In Vitro Spermatogenesis; Past, Present, and Future

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Abstract

The study of culturing spermatogonial stem cells (SSCs) dates back to the 1950s. However, regeneration of complete spermatogenesis process in vitro is still a greater challenge. Studying spermatogenesis in vitro is significant in elucidating germ cell biology, and the knowledge may be useful for genetic manipulations of defective germ cells or producing transgenic animals, fertility preservation, and treatment of infertility. Fertility preservation would be more beneficial for adult and prepubescent patients who develop sterility due to gonadotoxins. Discovering of the stepwise stages in spermatogenesis and various forms of arrests at specific stages would help in the diagnosis of especially, idiopathic infertility and deciding treatment options. Different techniques have been tried to differentiate stem cells into germ cells over decades. A larger number of studies has used genetically manipulated stem cells to achieve differentiated germ cells. In contrast, differentiation of stem cells directly into SSCs bypassing the step into primordial germ cells (PGCs) to minimize time frame and employing techniques involved in least genetic manipulations are other important techniques to increase utilization within a clinical setting. As the use of transfected cell lines disqualifies the putative gametes obtained for clinical applications, trying to generate patient-specific germ cell with least genetic manipulations will be more effective in future applications, especially for patients with pre-pubertal cancer and azoospermic men who desire to become biological fathers.

Keywords: spermatogonial stem cells, germ cells, 3D culture, sperm, infertility

1. Introduction

Treatment of male infertility is always a challenge. Understanding correct pathological processes is difficult and time consuming as different etiologies may be responsible for a given semen parameter abnormality. It has been estimated that 8% of men in reproductive ages seek
medical reproductive assistance [1]. Among half of subfertile couples, male factor is the causative or contributory factor and according to our experience around 12% of subfertile men are severe oligozoospermics or azoospermics. In majority of azoospermia cases, especially in non-obstructive azoospermics, the etiologies are genetically manipulated, and treatment with foci of sperm using assisted reproductive technologies (ART) may carry a greater chance of genetic diseases in the outcome. In vitro matured sperm are a greater hope for those men to attain the biological fatherhood.

Spermatozoa are not only act as a vehicle for delivering paternal DNA to the oocyte, but also robustly contribute to epigenetic processes in embryogenesis. Sperm DNA and the chromatin structure as a unit, drive genes toward activation or silencing upon delivery to the egg [1]. For better performance, it has to undergo several rounds of morphological, biochemical, physiological, and epigenetic changes during spermatogenesis. Even after leaving the testis, sperm is subjected to further maturation in the epididymis, and is not fully competent to do the deterministic task until mixing with accessory gland secretions and activating several proteins, cytokines and signaling pathways. All those processes are interrelated with the stability of DNA it carries.

Modeling spermatogenesis will ease the study of complex biological interactions in vitro, in relation to gametogenesis and fertilization (i.e., epigenetic processes, transcription, translation variations, activation or silence of signaling pathways, etc.). In addition, the modeling will helps to elaborate genetic disorders or other pathological conditions and to discover new drugs (fertility drugs or contraceptive drugs). Rapid development of the field of bioinformatics is immensely useful toward this progress. However, the use of artificial gametes for fertility treatment is far from the vicinity considering the questions still to be answered.

One of the technical challenges in the study of spermatogenesis is lack of a proper in vitro model to recapitulate the process [2]. Recent development of techniques and technologies such as different cell culture systems gene cloning/transgenic animals, gene expression, gene silencing, mass spectrometry and microarray, etc., has immensely been contributed to identify a plethora of endogenous and exogenous factors in the regulation of this process. Compiling all these data in a proper order, for example, grouping expressed genes, proteins, and metabolites into functional categories may allow in recapitulating spermatogenesis process and better understanding of the underlying mechanisms of normal and abnormal pathways [3].

Attempts to make gametes outside the body (in vitro) or outside its niche (ex vivo) have been ongoing for more than a century [4], and there is a rapid escalation of research in the past decade. Main approaches in achieving this goal include (a) autologous or allogenic testicular transplantation of SSCs, stem cells or differentiated putative germ cells from other sources; (b) auto or xeno-grafting of testicular tissues, SSCs, differentiated putative germ cells into other parts of the body, for example, under the skin; (c) in vitro culture of SSCs, stem cells or differentiated putative germ cells with testicular tissues/cells (organ culture systems) or without testicular tissues; (d) sperm cloning, etc. Two main barriers encountered in the in vitro spermatogenesis process are; haploidization of stem cells or progression beyond pachytene stage, and inability to further differentiation of the few round spermatids obtained by culture, especially up to formation of tail.
2. Understanding the natural process of spermatogenesis

2.1 Models to describe spermatogenesis

Spermatogonial stem cells represent a very rare population of germ cells consisting about 0.03% (20,000–35,000) in adult mouse testes [5] or even lesser 2000–3000 [6]. Self-renewal of SSCs and spermatogenesis are described using different models. Among them, more detailed studies have been done with mouse. The “A-single” (A\textsubscript{s}) model originally proposed by Huckins et al., and according to them two types of SSCs are present in the seminiferous tubules; Type A and Type B. Type A—SSCs are more primitive due to absence of heterochromatin, while Type B cells are more differentiated as their nuclear heterochromatin content is high. Type A spermatogonia are subdivided into three groups according to their topological arrangements in the seminiferous tubule; A-single (A\textsubscript{s}), A-paired (A\textsubscript{pr}), and A-aligned (A\textsubscript{al}). Division of A\textsubscript{s} spermatogonia leads either to produce individual two new cells (self-renewing cells) or connected two cells by intercytoplasmic bridges (A\textsubscript{pr}). Further divisions of A\textsubscript{pr} lead to formation of A\textsubscript{al} or chains of 4, 8, 16, and occasionally 32 cells. A\textsubscript{s} represents the stem cell pool and same characteristics may remain among few A\textsubscript{pr} cells as well. Larger chains of A\textsubscript{al} (8, 16, 32) differentiate toward the Type A1 spermatogonia and then give rise to A2, A3, A4, Intermediate and B, respectively. These differentiated spermatogonia divide in a synchronize manner and found at specific stages of the seminiferous epithelial cycle. B spermatogonia differentiate into spermatocytes, and they undergo further divisions by meiosis to produce secondary spermatocytes and haploid spermatids, respectively. Single A\textsubscript{pr} cell passes eight mitotic steps resulting 1024 spermatocytes, and total 4096 haploid spermatids from subsequent meiotic division. Spermatids are subjected to 16 steps of morphological changes to become mature spermatozoa [7–9].

