

Differentiation of bone marrow derived mesenchymal stem cells into male germ-like cells in co-culture with testicular cells

Nasim MALEKMOHAMADI¹, Alireza ABDANIPOUR¹, Mehrdad GHORBANLOU², Saeed SHOKRI¹,
Reza SHIRAZI², Eva DIMITRIADIS³, Reza NEJATBAKHSH¹

¹Department of Anatomical Sciences, School of Medicine, Zanzan University of Medical Sciences (ZUMS), Zanzan, Iran;

²Department of Anatomical Sciences, School of Medicine, Iran University of Medical Sciences (IUMS), Tehran, Iran;

³Department of Obstetrics and Gynaecology, University of Melbourne, The Women's Hospital, Melbourne, Australia.

E-mail: abdanipour@zums.ac.ir

Objective. Stem cell therapy, specifically, pre-induction of mesenchymal stem cells toward male germ-like cells may be useful in patients with azoospermia. The aim of this study was to evaluate *in vitro* differentiation of mouse bone marrow-derived mesenchymal stem cells (BMSCs) into male germ-like cells by indirect co-culture with testicular cells in the presence of bone morphogenetic protein 4 (BMP4).

Methods. Experimental groups included: control (mouse BMSCs), treatment group-1 (BMSCs treated with BMP4), treatment group-2 (indirect co-culture of BMSCs with mouse testicular cells in the presence of BMP4) and treatment group-3 (indirect co-culture of BMSCs with testicular cells). BMSCs-derived male germ-like cells were evaluated by the expression of *Dazl*, and *Stra8* using RT-qPCR.

Results. *Stra8* gene expression was significantly increased in the treatment group-2 and *Dazl* gene was significantly increased in the treatment group-1 compared to other groups. In conclusion, indirect co-culturing of BMSCs with testicular cells and BMP4 leads to the differentiation of BMSCs into male germ-like cells which express specific male germ-like genes. Testicular cells released factors that contributed to the differentiation of BMSCs into male germ progenitor cells.

Conclusion. This study suggests that mesenchymal stem cells may be differentiated into male germ-like cells and therefore, may be a novel treatment option for men with azoospermia.

Key words: BMSCs, Bone Morphogenetic Protein 4, indirect co-culture, *Stra8*, *Dazl*

Infertility is defined as failure to achieve pregnancy after one year of regular unprotected sexual intercourse (Singh et al. 2016). Infertility in men may be caused by incomplete spermatogenesis, pituitary gland disorders, testicular cancer, aplasia of germ cells, varicoceles, environmental factors, congenital abnormalities, immune system disorders, and neurological factors (Iammarrone et al. 2003). There are two types of azoospermia: obstructive and non-obstructive. In the obstructive azoospermia, sperm

release is blocked from the ejaculatory ducts, meanwhile in non-obstructive azoospermia, there is low levels of sperm in the semen (Hussein 2013). In recent years, several studies have focused on the stem cell differentiation towards germ like cells for the treatment of non-obstructive azoospermia (Shirazi et al. 2012; Miryounesi et al. 2013; Makoolati et al. 2016). The use of mesenchymal stem cells may be an appropriate approach for the treatment of azoospermia (Gimble et al. 2007).

Bone morphogenetic protein 4 (BMP4) is a member family of transforming growth factor beta (TGF- β) (de Rooij 2001; West et al. 2009). At the cell surface of epiblast cells, BMP4 bind ALK3 and BMPR-II. BMP4 receptors consisting heteromeric complexes. The BMPR-II receptor phosphorylates the ALK3 receptor, BMP4 receptor regulated phosphorylation Smads (Smad1, Smad5, or Smad8). As soon as the activation, the Smads bind to Smad4 and are transmitted from the cytoplasm to the nucleus, they regulate the transcription of BMP4 target genes such as *Fragilis* gene (Saitou et al. 2003; de Sousa Lopes et al. 2004; Surani et al. 2004). Following this, cells lose their ability to respond to BMP4 and express *Stella*. At this stage, cells are called primordial germ cells (PGCs) expressing *c-Kit* (Pellegrini et al. 2003).

