.0144 mg of carboplatin, taxol, and VCR, respectively (bars=50 µm).

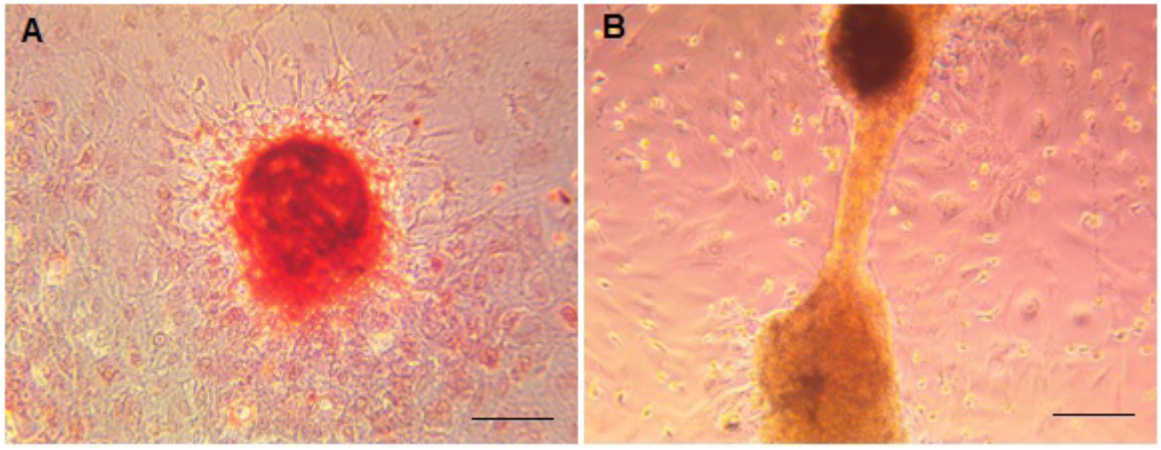

Figure 6. Alkaline phosphatase staining of ovine SSCs (A) and colony bridge (B). The appearance of SSC colonies was accomplished after 7 days in culture and after 10 days they were observed (Bar=0.5 mm).

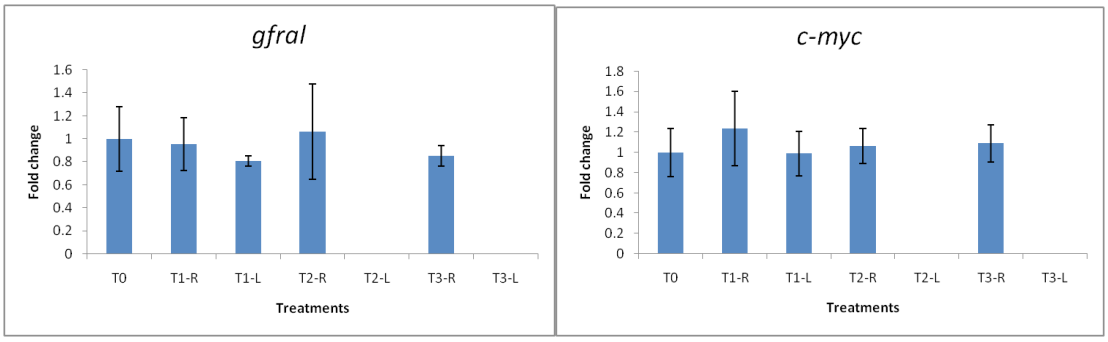

Figure 8. Real-time-PCR analysis of gfral and c-myc genes of different treatments

R: Right testis; L: Left testis.

Note: T0: control; T1: 1.0316, 0.453, and 0.0036 mg of Carboplatin, Taxol, and VCR, respectively; T2: 2.0632, 0.906 and 0.0072 mg of carboplatin, taxol, and VCR, respectively; and T3: 4.1264, 1.812 and 0.0144 mg of carboplatin, taxol, and VCR, respectively.