There are two other models to describe SSCs self-renewal: A0/A1 model and A-dark and A-pale model. In A0/A1 model normal spermatogenesis is maintained by an “active” pool of SSCs (A1) and other quiescent “reserve” pool of SSCs (A0) is mobilized only following an insult to spermatogenesis [10]. In higher primates and humans two types of morphologically distinct SSCs are described, A\textsubscript{dark} and A\textsubscript{pale}. Observing biological functions of two cell types, A\textsubscript{pale} is considered as progenitor cells and A\textsubscript{dark} as true stem cells. A\textsubscript{dark} represents only 1% of spermatogonia population, and stay dormant or divide very rarely if only progenitor cells have been destroyed. A\textsubscript{pale} proliferate at defined periods during each cycle of the seminiferous epithelium and differentiate into B spermatogonia while leaving sufficient amount A\textsubscript{pale} as functional reserve. In primates, single A\textsubscript{pale} involve 5 mitotic divisions producing 32 spermatocytes and finally 128 spermatids. Amount of clonal expansion is very low in humans, and only 16 haploid cells are produced through 2 mitotic and meiotic divisions as depicted in Figure 1 [11]. Due to low number of haploid cells produced by a single cell, both humans and primates maintain a population of progenitor cells (A\textsubscript{pale}) as a replenishment reserve. This is to minimize mitotic activity of true stem cells and preserve their genetic stability. Thus, the role of SSCs is to regenerate and sustain a cycling cell lineage, while progenitor population which is lacking regenerative capacity contributes to steady-state conditions [12]. There is no consensus on SSCs self-renewal in aforementioned models; whether it is through symmetrical (produce two stem cells or two interconnected cells destined to differentiate) or asymmetrical (produce one stem cell and other cell committed to differentiate). Using a mouse model, Wu
et al. support the theory of asymmetrical division. Furthermore, they have proposed that fate decision of mammalian SSCs bifurcation is autonomous and stochastic [13].

Spermiogenesis is the process of transformation of spherical, haploid spermatids (n) to sperm-like mature spermatids. Human spermatid develops into a mature sperm through a series of 12 steps and it takes about 5 weeks. It is assumed that nuclear condensation during this process shuts RNA synthesis, and proteins required in the period (mainly protamine) are produced by stored mRNAs derived from the diploid phase of spermatogenesis [14]. Contrary to this suggestion, supportive evidences are emerging on the minor activity of transcription in haploid spermatids as well [15]. Spermiation is the last process involving breakage of the structures and bonds anchoring mature spermatids to Sertoli cells in order to release spermatozoa into the tubule lumen. Peristaltic waves created by peritubular smooth muscle cells help to move spermatozoa and testicular fluids through the seminiferous tubules to the epididymis [16]. This ~10–16 days migration through epididymis helps sperm to attain motility and natural fertilization capacity up to a certain extent [17, 18]. The total motility and fertilizability is gained only after mixing with accessory sex gland secretions [19].

2.2. Regulatory mechanisms of natural spermatogenesis

Number of sperm produced per day by testes (daily sperm production, DSP) is a tool for quantitative assessment of spermatogenesis. DSP can decrease with reduced amount of true stem cells present, failure to produce committed $A_{\text{pale}}$ cells, changes in niche environment due to multitude of causes, age (DSP is low in very young and older men), etc. [20]. However, even in the normal spermatogenic procedure germ cells may degenerate at various levels; pre-leptotene and leptotene spermatocytes in older men, and pachytene/diplotene spermatocytes across all ages. This would be a mechanism of eliminating cells with genetic abnormalities [21]. Other possible reason is to maintain the ratio of Sertoli cells to germ cells, as one Sertoli cell can assist only to a specific number of cells. Furthermore, there is no fine regulation of formation of spermatocytes in different areas of tubules, resulting unequal distribution of those cells. The apoptosis mainly involving the BCL-2 family of apoptosis regulating proteins helps to maintain an equal density of spermatocytes along the seminiferous tubule [22, 23].
In normal seminiferous epithelium, there is a well balance between SSCs self-renewal and differentiation. Loss of the equilibriums may cause either germ cell tumor or infertility subsequent to SSCs depletion. However, in specific situations, such as toxicity-induced spermatocytes destruction, this balance may be shifted toward differentiation over proliferation. One of the main regulators identified in the SSCs self-renewal is glial cell line-derived neurotrophic factor (GDNF) secreted by Sertoli cells [24]; whereas, well-known differentiation factors are stem cell factor (SCF) secreted by Sertoli cells and biologically active derivative of vitamin A; retinoic acid (RA).