In the next stages of the differentiation, the cells express pre-meiotic (*Stra8*) and meiotic (*Sycp3*) genes (Shirazi et al. 2012). *Dazl* is introduced as a specific post-migratory marker of PGCs and mutations in this gene can cause azoospermia (Foresta et al. 2001; Shirazi et al. 2012). *Stra8* and *Piwil2* are specific markers for spermatogonial stem cells (SSCs) (Lee et al. 2006; Zhou et al. 2008).

Sertoli cells are chief somatic cells in the testis and are necessary for the spermatogenesis process because of their major role in the interactions with germ cells and facilitation of necessary nutrient transfer between the two (Skinner 1991). Additionally, Sertoli cells contribute to the development of the germ cells via follicle-stimulating hormone (FSH) and its receptor (Hansson et al. 1975). Other important cells in testis are myoid cells, which regulate the function of Sertoli cells through secretion of PmodS factor (Skinner and Fritz 1985). In addition, Leydig cells are testosterone producing cells, which interact with Sertoli cells to maintain spermatogenesis (Margioris et al. 1983; Skinner 1991). Leydig cells release several peptides that regulate Sertoli cells including β -endorphins, α -melanocyte stimulating hormone, and adrenocorticotrophic hormone (Fabbri et al. 1988).

In this study, the effect of testicular cells, as optimum micronutrient, on the differentiation of BMSCs to male germ-like cells using *in vitro* co-culturing of mouse BMSCs with mouse testicular cells was investigated. BMP4 was used to induce the differentiation process of the BMSCs toward germ-like cells.

Materials and methods

BMSCs isolation and culture. BMSCs were collected from the femur and tibia of 4–6 weeks old NMRI mice by flushing with high glucose DMEM

(Dulbecco's Modified Eagle's Medium; Gibco, Paisley, UK) containing 1% penicillin/streptomycin (Gibco, Paisley, UK). Fetal bovine serum (FBS) (20%) (Gibco, Paisley, UK) was also used for BMSCs culture. Cells were incubated for 48 h and non-adherent cells were removed by changing the medium after 2 days. The medium was changed every two days and continued until the third passage. Mesenchymal (CD90, CD44, and CD73) and hematopoietic (CD34, CD45) cell surface markers were used for identification of the BMSCs by flow cytometry. Briefly, BMSCs, at passage 3, were dissociated and the cell suspension was stained with fluorescence conjugated antibodies phycoerythrin-conjugated rat anti-mouse CD73, phycoerythrin-conjugated rat anti-mouse CD90, fluorescein isothiocyanate-conjugated rat anti-mouse CD44, phycoerythrin-conjugated rat anti-mouse CD34, fluorescein isothiocyanate-conjugated rat anti-mouse CD45 and (Abcam, USA) for 45 min at 4°C. After washing with PBS, staining buffer was added and the cells were used for flow-cytometry analysis. Cells were incubated by isotype control anti-bodies to measure the nonspecific background signal. Flow-cytometry analysis was performed using the BD FACsort device (BD Biosciences, USA).

Isolation and preparation of testicular cells. Testicular cells were isolated from 2–3-day-old NMRI male mice. Mice were sacrificed by cervical dislocation and then two incisions were performed in the skin of the lower part of the abdomen. The testicles were separated and placed in Petri dishes containing PBS. The testicles were then dissociated by sharp-tip scissors and digested enzymatically using trypsin-EDTA (Gibco, Paisley, UK). After additional vigorous pipetting, the relatively homogenous solution was centrifuged at 2500 g for 10 min, the supernatant was removed and enzyme was neutralized by FBS. This method is in accordance with Lacham-Kaplan et al. (2006).

BMSCs co-culture and BMP4 treatment. BMP4 (10 ng/ml; Sigma-Aldrich) treatment and indirect co-culture for 7 days, was used for BMSCs differentiation toward male germ-like cells (Dudley et al. 2007; Hamidabadi et al. 2011; Yang et al. 2016). BMSCs of third passage were placed at the bottom of the culture plate and the testicular cells were placed on the 0.4 μ m pore diameter biological barrier (ThinCert™ cell culture insert for 24-well plates, Greiner Bio-One International, Australia). Cells were incubated for 7 days in DMEM medium supplemented with 2–5% fetal bovine serum added to BMP4.