3.8. Formation of SSCs colony in vitro and their expression of specific gene

Four weeks after injection of carboplatin + taxol + VCR at three levels into the testes of the studied lambs, stem cells were extracted from the testes and cultured for 10 days. The results of staining the colonies with alkaline phosphatase as a specific marker of stem cells, as well as the formation of bridges between the colonies, are shown in Figure 6. It was found that double and quadruple concentrations of carboplatin + taxol + VCR led to a significant reduction in colony formation and the bridges between them (P<0.05) (Figure 7). Also, the expression of *gfral* and *c-myc* genes, as specific markers of stem cells, was significantly reduced in double and quadruple concentration groups of carboplatin + taxol + VCR compared to other treatments (P<0.05) (Figure 8).

4. Discussion

Previous studies have proposed that SSCT is possible in livestock such as pigs, cattle, sheep, and goats. However, none have yet simplified the approach enough to make it practical in an agricultural production context. A major difficulty in advancing this technology lies in the preparation of appropriate recipients [15]. Previously, in rodents, busulfan (a DNA alkylating agent) was utilized to eradicate germ cells in transplant recipients before transplantation. Nonetheless, the effective dose of Busulfan varies significantly depending on the species and strain, and the treatment may cause severe bone marrow depression, which can be fatal [16]. Due to the biological similarities of stem and cancer cells, this current study utilized herbal medicines such as taxol, VBL, and VCR, alongside car-

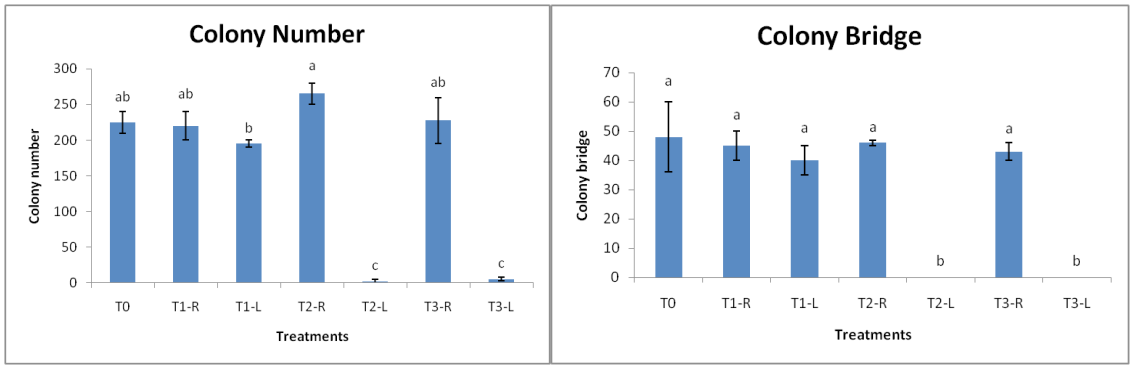

Figure 7. The effect of different treatments on the mean number of SSCs colonies and colony bridge

R: Right testis; L: Left testis.

Note: T0: control; T1: 1.0316, 0.453, and 0.0036 mg of carboplatin, taxol, and VCR, respectively; T2: 2.0632, 0.906 and 0.0072 mg of carboplatin, taxol, and VCR, respectively; and T3: 4.1264, 1.812 and 0.0144 mg of carboplatin, taxol, and VCR, respectively.

boplatin (a platinum derivative used in cancer treatment) to prepare recipients. The results reveal that the use of a combination of carboplatin, taxol, and VCR is recommended for the preparation of SSCs recipients in sheep.

The combination of anticancer drugs with complementary mechanisms often demonstrates strong synergistic effects. For instance, combinations such as carboplatin, taxol, and gemcitabine [17], taxol and verapamil [18], eribulin and taxol [19], and coralyn and taxol [20] have been shown to inhibit the growth of cancer cells and induces apoptosis. Additionally, combinations such as etoposide with cisplatin and mitomycin C with VBL, exhibit potent synergistic effects in breast cancer treatment [21]. The combination of vincristine and SAHA (a histone deacetylase inhibitor) also synergizes strongly by arresting the cell cycle and inducing apoptosis [22]. Furthermore, combining taxol with flavonoids reduces drug resistance and enhances therapeutic efficacy [23]. The combination of taxol and vincristine also shows strong synergistic effects in inhibiting cancer cell growth by disrupting cell division [24]. However, while sequential administration of taxol and VBL results in strong synergy, co-administration may lead to antagonistic effects [25]. These findings highlight that combining drugs with complementary mechanisms can enhance treatment efficacy and reduce drug resistance.