2.3. Markers expression during spermatogenesis

Knowledge on cytological markers expressed or suppressed at different stages of spermatogenesis is a key factor on rapid development of in vitro spermatogenesis strategies. Several cytological markers such as genes, transcription factors, cytokines, growth factors, enzymes, other proteins and micro RNAs (miRNAs), etc., have been studied at distinct phases of spermatogenesis pathway from embryonic germ cells allocation to postnatal spermatogenesis process which is broadly divided into three phases; proliferation, differentiation, and spermiogenesis. Some of them are surface antigens found in different regions of the sperm and others are intracellular; in the nucleus or cytoplasm. Knowledge on the expression of stage-specific cytological markers is vital on studying germ cells biology, normal and abnormal pathways of spermatogenesis and deciding corrective measures. Proper process of spermatogenesis requires precise coordination of multitude of genes. Stage-specific surface markers may be involved in differentiation process at least part by interaction with Sertoli cells [25]. Surface antigens are extensively used for tracking subset of germ cells at specific differentiation stages, but the process is hampered as very few markers have been identified so far. Although most of these markers expressed on SSCs and early stages of differentiation, little or none of these antigens remaining on the head or tail of the sperm [26]. Majority of markers have characterized with animal germ cells, specifically using rat and mouse germ cells, and very few of them have tested in humans. We assume that the presence and behavior of majority of these genes are more or less similar between animals and humans.

2.3.1. PGCs, SSCs, and spermatogonial progenitor cells (SPCs) markers

The chemokine receptor type 4 receptor (CXCR4) and DDX4 or mouse vasa homolog (MVH) genes are first expressed during migratory phase of PGCs, and MVH expression is continued until post-meiotic germ cells are formed. Decreased proliferative capacity of PGCs and defective spermatogenesis has been observed in MVH null mice. PIWI, Fragilis, SSEA1, and STELLA are other genes expressed in different levels in migratory PGCs. Fragilis is considered to be important for the migration of PGCs toward the genital ridges [27, 28]. B-lymphocyte-induced maturation protein-1 gene (BLIMPI) is involved in the initial specificiation of PGCs. Germ cells positive for BLIMP1 proliferate continuously, and this process can be helpful to express other PGCs markers such as Fragilis and STELLA. A network of transcription factors are involved in maintaining embryonic properties of stem cells. SALL4 is a member of Spalt-like transcription factor family, highly expressed in multiple embryonic tissues including PGCs and gonia-
ZBTB16) shows lower expression levels in embryonic germ cells and its peak in postnatal SPCs. It helps to maintain the properties of SPCs and also detected in early stages of SSCs differentiation. SALL4 and PLZF physically interact and mutually oppose one another’s localization to cognate chromatin domains depending on their relative expression levels at distinct stages of germ cells development. c-KIT, the transmembrane tyrosine kinase receptor for stem cell factor (SCF), also known as KIT ligand (KL) is essential to the proliferation and survival of differentiating spermatogonia, and its expression directly repressed by PLZF. At the time of differentiation, SALL4 level increases with suppression of PLZF facilitating to expression of c-KIT [29]. GPR125, an orphan adhesion-type G-protein-coupled receptor, is another gene exclusively expressed in SPCs and SSCs, and not in differentiated spermatocytes. GPR125 positive cells can be cultured in undifferentiated state with remarkable increase in their number [30]. A gene named transcriptional repressor inhibitor of differentiation 4 (ID4) was recently identified using a transgenic mouse model and it was highly expressed in most gonocytes, a subpopulation of SSCs, and a minor subset of pachytene spermatocytes [12]. But, they conclude the appearance of ID4 in pachytenic stage may be nonspecific, and proposed that ID4 positive subpopulation may be a heterogeneous population of SPCs and SSCs in mouse. Another subset of rare and highly proliferative Asingle spermatogonia has been characterized in mouse by expression of the paired box transcription factor (PAX7). Using cell lineage tracing studies they have confirmed that PAX7 cells function as bona fide stem cells [31]. The marker is co-expressed with well characterized other spermatogonial markers such as, c-KIT, PLZF, FOXO1, RET, and GFRα1. PAX7 was reported perfectly conserved in 11 different species, and it is resistant to chemo and radiotherapy insults [32]. GDNF seems to stimulate SSCs self-renewal by signaling through Ret and GFRα1 receptors system, and overexpression causes to an increase of undifferentiated spermatogonia in the testis [24]. POU family transcription factor 1 or octamer-binding transforming factor4 (POU5F1/OCT4) is expressed throughout the PGCs migration and later on in SSCs and differentiation male germ cells up to pachytenic stage [5]. Oct4 is rather considered as a pluripotency marker and expression is inhibited when RA binds to the responsive site, allowing the cells for differentiation. Many other markers expressed by SSCs and SPCs have described such as, TERT, POUSF1, RBM, HSP90x, NGN3, NANOS2 & 3, SOHLH1 & 2, integrin alpha chain 6 (ITGA6 /α6-Integrin/CD49f), LIN28, UTF1, CDH1, ITGB1 (β1-Integrin/CD29), EPCAM (CD326), CD9, CD24 and THY1 (CD90). LIN28 and EPCAM are increasingly expressed in malignant germ cell tumors indicating their role as maintenance of cells in undifferentiated state. The NANOS2 is also reported to block germ cells differentiation and lack of the gene induces progressive loss of germ cells in the postnatal testis [24, 28, 33–35]. New four marker genes specifically found in mouse PGCs and SSCs, but not in somatic cells were described as, FKBP6, MOV10l1, 4930432K21Rik, and TEX13 recently [36].

The above markers have been described using different techniques and most of them may have conserved among closely related animals during evolution. Results from RT-PCR analysis of freshly isolated human spermatogonia indicated that they are positive for GPR125, GFRα1, PLZF, ubiquitin carboxyl-terminal esterase L1 (UCHL1), and RET transcripts [37]. Using immunofluorescence and colorimetric staining it has been shown that human spermatogonia on the basement membrane express UTF1, SALL4, ZBTB16, GFRα1, UCHL1, GPR125, LIN28, EXOSC10, FGFR3, DSG2, CBL, SSX2, OCT2, OCT4alb, TERT, NANOG, ENO2, and PCNA (a proliferation marker). Not like in rodents, GPR125 is expressed only in subset
of SSCs in humans. SSCs expressing epithelial cell adhesion molecule (*EPCAM*), *THY1* and *ITGA6* have been enriched using fluorescence-activated cell sorting (FACS) and magnetic-activated cell sorting (MACS) techniques [38–41].