RT-qPCR analysis. Real-time qPCR assay was used for *Dazl*, *Stra8*, and *Piwil2* mRNA expression analysis and the fold changes between the treatments relative

to control groups determined. All gene expression values were normalized to β -Actin gene as internal control. Total RNA was isolated using TRIZOL reagent according to the manufacturer's instructions (Invitrogen, Carlsbad, CA). Isolated RNA was treated with 1 μ L DNase I enzyme according to the manufacturer's instructions (Fermentas, Germany). After that, 25 ng of purified RNA was used for synthesizing 25 μ L cDNA using RevertAid™ First strand cDNA synthesis kit (Fermentas, Germany) according to the manufacturer's instructions. To perform real-time PCR, cDNA (25 ng of RNA) was used to quantify *Dazl*, *Stra8*, and *Piwil2* mRNA levels. All primers are listed in Table 1. The PCR reaction was synthesized in a 12.5 μ L volume (sense and anti-sense primers, cDNA, SYBR Green,) and carried out for 40 cycles (Applied Biosystems). The delta CT method was used to analyze relative changes in mRNA levels.

Statistical analysis. In this experimental study, the quantification was performed using SPSS15 software based on three independent experiments. The results were presented as a mean \pm SEM. Normal distribution of data was determined using the Kolmogorov Smirnov test and values of $p > 0.05$ was considered normal. After testing for normality one-way analysis of variance (ANOVA) followed by Tukey's post hoc multiple group comparison test was performed. Values of $p \leq 0.05$ were considered statistically significant.

Table 1

Primer sequences and PCR parameters. Primers for amplification of target sequences, their Gen Bank accession number and the size of the fragment amplified are presented

Gene	Accession no.	Sense 5 \rightarrow 3 Anti-sense 5 \rightarrow 3	Size (bp)
B-actin	NM_007393.5	GGTCATCACTATTGGCAACG ACGGATGTCAACGTCACACT	72
<i>Dazl</i>	XM_006523583.3	AAGGCAAATCATGCCAAAC TCCTGATTCGGTTTCATCC	133
<i>Stra8</i>	XM_006505829.2	CTCCTCCTCCACTCTGTG GCGGCAGAGACAATAGGAAG	135
<i>Piwil2</i>	XM_006519329.3	CCTCCAGCTCTGTCTCCAAC CCTTGCTGACCAAAAGCTC	95

Primers were designed by Gene Runner 3.05 software (Product by: info@genfanavar.com). *Dazl* (Deleted in Azoospermia Like), *Stra8* (Stimulated by RA gene 8) and *Piwil2* (Piwi-like homolog2).

Results

BMSCs culture. Primary cultured BMSC cells were round, floating and their nuclei were invisible 12 h after culture (Figure 1A). After 3–4 days, BMSCs developed into colonies (Figure 1B). After 7–8 days, BMSCs reached 70–80% confluency after which the first passage was performed (Figure 1C). The cells were subsequently passaged every 3–4 days. BMSCs were