The results of Borovskaya et al. [26] showed a significant reduction in the maturity of the seminiferous tissue and the population of SSCs following treatment. Taxol inhibits DNA, RNA, and protein synthesis and arrests cells in the G2-M phases of the cell cycle, which results in the formation of genetically abnormal aneuploid cells. The antitumor effect of taxol is based on its capacity to bind formed microtubules and induce their polymerization.

VCR and VBL are types of plant alkaloids that prevent the formation of microtubules [27]. This leads to a halt in the mitosis process and ultimately results in cell death. These alkaloids also have a minor impact on pachytene spermatocytes, while higher doses mainly affect Sertoli cells by destroying their microtubules and mitochondria [28].

Delessard et al. [29] discovered that the testicular tissues of mice treated with VCR contained Sertoli cell-only tubules. It was suggested that prepubertal exposure may lead to the depletion of SSC in certain tubules. Furthermore, exposure to cyclophosphamide, VCR, and doxorubicin at concentrations used in humans can lead to a significant reduction in SSCs. Intraperitoneal injection of VCR was found to be more effective in eliminating the SSCs compared to intravenous injection [30]. Delessard et al. reported that pre-pubertal exposure to VCR or CYP caused sperm morphological abnormalities and DNA damage in adult mice. VCR also negatively impacted RNA synthesis [29]. Exposure to VCR may cause pachytene arrest in some seminiferous tubules by activating the pachytene checkpoint. Furthermore, DNA damage was observed in spermatocytes and spermatids, which hampers the progression of germ cells and leads to the demise of non-proliferating spermatid cells in mice [31]. Al-Ahmed found that some degenerated meiotic cells might cause damage to young spermatids' acrosomic system and cytoplasmic bridges. In mouse spermatogenesis, VCR has also been observed to inhibit thymidine uridine and l-leucine [32].

The human fetal testis is negatively impacted by chemotherapeutic drugs, specifically cisplatin and carboplatin, leading to a reduction in the quantity of germ cells, including gonocytes and pre-spermatogonia, as well as a decrease in germ cell proliferation. The inhibition of cell division during spermatogenesis, particularly following treatment with carboplatin, is likely attributed to the interaction between the platinum-based compounds present in carboplatin and DNA molecules. This disruption in cell division phases may have detrimental effects on the maturation of sperm cells [33].

In summary, both *GFRα1* and *Myc* play pivotal roles in regulating stem cell behavior; *GFRα1* acts as a receptor for GDNF signaling, which is essential for the survival and self-renewal of SSCs, while *Myc* controls the balance between self-renewal and differentiation, thereby modulating the dynamics and functionality of stem cells within various microenvironments [34-36]. Both *c-myc* and GFRa1 play key roles in SSCs: *C-myc*, as a transcription factor, regulates self-renewal and cell proliferation, and its expression is upregulated by GDNF through the PI3K/Akt pathway. *GFRa1*, as the GDNF receptor, provides essential signaling for the survival and function of these cells. In summary, *cmyc* is involved in proliferation, while GFRa1 supports signaling and survival in SSCs [37].

5. Conclusion

In conclusion, it is imperative to explore strategies for restoring sperm production in cases of impaired SSC. One potential approach under extensive investigation involves the combination of pharmaceutical intervention and the transplantation of testicular cells, aiming to augment the regenerative potential of the testes. The findings from in vivo experiments, including SSC culture,

gene expression analysis, and histology, demonstrated that the injection of a combination of carboplatin, taxol, and VCR at concentrations of 2/0632 mg, 0/906 mg, and 0/0072 mg, respectively (equivalent to twice the manufacturer's recommended concentration for cancer treatment), resulted in a significant reduction in the cell population when administered under the scrotum of four-month-old Shal lambs. The results of the present study recommended utilizing a combination of carboplatin, taxol, and VCR for the preparation of SSC transplant receptors in sheep.