### 2.3.2. Differentiation markers

These markers can be categorized according to the timing of meiotic cycle; pre-meiotic, meiotic, and post-meiotic markers.

#### 2.3.2.1. Pre-meiotic

c-**KIT** is an early differentiation marker highly expressed in A$_{al}$ spermatocytes onward. c-**KIT** and its ligand SCF or KL are involved in growth and survival of germ cells. Interaction between the SCF positive Sertoli cells and the c-**KIT** positive germ cells are helpful for the progression through meiosis. Cytochrome p450 family 26, sub family b, polypeptide1 (*CYP26b1*) gene is increasingly expressed in pre-meiotic germ cells. It may prevent spermatocytes enter into meiosis by blocking the action RA, which is one of the key signaling molecule that helps to induce meiosis by binding through nuclear RA receptors. Stimulated by retinoic acid 8 (*STRA 8*) is the major responsive gene for RA induction and prominently expressed in pre-meiotic cells. At the same time RA receptors are expressed from type A spermatogonia to pre-leptotene spermatocytes in mice. Similarly, growth factor KL increases the percentage of meiotic entry in cultured spermatogonia concomitantly with an upregulation of *STRA8*. Activation of phosphatidyl inositol 3 kinase (*PI3K*) signaling appears to be important in meiotic initiation of germ cells [33, 42, 43].

**XT-1** is an adhesion related surface antigen found on differentiation spermatocytes in mouse testes. It is first detectable and uniformly distributed on leptotene spermatocytes, and later localized on the base of the head, tail and cytoplasmic lobe of the elongating spermatids [26]. Bone morphogenetic protein4 (*BMP4*) is an early differentiation marker, mainly activate through cell adhesion pathways and also upregulate c-**KIT** expression. It is prominently expressed in pachytene stage spermatocytes, and downstream proteins, SMAD1, 5, 8 are phosphorylated during BMP4-induced differentiation [17, 33]. SMAD1, 4, and 5 proteins are found in SSCs to round spermatids, while SMAD7 is found in differentiating spermatogonia up to round spermatids. SMAD8 is detected from spermatocytes to elongating spermatids [44]. Deleted in azoospermia-like gene (*DAZL*), *VASA*, *BLIMP1*, *STELLA* are also considered as pre-meiotic early germ cells differentiation markers [34]. Highest expression of *DAZL* is found in pachytene spermatocytes, and is assisted in the translation of MVH in the males. **Cyclin D2** is another gene expressed around epithelial stage VIII when the A$_{al}$ spermatogonia differentiate into A$_{1}$ stage [23].

#### 2.3.2.2. Meiotic

Specific markers well defined for meiotic germ cells are synaptonemal complex protein 3 (*SCP3*) gene and dosage suppressor of mck1 homolog (*DMC1*). Both SCP2 and SCP3 are components of the lateral element of the synaptonemal complexes and are associated with the centromeres in meiotic metaphase I cells. Another antigen named testicular differentiation antigen 95 (*TDA95*), residing on zygotene and early pachytene spermatocytes has been defined using two monoclonal antibodies, CA12 and BC7. *TDA95* may be one of the cell adhesion molecules between
spermatocytes and Sertoli cells, and plays an essential role during early meiotic prophase of spermatogenesis. SCP1, CREST, and Tesmin are other markers present in human pachytene spermatocytes. Tesmin expression coincides with meiotic entry of germ cells [25, 37]. BOULE
is a candidate meiotic regulator gene conserved among different species from drosophila to human, and deficient animals are infertile due to meiotic arrest in their male germ cells. The protein is detectable from pro-metaphase of first meiotic division to diplotene spermatocytes in humans and up to early spermatids in mice [45]. Similar expression pattern showed another meiotic promoter protein CDC25A, which was found in 11th and 11th spermatocytes and in some species up to elongating spermatids. Variations of three different isoforms of BOULE (BOULE1, 2, & 3) during spermatogenesis were described in humans [46]. SPO11 (a type II topoisomerase), H2A, TH2b are other few genes, needed for meiotic recombination [43, 47].

2.3.2.3. Post-meiotic

Expression of acrosin (ACR), transition protein 1 & 2 (TNP1, 2), ubiquitin-activating enzyme (UBE1Y), Kinesin light chain proteins (KLC3) and protamine1 & 2 (PRM1, 2) genes has been reported in post-meiotic cells [37]. ACR gene is transcribed in the diploid stage, and translationally expressed in the post-meiotic haploid cells. Hence, proacrosin is first localized in the cytoplasm of round spermatids. PRM1 and PRM2 are small and highly basic proteins that are reported to be transcribed in round and elongating spermatids. KLC3 is a testis specific protein and acts as an anchor protein for binding mitochondria to outer dense fibers of sperm tail. During the spermiogenesis, somatic histones are replaced with testis specific nuclear proteins, termed as transition proteins (TNP1 & TNP2), and subsequently TNPs are replaced with PRMs. Formation of extensive disulfide cross links between PRMs results in condensation of nuclear proteins and repression of transcriptional activity [48]. Alteration of PRM expression has been reported to affect human male fertility. For example, high susceptibility to DNA damage was reported with diminished levels [49]. Bone morphogenetic family proteins BMP8a and BMP8b receptors are expressed in male germ cells in a bimodal manner. First, low levels of transcripts are found in spermatogonia and primary spermatocytes, and subsequently higher levels are expressed in round spermatids. BMP8b is most important in initiation and maintenance of spermatogenesis [50]. Figure 2 depicts stage-specific expression of few selected markers commonly found in literature.