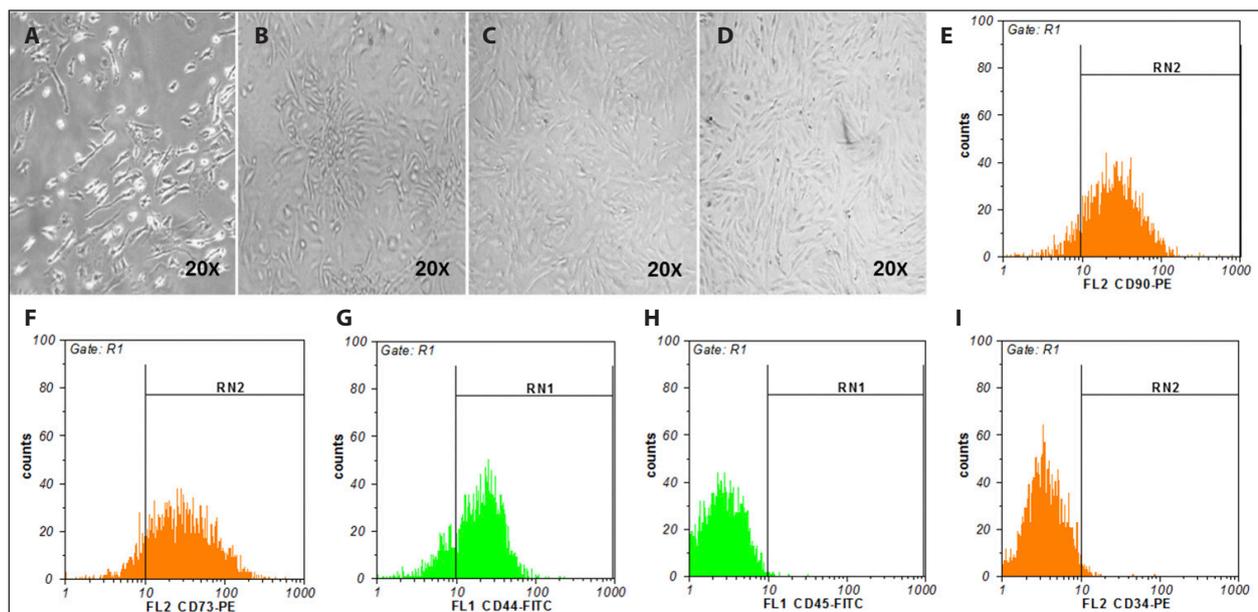


Figure 1. Representative photomicrographs of BMSCs isolation, culture and identification. (A) Primary culture after 12 h incubation; (B) cell colonies after 3–4 days of culture; (C) BMSCs after first passage; (D) homogenized BMSCs after 3 passages (day 14); (E, F, G) flow cytometric assay of CD90, CD73 and CD44, respectively (specific markers of mesenchymal stem cells); (H, I) flowcytometric assay of CD45 and CD34, respectively (markers for hematopoietic stem cells).

used for experiments at the third passage (Figure 1D). In order to identify BMSCs, flow cytometry analysis was used to detect specific mesenchymal stem cell markers. Isolated BMSCs were positive for specific mesenchymal cell surface markers including CD90 (87.48%), CD73 (85.86%) and CD44 (78.12%), and were negative for hematopoietic markers including CD45 (0.8%) and CD34 (2%) (Figure 1 E–I).

RT-qPCR results. Quantitative real time-PCR was used to detect the gene expression for specific germ-like cell markers *Dazl*, *Stra8*, and *Piwil2*. The control group (BMSCs without any treatment) was used as a calibrator and the expression of all genes were normalized to β -actin. The results are shown in Figure 2. The gene expression of *Dazl* in the BMSCs treated with BMP4 (3.73 ± 0.26) and in the indirect co-culture of BMSCs with testicular cells (4.16 ± 0.05) groups were increased significantly compared to the indirect co-culture of BMSCs with testicular cells in the presence of BMP4 group (0.46 ± 0.33), respectively ($p < 0.05$). *Piwil2* mRNA expression showed that its expression in groups of BMSCs treated with BMP4 (0.19 ± 0.42), indirect co-culture of BMSCs with testicular cells (0.22 ± 0.03) and indirect co-culture of BMSCs with testicular cells in the presence of

BMP4 (0.03 ± 0.00) were not significantly different compared to the control group, respectively. The expression level of *Stra8*, as a pre-meiotic gene, was increased significantly in the indirect co-culture of BMSCs with testicular cells in the presence of BMP4 group (6.18 ± 0.78) compared with BMP4-treated and co-culture groups (3.08 ± 0.29 and 2.01 ± 0.28 , respectively; $p < 0.05$).

Discussion

The findings of this study indicate that indirect co-culturing of BMSCs with testicular cells in the presence of BMP4 induces BMSCs differentiation toward the male germ-like cells (MG-LCs) expressing *Dazl* and *Stra8* genes. Additionally, factors released from the testicular cells had an important role on the differentiation of BMSCs toward MG-LCs.