Acknowledgements

The authors are grateful to the Agricultural Institute of the Iranian Research Organization for Science and Technology (IROST) for providing this project with laboratory facilities and other technical support.

Compliance with ethical guidelines

No live human samples were used in this study.

Data availability

The data that support the findings of this study are available upon request from the corresponding author.

Funding

This article is based on a project approved by the Iranian Research Organization for Science and Technology (IROST) (Project No.: 1011097005).

Authors' contributions

Conceptualization, study design, experiments, statistical analysis and data interpretation: Mohammad Zandi; Writing: All authors.

Conflict of interest

The authors declared no conflict of interest.

References

[1] Yu X, Riaz H, Dong P, Chong Z, Luo X, Liang A, et al. Identification and IVC of spermatogonial stem cells in prepubertal buffaloes. Theriogenology. 2014; 81(9):1312-22. [DOI:10.1016/j.theriogenology.2014.03.002] [PMID]

[2] Ma W, An L, Wu Z, Wang X, Guo M, Miao K, et al. Efficient and safe recipient preparation for transplantation of mouse spermatogonial stem cells: Pretreating testes with heat shock. Biol Reprod. 2011; 85(4):670-7. [DOI:10.1095/biolreprod.110.089623] [PMID]

[3] Rodriguez-Sosa JR, Dobson H, Hahnel A. Isolation and transplantation of spermatogonia in sheep. Theriogenology. 2006; 66(9):2091-103. [DOI:10.1016/j.theriogenology.2006.03.039] [PMID]

[4] Lin Z, Bao J, Kong Q, Bai Y, Luo F, Songyang Z, et al. Effective production of recipient male pigs for spermatogonial stem cell transplantation by intratesticular injection with busulfan. Theriogenology. 2017; 89:365-73.e2. [DOI:10.1016/j.theriogenology.2016.10.021] [PMID]

[5] Qin Y, Liu L, He Y, Wang C, Liang M, Chen X, et al. Testicular busulfan injection in mice to prepare recipients for spermatogonial stem cell transplantation is safe and nontoxic. PLoS One. 2016; 11(2):e0148388. [DOI:10.1371/journal.pone.0148388] [PMID]

[6] Ganguli N, Wadhwa N, Usmani A, Kunj N, Ganguli N, Sarkar RK, et al. An efficient method for generating a germ cell depleted animal model for studies related to spermatogonial stem cell transplantation. Stem Cell Res Ther. 2016; 7(1):142. [DOI:10.1186/s13287-016-0405-1] [PMID]

[7] Izadyar F, Den Ouden K, Stout TA, Stout J, Coret J, Lankveld DP, et al. Autologous and homologous transplantation of bovine spermatogonial stem cells. Reproduction. 2003; 126(6):765-74. [PMID]

[8] Suresh G, Kokila D, Suresh TC, Kumaran S, Velmurugan P, Vedhanayakisri KA, et al. Mycosynthesis of anticancer drug taxol by Aspergillus oryzae, an endophyte of Tarenna asiatica, characterization, and its activity against a human lung cancer cell line. Biocatal Agric Biotechnol. 2020; 24:101525. [DOI:10.1016/j.bcab.2020.101525]

[9] Panno ML, Giordano F, Mastroianni F, Morelli C, Brunelli E, Palma MG, et al. Evidence that low doses of Taxol enhance the functional transactivatory properties of p53 on p21 waf promoter in MCF-7 breast cancer cells. FEBS Lett. 2006; 580(9):2371-80. [DOI:10.1016/j.febslet.2006.03.055] [PMID]

[10] Sánchez-Carranza JN, Alvarez L, Marquina-Bahena S, Salas-Vidal E, Cuevas V, Jiménez EW, et al. Phenolic Compounds Isolated from Caesalpinia coriaria Induce S and G2/M Phase Cell Cycle Arrest Differentially and Trigger Cell Death by Interfering with Microtubule Dynamics in Cancer Cell Lines. Molecules. 2017; 22(4):666. [DOI:10.3390/molecules22040666] [PMID]