3. Attempts to differentiate spermatozoa outside the niche (in vitro, in vivo, and ex vivo)

Understanding the components of SSCs niche and their interactions with each other are vital aspects in regeneration of spermatogenesis in vitro. The in vivo niche of mammalian SSCs is comprised of Sertoli cells, peritubular cells, and a complex array of matrix proteins. The normal SSC pool is maintained throughout adulthood, through signals provided by adhesion molecules and other cell surface receptors. SSCs are exposed to signals from both tubular lumen and the interstitial space sides of the basement membrane. Fate of SSCs is regulated mainly by Sertoli cells, inter-tubular blood vessels, and surrounding Leydig cells also have a role [51]. Steady state of germ cell niche can be disturbed by physiological changes of individual components by intrinsic or external factors. Regeneration of sperm has been difficult due to incomplete understanding of complex interactions within the niche environment, and germ cell-specific events such as, meiosis, chromatin re-modeling/repackaging,
flagellum development and transcriptional reprogramming, etc. [52]. However, some recent advancements in sciences, such as construction of “omics” databases involving genomics, proteomics, and metabolomics have immensely contributed to rapid development of germ cell biology. Studies have shown that thousands of genes are successively expressed or suppressed leading to changes in biochemical composition in germ cells along the spermatogenesis pathway. Epigenetic reprogramming of genes and post transcriptional modifications of proteins are further favored this process. In addition, miRNAs play a significant role in regulating germ cells differentiation [37]. Based on the available data scientists have developed in vitro culture systems to induce male germ cells development from different types of stem cells. The improved culture systems facilitate to study the distinct pattern of gene expression in germ cells at various developmental stages.

Recapitulation of spermatogenesis completely or as in part, outside its niche is essential to understand the series of biological events associated with this complex process. The techniques can be utilized to study the germ cell biology (mitosis, meiosis, morphogenesis, initiation of motility, etc.) toxicological studies, fertility preservation, production of transgenic sperm, and have the potential for new therapeutic approaches in male infertility [53]. Continuous attempts have been made using pre-existing immature germ cells or various sources of stem or somatic cells as the starting source for in vitro derived gametes with satisfactory results [54]. However, same weight can be given for the doubts still have to be clarified. The strategies are broadly categorized into three aspects; development of different culture systems, haploidization, and differentiation of germ or somatic cells, and autologous or xenologous transplantation of germ or putative germ cells.

Methods to isolate SSCs from testicular tissue and differentiate into haploid cells or further to sperm, with feeder or feeder free conditions have been explored in different studies. Enrichment of SSCs in vitro facilitates dissection of germ cells biology, because SSCs represent a very rare population of germ cells consisting about 0.03% (20,000–35,000) in adult mouse testes [5] or even lesser 2000–3000 [6]. Early attempt to germ cell culture (in which whole segment of seminiferous tubules were maintained in culture) goes back to 1964 [55]. The first human SSC culture was reported in 1998 using a crude extract of testicular tissue, and the efficacy has now been improved with varying techniques [56]. Digested testicular tissues from obstructive azoospermic men cultured with high concentrations of follicle-stimulating hormone (FSH) and testosterone continued the in vitro reduction of germ cell ploidy with rapid morphological changes toward spermiogenesis. Two different mechanisms are possibly involved in endocrine regulation of the above process, and they would be, prevention of Sertoli cells apoptosis by testosterone and stimulation of the spermiogenesis by FSH [57]. Following a simple two enzymatic digestion protocol OCT4+ SSCs were isolated from human testis with 87% purity. SSCs colonies were able to culture for around 1 month on a Sertoli cells feeder layer [40]. In another study, THY1+ mouse SSCs have been cultured in the presence of Sertoli cells, hormones (FSH/testosterone) and vitamins (RA/vit.E/C), either with a mix of three components or with individual components. After 7 days of culture spermatid-like cells expressing post-meiotic markers were prominent in mixed supplement group compared to individual supplements [47]. Addition of FSH to bovine SSCs culture has proven the increased colonization capacity of spermatogonia [58].
Differential plating is the simplest technique isolating germ cells from digested testicular tissues. However, a highly purified SSCs population is expected only from sorting of cells using combination of surface markers. The array of potential markers reported for isolating SSCs are GPR125, ITGA6, CD9, or GFRα1 [51]. Culturing of SSCs isolated using differential plating technique from testicular tissue of cancer patients, in laminin or gelatin coated wells (feeder free conditions) and serum free culture media supplemented with human GDNF, bFGF, EGF and LIF resulted in the increase of GPR125+ cells from 2 to 70% [59]. In another study, human adult SSCs were able to culture in laminin coated plates, up to 28 weeks with 18,000-fold increased in number in the presence of LIF, bFGF, GDNF, and EGF [60]. In contrast, SSCs underwent massive apoptosis in feeder free conditions, but testicular somatic cells together with GDNF supported the propagation of SSCs more than 1 year [51].

Maintaining the spatial arrangement of testicular cells seems to be important in the process of regulation and completion of spermatogenesis. The goal may be achieved by arranging germ and somatic cells in three-dimensional (3D) culture systems by formation of embryoid bodies (EBs) or culturing the cells in soft agar or methyl cellulose [61]. Two culture systems are depicted in Figures 3 and 4. The studies have been highlighted that, low temperature (equal to testicular temperature), endocrine factors, and supporting somatic cells are prerequisites to be considered in in vitro spermatogenesis. Supportive mechanisms provided by somatic cells to develop germ cells are controversial. Presence of somatic cells, but not necessarily the direct contact is suggested for in vitro proliferation of male germ cells in one study [61] In contrast, significance of direct cell to cell contact between Sertoli cells and stem cells has been emphasized for successful germ cells formation from Warton’s jelly-derived mesenchymal stem cells [62]. Reasons of such kind of variations, whether due to the source of cells used for differentiation of germ cells or specific stage of supporting along the differentiation process, should further be investigated.