Clinically, mesenchymal stem cells are one of the best sources of stem cell therapy owing to their unique characteristics including their high rate proliferation and potential to differentiate into specific cells. Moreover, the cells can be harvested easily and are relatively safe for transplantation with no tumorigenicity making them attractive for using clinically (Gimble et al. 2007; Latifpour et al. 2014). In similar studies, Sertoli cells and biomolecules such as retinoic acid, testosterone, and bone morphogenetic proteins (BMPs) have been used as inducing factors for the differentiation of stem cells toward germ-like cells. In the present study, all the testicular cells were used as an effective micro-environment to derive germ-like cells from BMSCs. The Sertoli, Leydig and Myoid cells, as functional somatic testicular cells, can influence the spermatogenesis process and germ cell differentiation. Leydig, macrophage and myoid cells affect Sertoli cells, therefore they are in an indirect association with germ cell differentiation (Skinner 1991). Sertoli cells secrete metabolic biomolecules such as insulin-like growth factor (IGF) and transforming growth factor beta and alpha (TGF- β and α) that are needed for germ cell differentiation and the regulation of spermatogenesis (Walker and Cheng 2005). IGF, through specific receptors located on the surface of germ cells, regulates DNA synthesis (Vannelli et al. 1988).

BMP4 is produced by extra-embryonic ectoderm before and during gastrulation. BMP4 binding to R-Smad and Alk3 receptors on the surface of germ cells activates transcription factors leading to the expression of PGC specific genes (Saitou et al. 2002). Therefore, BMP4 signaling is effective in the formation and differentiation of PGCs. Collectively, testic-

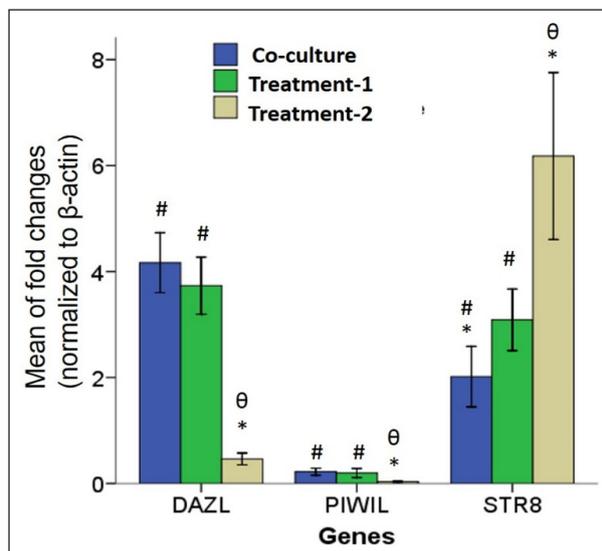


Figure 2. Quantitative real-time RT-PCR results of *Dazl*, *Piwil2*, and *Stra8* genes relative to control group. mRNA is presented as the relative expression normalized to β -actin mRNA amplification. Control (BMSCs without any treatment); treatment-1 (BMSCs treated with BMP4); Treatment-2 (indirect co-culture of BMSCs with testis cells in the presence of BMP4) and co-culture (indirect co-culture of BMSCs with testis cells). The bars indicate the mean \pm SEM; * $p < 0.05$ vs. treatment-1 group; θ $p < 0.05$ vs. co-culture; θ $p < 0.05$ vs. treatment-2 group.

ular cells are considered a potent source of many growth factors such as BMP4, leukemia inhibitory factor (LIF) and fibroblast growth factors (FGF- β), which are needed for spermatogenesis (Lacham-Kaplan *et al.* 2006). Several studies have shown that BMP4 is produced in the early stages of postnatal life by Sertoli cells and then its level decreases steadily. BMP4 receptors (Alk3 and BMPRII) are expressed on spermatogonial cells mainly during the first week after birth (Pellegrini *et al.* 2003). In consideration of these events, we used testicular cells from 2–3-day old male mice. The microporous barrier of the insert filters used for cell culture in this study, only transfer soluble factors secreted by the testicular cells, which induced BMSCs to differentiate toward male germ-like cells.