[11] Mora E, Smith EML, Donohoe C, Hertz DL. Vincristine-induced peripheral neuropathy in pediatric cancer patients. Am J Cancer Res. 2016; 6(11):2416-30. [PMID]

[12] Dvořák Z, Štarha P, Trávníček Z. Evaluation of in vitro cytotoxicity of 6-benzylaminopurine carboplatin derivatives against human cancer cell lines and primary human hepatocytes. Toxicology in Vitro. 2011; 25(3):652-6. [DOI:10.1016/j.tiv.2011.01.002] [PMID]

[13] Rasouli MH, Zandi M, Sadeghi AA, Emamjomeh-Kashan N. Spermatogonial stem cell survival in ram lambs following busulfan treatment. Anim Reprod. 2020; 17(2):e20200001. [DOI:10.1590/1984-3143-AR2020-0001] [PMID]

[14] Jafarnejad A, Zandi M, Aminafshar M, Sanjabi MR, Emamjomeh Kashan N. Evaluating bovine sperm transfection using a high-performance polymer reagent and assessing the fertilizing capacity of transfected spermatozoa using an in vitro fertilization technique. Arch Anim Breed. 2018; 61(3):351-8. [Link]

[15] Ciccarelli M, Giassetti MI, Miao D, Oatley MJ, Robbins C, Lopez-Biladeau B, et al. Donor-derived spermatogenesis following stem cell transplantation in sterile NANOS2 knockout males. Proc Natl Acad Sci U S A. 2020; 117(39):24195-204. [DOI:10.1073/pnas.2010102117] [PMID]

[16] Goharbakhsh L, Mohazzab A, Salehkhou S, Heidari M, Zarnani AH, Parivar K, et al. Isolation and culture of human spermatogonial stem cells derived from testis biopsy. Avicenna J Med Biotechnol. 2013; 5(1):54-61. [PMID]

[17] Bookman MA, Brady MF, McGuire WP, Harper PG, Alberts DS, Friedlander M, et al. Evaluation of new platinum-based treatment regimens in advanced-stage ovarian cancer: A Phase III Trial of the Gynecologic Cancer Intergroup. J Clin Oncol. 2009; 27(9):1419-25. [DOI:10.1200/JCO.2008.19.1684] [PMID]

[18] Li P, Zhong D, Gong PY. Synergistic effect of paclitaxel and verapamil to overcome multi-drug resistance in breast cancer cells. Biochem Biophys Res Commun. 2019; 516(1):183-8. [DOI:10.1016/j.bbrc.2019.05.189] [PMID]

[19] Oba T, Ito KI. Combination of two anti-tubulin agents, eribulin and paclitaxel, enhances anti-tumor effects on triple-negative breast cancer through mesenchymal-epithelial transition. Oncotarget. 2018; 9(33):22986-3002. [DOI:10.18632/oncotarget.25184] [PMID]

[20] Kumari S, Badana AK, Mohan GM, Shailender Naik G, Malla R. Synergistic effects of coralyne and paclitaxel on cell migration and proliferation of breast cancer cells lines. Biomed Pharmacother. 2017; 91:436-45. [DOI:10.1016/j.biopha.2017.04.027] [PMID]

[21] Decatris MP, Sundar S, O'Byrne KJ. Platinum-based chemotherapy in metastatic breast cancer: current status. Cancer Treat Rev. 2004; 30(1):53-81. [DOI:10.1016/S0305-7372(03)00139-7] [PMID]

[22] Chao MW, Lai MJ, Liou JP, Chang YL, Wang JC, Pan SL, et al. The synergic effect of vincristine and vorinostat in leukemia in vitro and in vivo. J Hematol Oncol. 2015; 8:82. [DOI:10.1186/s13045-015-0176-7] [PMID]

[23] Asnaashari S, Amjad E, Sokouti B. Synergistic effects of flavonoids and paclitaxel in cancer treatment: A systematic review. Cancer Cell Int. 2023; 23(1):211. [DOI:10.1186/s12935-023-03052-z] [PMID]