Transmeiotic differentiation is one of the critical step in the spermatogenesis pathway, and it is inducible employing bio-mechanical or chemical methods such as, simulated gravity, KL, or RA. c-KIT+ spermatogonia cultured under simulated microgravity for 48 h entered into meiosis even in the absence of exogenous supplements or Sertoli cells. Microgravity may act as an inducer or accelerator in the progression of meiosis [43]. Co-culture with testicular somatic cells, induction with RA and BMP4 are other well documented methods for meiotic initiation of SSCs. Mouse embryonic stem cells (ESCs) are reported to enter early meiosis when co-cultured with Sertoli cells compared to culture provided with RA. Sertoli cells provide RA for germ cells in two ways; by direct delivery of RA and delivery of retinol via membrane receptor STRA6 [63]. Rate of germ cells formation and meiotic entry may also vary in...
different culture systems, and with the source of cells used. For example, 3% of bone marrow mesenchymal stem cells (MSCs) were differentiated into germ cells when treated with RA [64]. Another study achieved around 20% of germ cells after co-culturing human ESCs with fetal gonadal stromal cells [65]. Mouse-induced pluripotent stem cells (iPSCs) treated with BMP4 led to formation of 41% primordial germ cells like cells [66]. However, very limited or pseudoentry of meiosis was noted by many studies. Around 3–5% of haploid cells were present in FACS sorted cells after induction of mouse SSCs in differentiation medium [67]. Similarly, 1–5% of post-meiotic cells were emerged when hESCs derived embryoid bodies (EBs) were treated with mouse testes conditioned medium supplemented with RA and BMP4 [68]. In contrast, 20% of haploid cells were observed in BMP4-induced human IPCs culture, and around 70% was positive for acrosin after sorting for 1 N cells [69]. Cell organization in EBs may reflect more of the arrangement of embryonic gonadal ridge [64], and correct erasure of imprinting genes was observed with EBs culture system [70]. It has been reported that, testosterone causes to increase in STRA8 mRNA levels (pre-meiotic marker) when cells were treated with both RA and testosterone [71]. The spontaneous differentiation of stem cells into haploid state may also be possible in appropriate culture conditions with a very low efficiency, amounting around 2% in human iPSCs culture [69]. Spontaneous differentiation may increase with prolongation of culture, and due to inducing factors contained in culture medium. For example, media supplemented with 10% fetal bovine serum contain approximately $3.6 \times 10^{-8}$ M of RA [72]. However, spontaneous differentiation of ESCs into germ line is generally low and inefficient with majority of germ cells undergoing degeneration [71].

Most of data have produced from very short period of cultures (2–30 days), indicating germ cell differentiation proceed an unusual speed in vitro. It is not clear how the timing went shorten, and it has been suggested that in the absence of environmental cues, germ cells may develop according to an intrinsic clock [73]. However, establishing a standard culture system of SSCs is difficult due to many reasons. Inherent variability between cells of different species leads to inconclusive results. For example, feeder cells and serum in culture may positively be

Figure 4. SSCs co-cultured with Sertoli cells in embryoid bodies culture system. A—initial culture (day 5) showing spermatocytes and spermatids like stages. B—late phase of culture (day 14), few sperms with normal morphology are observed (arrow heads).
affected on some cell lines, but not on others. Batch to batch variations of serum and positive or negative impact of unknown factors added by both feeder cells and serum are also concern [56]. Many authors emphasize the requirement of refined culture system eliminating serum and feeder cells to better understanding of individual cellular and molecular interactions.

The in vitro maturation of available germ cells has a little value considering the therapeutic aspects of infertile men especially for men with non-obstructive azoospermia. To overcome this situation, ESCs derived gametes were tested as a first line remedial step by scientific community. Initial attempts were least successful due to unresponsiveness of cells for specific media or culture conditions [74]. However, encouraging models have been described later on by different authors, not only for ESCs but also for other multipotent cell types including iPSCs and somatic stem cells. Two main approaches for this are (a) direct differentiation of stem cells into germ cell lineage using exogenous factors; (b) transfection of stem cells with marked or fluorescent proteins linked to specific gene promoters, such as STRA8 and PRM1 [75]. These methods can be employed as monolayer adherent cell culture or three-dimensional embryoid bodies, with or without feeder cells. Optimum time point for obtaining germ-like cells from human pluripotent stem cells (PSCs) was recorded day 10, while day 7 cultures yielded lower numbers and day 15 not indicated a significant increase [67]. It is reported that germ cell formation in EB culture system seems to faster than in monolayer culture system [76]. Given the priority for direct differentiation method is more acceptable as gene transfection method disqualifies in clinical applications. However, the gene transfection and iPSCs systems may provide the necessary information on the behavior of related genes in germ cell development. Whatever the method employed, the imprinting regulation of gametes obtained from concerned methods has to be further validated, if ever they are to be used for clinical applications [73].

The possibility of using PGCs and germ line stem cells (GSCs) in transplantation studies to restore fertility has been studied with varying degrees of success [65]. Grafting or transplantation of gonadal fragments, germ cells or genetically modified germ cells and transmeiotic pluripotent stem cells onto immune compromised animals is an alternative strategy to investigate germ cell development. Successful autologous-transplantation of spermatogonial stem cells has achieved in a wide range of species so far [77]. Autologous cryopreserved testicular tissue grafting is an option for preserving genetic materials in endangered species and immature cancer patients. Success of homing ability of grafts may depend on various factors such as, age of collecting graft (immature is the better), low GnRH level (suppressed spermatogenesis with more primitive cells), method of cryopreservation, etc. [78]. Homing ability of SSCs from different species including human, to basement membrane of seminiferous tubules of nude mice has been proven by many authors [60]. The niche for spermatogonial proliferation appears to be generally similar among different species, because proliferation is undisturbed between cross-species after xenotransplantation of spermatogonia. However, the niche for spermatogonial differentiation is thought to work through a species-specific mechanism [78].