Several studies have indicated that over-expression of specific genes related to germ cells differentiation (*Dazl*, *Stra8* and *Piwil2*) are important for *in vitro* induction of BMSCs into germ-like cells (Yu *et al.* 2009). The expression of *Dazl* also provided preliminary evidence of mitosis (type A and type B spermatogonia), meiosis (primary and secondary spermatocytes), and spermiogenesis (Silva *et al.* 2009). We demonstrated higher expression of *Dazl* in the treatment-1 group (BMSCs treated with BMP4) after 7 days of treatment, which confirmed the findings of other studies on the role of BMP4 on the differentiation of BMSCs to germ-like cells. Another study conducted by Shirazi *et al.* (2012) has shown stage specific embryonic antigen 1+ (SSEA1+) cells treated with BMP4 expressed specific molecular markers of PGCs such as *Oct4*, *fragilis*, *stella*, and *Mvh* (Shirazi *et al.* 2012). Our results indicate that the indirect co-culture differentiation of BMSCs for 7 days, resulted in significant up regulation of *Dazl*. Xie *et al.* (2015) have shown that umbilical cord mesenchymal stem cells co-cultured with Sertoli cells for 4, 7, and 14 days increase expression of *VASA*, *Dazl*, and *Stella* (Xie *et al.* 2015). Miryounesi *et al.* (2013) have reported that *Oct4*, *Dazl*, and *Stra8* are expressed in the germ cells derived from embryonic stem cells after 7 days co-culturing with Sertoli cells (Miryounesi *et al.* 2013). Our results are in concordance with these previous findings.

Silva *et al.* (2009) have treated embryonic stem cells with testosterone for 2, 4, 7, and 14 days and reported the expression of *Dppa3*, *Sycp3*, *Msy2*, *Stra8*, *Sycp1*, *Dazl*, *Prm1*, *Piwil2*, *Tex14*, *Akap3*, and *Odf2* in the cells, which were induced for 14 days (Silva *et al.* 2009). According to the findings of the above mentioned study, it can be concluded that testicular cells are more effective than Sertoli cells and testos-

terone hormones in the differentiation of stem cells into germ cells. Zhang *et al.* (2014) have shown that the *in vitro* co-culture of BMSCs with Sertoli cells followed by the transplantation of induced cells to testis of mice with azoospermia can lead to the expression of specific spermatogonial genes such as *VASA*, *Dazl*, and *c-Kit* (Zhang *et al.* 2014). In accordance with our findings, studies have demonstrated the role of testicular cells and their interactions with stem cells in the derivation of germ cells from stem cells (Geens *et al.* 2011). *Piwil2*, also known as the *Mili* gene, is a known molecular marker of spermatogonia and has functions in many processes including gametogenesis and spermatogonial stem cell self-renewal. *Piwil2* is expressed between 12–14 days post coitum (dpc) in mice (Lee *et al.* 2006). The data from the present study showed no significant increase in *Piwil2* mRNA expression during the 7 days co-culture treatment alone or in presence of BMP4 which suggests that longer periods of co-culturing may be needed for *Piwil2* to be expressed. *Stra8* is expressed when the germ cells pass the fetal stage from mitosis to meiosis. This change has been indicated in the mouse germ cells around 12.5 (dpc) (Zhou *et al.* 2008).

According to our knowledge, this is the first report demonstrating that BMP4 and indirect BMSCs co-culture with testicular cells may result in germ-like cells, which expressed *Dazl* and *Stra8*. In recent years, the production of PGCs has been challenged in different types of stem cells in animals. Several studies were performed in order to differentiate different kinds of stem cells, such as embryonic stem cells (ESCs), induced pluripotent stem cells (iPSCs), bone marrow-derived mesenchymal stem cells (BMSCs) and umbilical cord stem cells (UCSCs) into germ cells. Makoolati *et al.* (2016) have demonstrated that in presence of BMP4 the embryonic stem cells can be induced into germ cells, which expressed β -Integrin, *Stra8* and *Mvh* genes (Makoolati *et al.* 2016). Latifpour *et al.* (2014) have shown that in the presence of BMP4 and retinoic acid human mesenchymal stem cells derived from umbilical cord can be induced into germ cell-like cells (Latifpour *et al.* 2014). Miryounesi *et al.* (2013) have shown the differentiation of embryonic stem cells into germ cells when co-cultured with Sertoli cells. The induced cells in their report express *Stra8*, *Sycp3* and *Dazl* genes after 7 days (Miryounesi *et al.* 2013). Additionally, Shirazi *et al.* (2012) have demonstrated that BMP4 can generate male germ-like cells from pluripotent bone marrow-derived SSEA-1+ cells (Shirazi *et al.* 2012).