[24] Zandi M. Synergistic Effect of Taxol and Vincristine Against MCF-7 Cell Line. Gene Cell Tissue. 2023; 10(3):e126544. [DOI:10.5812/gct-126544]

[25] Giannakakou P, Villalba L, Li H, Poruchynsky M, Fojo T. Combinations of paclitaxel and vinblastine and their effects on tubulin polymerization and cellular cytotoxicity: characterization of a synergistic schedule. Int J Cancer. 1998; 75(1):57-63. [PMID]

[26] Borovskaya TG, Shchemerova YA, Poluektova ME, Vychuzhanina AV, Goldberg VE, Kinsht DN, et al. Mechanisms of reparative regeneration of rat testis after injection of paclitaxel. Bull Exp Biol Med. 2014; 156(4):483-5. [DOI:10.1007/s10517-014-2380-9] [PMID]

[27] Velez D, Ohlander S. Medical therapies causing iatrogenic male infertility. Fertil Steril. 2021; 116(3):618-24. [DOI:10.1016/j.fertnstert.2021.07.1202] [PMID]

[28] Vaisheva F, Delbes G, Hales BF, Robaire B. Effects of the chemotherapeutic agents for non-Hodgkin Lymphoma, Cyclophosphamide, Doxorubicin, Vincristine, and Prednisone (CHOP), on the male rat reproductive system and progeny outcome. J Androl. 2007; 28(4):578-87. [DOI:10.2164/jandrol.106.002428] [PMID]

[29] Delessard M, Saulnier J, Dumont L, Rives-Feraille A, Rives N, Rondanino C. Paradoxical risk of reduced fertility after exposure of prepubertal mice to vincristine or cyclophosphamide at low gonadotoxic doses in humans. Sci Rep. 2020; 10(1):17859. [DOI:10.1038/s41598-020-74862-8] [PMID]

[30] Hansen PV, Sørensen D. Effect of vincristine or bleomycin on radiation-induced cell killing of mice spermatogonial stem cells: The importance of sequence and time interval. Int J Radiat Oncol Biol Phys. 1991; 20(2):339-41. [DOI:10.1016/0360-3016(91)90116-l] [PMID]

[31] Zhang Y, Sun K. Unscheduled DNA synthesis induced by the antitumor drug vincristine in germ cells of male mice. Mutat Res. 1992; 281(1):25-9. [DOI:10.1016/0165-7992(92)90032-d] [PMID]

[32] Al-Ahmed HI. Effect of vincristine and vinblastine on mice spermatozoa in vitro. Baghdad Sci J. 2010; 7(4):1377-83. [Link]

[33] Tharmalingam MD, Matilionyte G, Wallace WHB, Stukenborg JB, Jahnukainen K, Oliver E, et al. Cisplatin and carboplatin result in similar gonadotoxicity in immature human testis with implications for fertility preservation in childhood cancer. BMC Med. 2020; 18(1):374. [DOI:10.1186/s12916-020-01844-y] [PMID]

[34] Cai Y, Deng M, Liu Z, Zhang G, Pang J, An S, et al. EZH2 expression and its role in spermatogonial stem cell self-renewal in goats. Theriogenology. 2020; 155:222-31. [DOI:10.1016/j.theriogenology.2020.06.013] [PMID]

[35] Oatley JM, Avarbock MR, Telaranta AI, Fearon DT, Brinster RL. Identifying genes important for spermatogonial stem cell self-renewal and survival. Proc Natl Acad Sci U S A. 2006; 103(25):9524-9. [DOI:10.1073/pnas.0603332103] [PMID]

[36] Kanatsu-Shinohara M, Tanaka T, Ogonuki N, Ogura A, Morimoto H, Cheng PF, et al. Myc/Mycn-mediated glycolysis enhances mouse spermatogonial stem cell self-renewal. Genes Dev. 2016; 30(23):2637-48. [DOI:10.1101/gad.287045.116] [PMID]

[37] Nasri Ahangar F, Zandi M, Sanjabi MR, Ghaedrahmati A. Comparative expression analysis of spermatogonial stem cell markers in cattle and sheep. Iran J Appl Anim Sci. 2023; 13(4):685-93. [Link]