The most advanced progress in meiosis and qualified male gametes may be obtained following transplantation of in vitro derived PGCs or GSCs into the testis. The ability to develop more mature germ cells from PGCs like cells derived from mouse iPSCs has shown after
| Source of cells | Method used | Observations | References |
|----------------|-------------|--------------|------------|
| BM stem cells from STRA8-EGFP transgenic mouse line | Induced with RA (10 μm) for 10 days, and EGFP positive cells were sorted using FACS | 3% cells differentiated into male germ cells assessed by OCT4, Fragilis, STELLA, MVH, RNF17, DAZLI, c-KIT, PIWIL2, RBM, STRA8, TEX 18. But arrested at pre-meiotic stage | Nyernia et al. [64] |
| hESCs (HSF1, HSF6 and H9) and hIPS | Co-cultured with human fetal gonadal stromal cells for 14 days | 20% germ cells with triple positive markers (cKIT, SSEA1 & PLAP or VASA). Repression of HOX genes and imprint erasure by day 7. No report of meiosis | Park et al. [65] |
| hESCs (H1) and iPSCs (HFF1) | Cultured in mouse SSCs differentiation medium for 10 days and haploid cells were confirmed after sorting by FACS | UTF1, PLZF and CDH positive spermatogonia, HIWII and HILL-positive spermatocytes, and ACR, TP1 and PRM1 expressing haploid cells (3.9–4.5%) were observed. Unimpaired uniparental genomic imprints on two loci: H19 and IGF2 | Easley et al. [67] |
| iPSCs (iHUF4/IMR90) | Induced with BMP-4, 7, and 8b for 14 days in feeder free conditions | Increased Vasa and DAZL expression. 4–6% GFP positive cells within 14 days. | Panula et al. [69] |
| hESCs (H9/HSF1) | Transduced with VASA-GFP reporter | Increased number of meiotic cells in DAZL overexpressed cells | Miryounesi et al. [63] |
| STRA8-EGFP transfected Mouse ESC line (C57BL6) | Co-cultured with Sertoli cells or RA (on gelatin coated plates) | DAZL, SYCP3, PRM expression in both groups after 12 days of induction. Number of colonies and positive cells were high in Sertoli cell group | Aflatoonian et al. [68] |
| hESC lines (Shef1–6 & H7) | EBs were induced with RA, Bmp4 and neonatal mouse testis conditioned medium for 14 days | Progressive elevation of both spermatogenesis and oogenesis markers. Effect was prominent with RA treatment. 1–5% post-meiotic cells & few with the beginning of flagellum formation | Aflatoonian et al. [68] |
| Mouse C2C12 myoblast cells | STRA8-positive C2C12 myoblasts were treated with 10 μM all-trans-RA for 8 days | Pre-meiosis, meiosis and post-meiosis gene markers were expressed. Few cells exhibited spherical morphology with tail like structure. But the cells were diploid indicating arrest at pre-meiotic stage | Jia et al. [35] |
| Pre-meiotic male germ cells from immature mouse | Cells were cultured in gel matrices (soft agar or methyl cellulose) with the support of somatic cells and gonadotropins for 40 days | Morphologically normal but immotile spermatozoa | Stukenborg et al. [61] |
| Source of cells                          | Method used                                                                 | Observations                                                                                                                                                                                                 | References |
|-----------------------------------------|------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Stella-GFP+ ES cells                    | Cells were cultured in Ham’s F12/IMDM medium with BMP4 as adherent or EBs culture systems | Cells in both cultures, predominantly in EBs were differentiated, into primordial germ cells with correct gene expression patterns. Correct pattern of parental imprint erasure was confirmed (PEG3 and IGF2R) | Wei et al. [70] |
| Porcine skin-derived somatic stem cells | Induced with porcine follicular fluid for 50 days | Large, round PGCs like cells with 0.25% positive for alkaline phosphatase (AP). Cells were positive for c-KIT, OCT4, VASA, STELLA, DAZL. 99% of CpG sites were unmethylated in DMR1 of PGCs | Linher et al. [86] |
| Human ESCs (HSF-6 & H-9)                | 50–250 cell colonies were cultured on mouse primary embryonic fibroblast in ESCs growth medium for 7d. The cells were co-cultured with putative Sertoli cells | AP & CXCR4, c-KIT positive primordial germ cells arose. Electron microscopic pictures showed large round nucleus with numerous mitochondria | Bucay et al. [87] |
| Mouse SSCs from 7d old male             | 3D agar culture system consisting 0.5 agar and 25% FCS in lower layer and 0.37 agar and 20% FCS in upper layer. Culture continued for 30d with PRMI media | Different stages of spermatogenesis were observed with increasing meiotic and post-meiotic markers with time. Average 15 spermatozoa per well of 24 well plate were present | Elhija et al. [88] |
| Laminin binding spermatogonia from Sprague-Dawley rats | Cells were cultured in gelatin coated wells with a serum free formulated medium for 120 days. Other supplements were GDNF and FGF | Cultured SSCs effectively regenerated spermatogenesis in testes of busulfan-treated recipient rats | Wu et al. [89] |
| Immature spermatogenic cells isolated from non-obstructive azoospermic men | 3D culture in a collagen gel matrix with somatic cells. The media supplemented with RA and rFSH | More round and elongating spermatids emerged at day 12 of culture. PRM2 + ve cells and haploid cells were increased with time | Lee et al. [90] |
| in vitro generated germ cell line from teratocarcinoma cells (F9) | TC cells were transfected with Stra8-EGFP fusion construct and positive cells were induced with RA. FACS sorted germ-like cells were transplanted. | Mature sperm after 7 months of transplantation in recipient mice testes. Performance of ICSI confirmed the oocytes activating capacity of these sperm | Nayernia et al. [91] |
| TESE dissociated CD49f positive cells from azoospermic men | Cells were cultured with Sertoli cells and culture media containing RA, GDNF, FSH & testosterone for 15 days | Progression of meiosis up to day 5. Correct gene expression pattern (SCP3 and CREST and haploid cells were obtained | Riboldi et al. [92] |
transplantation into testis of infertile mice [66]. Nayernia et al. reported 300–500-fold increase in spermatogonial population after transplantation of mouse bone marrow (BM) derived SSCs into germ cells depleted recipient mice, but the cells were arrested at pre-meiotic stage [64]. A similar study has shown that transplanted green fluorescence protein positive (GFP+) mouse BM cells can differentiate into both somatic and germ cell lineages in a favorable testicular niche [79]. Transplanted adipose tissue-derived MSCs could induce spermatogenesis in busulfan-treated recipient rats in another study [80]. Toyooka et al. cultured Moh knock-in GFP or Lac-Z mouse embryoid bodies with BMP 4,8 expressing embryonic trophoblast cells, and they could achieve morphologically normal sperm after transplantation of MVH overexpressing cells under the testis capsules of nude mice [81]. Use of combination of gene transfection and subsequent germ cells transplantation techniques could results live sperm (with reduced motility) and offspring after intracytoplasmic sperm injection (ICSI) in mice. Though the newborns died within few months due to imprinting defects, this finding paves the way to promising in vitro- and/or ex vivo-derived functional gametes in the future [82]. Additional treatment with hormones (hCG) after stem cell transplantation may be a powerful tool for increasing the efficiency of transplantation [83]. It is suggested that FSH and testosterone favor the survival of germ cells by regulating both intrinsic and the extrinsic apoptotic pathways. Furthermore, FSH is needed to initiation of meiosis and androgen is necessary for the completion of meiosis and spermiogenesis [84].