It can be concluded that indirect co-culture of BMSCs with testicular cells in presence of BMP4 resulted in the derivation of germ-like cells. Our data may present a novel approach in the *in vitro* production of gametes and its use for the clinical applications.

Acknowledgments

The present study was funded by Zanjan University of Medical Sciences, Zanjan, Iran (grant number A-12-821-6).

References

- de Rooij DG. Proliferation and differentiation of spermatogonial stem cells. *Reproduction* 121, 347–354, 2001.
- de Sousa Lopes SM, Roelen BA, Monteiro RM, Emmens R, Lin HY, Li E, Lawson KA, Mummery CL. BMP signaling mediated by ALK2 in the visceral endoderm is necessary for the generation of primordial germ cells in the mouse embryo. *Genes Dev* 18, 1838–1849, 2004.
- Dudley BM, Runyan C, Takeuchi Y, Schaible K, Molyneaux K. BMP signaling regulates PGC numbers and motility in organ culture. *Mech Dev* 124, 68–77, 2007.
- Fabbri A, Knox G, Buczko E, Dufau ML. β -endorphin production by the fetal Leydig cell: Regulation and implications for paracrine control of Sertoli cell function. *Endocrinology* 122, 749–755, 1998.
- Foresta C, Moro E, Ferlin A. Y chromosome microdeletions and alterations of spermatogenesis. *Endocr Rev* 22, 226–239, 2001.
- Geens M, Sermon KD, Van de Velde H, Tournaye H. Sertoli cell-conditioned medium induces germ cell differentiation in human embryonic stem cells. *J Assist Reprod Genet* 28, 471–480, 2011.
- Gimble JM, Katz AJ, Bunnell BA. Adipose-derived stem cells for regenerative medicine. *Circ Res* 100, 1249–1260, 2007.
- Hamidabadi HG, Pasbakhsh P, Amidi F, Soleimani M, Forouzandeh M, Sobhani A. Functional concentrations of BMP4 on differentiation of mouse embryonic stem cells to primordial germ cells. *Int J Fertil Steril* 5, 104–109, 2011.
- Hansson V, Weddington SC, McLean WS, Smith AA, Nayfeh SN, French FS, Ritzen EM. Regulation of seminiferous tubular function by FSH and androgen. *J Reprod Fertil* 44, 363–375, 1975.
- Hussein A. Evaluation of diagnostic testis biopsy and the repetition of testicular sperm extraction surgeries in infertility patients. *Fertil Steril* 100, 88–93, 2013.
- Iammarrone E, Balet R, Lower AM, Gillott C, Grudzinskas JG. Male infertility. *Best Pract Res Clin Obstet Gynaecol* 17, 211–229, 2003.
- Lacham-Kaplan O, Chy H, Trounson A. Testicular cell conditioned medium supports differentiation of embryonic stem cells into ovarian structures containing oocytes. *Stem Cells* 24, 266–273, 2006.
- Latifpour M, Shakiba Y, Amidi F, Mazaheri Z, Sobhani A. Differentiation of human umbilical cord matrix-derived mesenchymal stem cells into germ-like cells. *Avicenna J Med Biotechnol* 6, 218–227, 2014.
- Lee JH, Engel W, Nayernia K. Stem cell protein Piwil2 modulates expression of murine spermatogonial stem cell expressed genes. *Mol Reprod Dev* 73, 173–179, 2006.
- Makoolati Z, Movahedin M, Forouzandeh-Moghadam M. *In vitro* germ cell differentiation from embryonic stem cells of mice: induction control by BMP4 signalling. *Biosci Rep* 36, pii: e00407, 2016.
- Margioris AN, Liotta AS, Vaudry H, Bardin CW, Krieger DT. Characterization of immunoreactive proopiomelanocortin-related peptides in rat testes. *Endocrinology* 113, 663–671, 1983.
- Miryounesi M, Nayernia K, Dianatpour M, Mansouri F, Modarressi MH. Co-culture of mouse embryonic stem cells with Sertoli cells promote *in vitro* generation of germ cells. *Iran J Basic Med Sci* 16, 779–783, 2013.
- Pellegrini M, Grimaldi P, Rossi P, Geremia R, Dolci S. Developmental expression of BMP4/ALK3/SMAD5 signaling pathway in the mouse testis: a potential role of BMP4 in spermatogonia differentiation. *J Cell Sci* 116, 3363–3372, 2003.
- Saitou M, Barton SC, Surani MA. A molecular programme for the specification of germ cell fate in mice. *Nature* 418, 293–300, 2002.
- Saitou M, Payer B, Lange UC, Erhardt S, Barton SC, Surani MA. Specification of germ cell fate in mice. *Philos Trans R Soc Lond B Biol Sci* 358, 1363–1370, 2003.
- Shirazi R, Zarnani AH, Soleimani M, Abdolvahabi MA, Nayernia K, Ragerdi Kashani I. BMP4 can generate primordial germ cells from bone-marrow-derived pluripotent stem cells. *Cell Biol Int* 36, 1185–1193, 2012.
- Silva C, Wood JR, Salvador L, Zhang Z, Kostetskii I, Williams CJ, Strauss JF 3rd. Expression profile of male germ cell-associated genes in mouse embryonic stem cell cultures treated with all-trans retinoic acid and testosterone. *Mol Reprod Dev* 76, 11–21, 2009.

- Singh A, Jahan N, Radhakrishnan G, Banerjee BD. To evaluate the efficacy of combination antioxidant therapy on oxidative stress parameters in seminal plasma in the male infertility. *J Clin Diagn Res* 10, QC14–QC17, 2016.
- Skinner MK, Fritz IB. Testicular peritubular cells secrete a protein under androgen control that modulates Sertoli cell functions. *Proc Natl Acad Sci U S A* 82, 114–118, 1985.
- Skinner MK. Cell-cell interactions in the testis. *Endocr Rev* 12, 45–77, 1991.
- Surani MA, Ancelin K, Hajkova P, Lange UC, Payer B, Western P, Saitou M. Mechanism of mouse germ cell specification: a genetic program regulating epigenetic reprogramming. *Cold Spring Harb Symp Quant Biol* 69, 1–9, 2004.
- Vannelli BG, Barni T, Orlando C, Natali A, Serio M, Balboni GC. Insulin-like growth factor-1 (IGF-I) and IGF-I receptor in human testis: an immunohistochemical study. *Fertil Steril* 49, 666–669, 1988.
- Walker WH, Cheng J. FSH and testosterone signaling in Sertoli cells. *Reproduction* 130, 15–28, 2005.
- West FD, Roche-Rios MI, Abraham S, Rao RR, Natrajan MS, Bacanamwo M, Stice SL. KIT ligand and bone morphogenetic protein signaling enhances human embryonic stem cell to germ-like cell differentiation. *Hum Reprod* 25, 168–178, 2010.
- Xie L, Lin L, Tang Q, Li W, Huang T, Huo X, Liu X, Jiang J, He G, Ma L. Sertoli cell-mediated differentiation of male germ cell-like cells from human umbilical cord Wharton's jelly-derived mesenchymal stem cells in an in vitro co-culture system. *Eur J Med Res* 20, 9, 2015.
- Yang Y, Feng Y, Feng X, Liao S, Wang X, Gan H, Wang L, Lin X, Han C. BMP4 cooperates with retinoic acid to induce the expression of differentiation markers in cultured mouse spermatogonia. *Stem Cells Int* 2016, 9536192, 2016.
- Yu Z, Ji P, Cao J, Zhu S, Li Y, Zheng L, Chen X, Feng L. *Dazl* promotes germ cell differentiation from embryonic stem cells. *J Mol Cell Biol* 1, 93–103, 2009.
- Zhang D, Liu X, Peng J, He D, Lin T, Zhu J, Li X, Zhang Y, Wei G. Potential spermatogenesis recovery with bone marrow mesenchymal stem cells in an azoospermic rat model. *Int J Mol Sci* 15, 13151–13165, 2014.
- Zhou Q, Nie R, Li Y, Friel P, Mitchell D, Hess RA, Small C, Griswold MD. Expression of stimulated by retinoic acid gene 8 (*Stra8*) in spermatogenic cells induced by retinoic acid: an in vivo study in vitamin A-sufficient post-natal murine testes. *Biol Reprod* 79, 35–42, 2008.