| Source of cells                        | Method used                                                                 | Observations                                                                                                                                                                                                 | References        |
|----------------------------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|
| Human Wharton’s jelly-derived MSCs     | MSCs were co-cultured with mitotic inactivated newborn mouse Sertoli cells for 3 weeks | Typically round germ-like cells were appeared with time. The cells were positive for early germ cell specific STELLA & VASA and male germ cells specific DAZL markers                                                                 | Xie et al. [62]   |
| Human testicular tissues from first and second trimester fetuses | Testis tissues were inserted subcutaneously into mice. Mice with second-trimester xenografts were randomly given hCG injection | Completed the normal seminiferous cord formation. Induction of steroidogenesis was observed with hCG treatment. Germ cells differentiation was confirmed by decreasing OCT4 and increasing Vasa expressing cells | Mitchell et al. [93] |
| MSCs from human umbilical cord Wharton’s jelly | Cells were induced with 2 × 10^-6 M RA and 10 ng/ml BMP4 in DMEM for 7–14 days | Small number of germ cells expressing SCP3 and VASA were formed                                                                                                                                               | Hua et al. [94]   |
| Mouse ESCs                             | ESCs derived PGCs like cells were cultured with testicular somatic cells in the presence of Knockout serum, RA, BMP 2, 4, 7, Activin A, FSH, Testosterone and bovine pituitary extract for 14 days. Resultant spermatids like cells were used for ICSI | Confirmed meiosis in 84% of colonies and erasure of genetic imprinting. ICSI procedure using spermatids like cells produced viable and fertile offspring                                                                 | Zhou et al. [95] |

Table 1. A summary of selected studies designed to differentiate male germ cells from different sources of stem cells.
Adult somatic cells induction (SCI) and sperm cloning (male genome cloning) are recent advancements and future directions for generating clinically applicable germ cells from stem cells. In SCI technique, somatic cell nucleus is injected into enucleated oocyte and cells are cultured further to produce two separated chromosome sets. Thus, the immature oocyte helps somatic cell to become haploid. The resultant cells are genetically identical and immune-compatible with the donor of the somatic cells. In case of severe oligozoospermia, a single viable sperm from testicular biopsy sample can be used for replicating its genome. Here, a single sperm is injected into enucleated oocyte and allows it to become a haploid embryo dividing through parthenogenesis process. Resulting blastomeric cells may be used for further in vitro maturation or direct injection into oocyte. These new techniques still remain in experimented animal models with low efficiency [85]. The contribution by various authors for development of this field is summarized in Table 1.

4. Conclusion

Among the different models used in in vitro spermatogenesis better results have been achieved through 3D culture systems. Formation of EBs using germ and Sertoli cells seems to be more efficient and resemble the testicular niche environment compared to soft agar culture system. Although this system is well supported for the proliferation and differentiation of putative germ cells obtained from somatic stem cells up to the spermatids state there is no firm evidence to conclude the support for an efficient spermiogenesis process. Complete spermiogenesis has been achieved by transplanting stem cells or putative germ cells into testes in few studies, but with lower efficiency. Clinical applications of xeno or autologous transplantation studies among humans, and between humans and animals are still far away due to ethical and safety related issues. Similarly, use of autologous stem cells for differentiation of germ cells and infertility treatment may have little value for the patients with cancer or genetic diseases, as there is a possibility to re-infuse cancer cells or passing genetic abnormalities to offspring. However, in vitro maturation of germ cells may be immensely helpful for men with maturation arrest or azoospermia due to non-genetic causes.

Abbreviations

| Abbreviation | Definition                                      |
|--------------|------------------------------------------------|
| AP           | alkaline phosphatase                           |
| ART          | assisted reproductive technologies             |
| bFGF         | basic fibroblast growth factor                 |
| BM           | bone marrow                                    |
| DMEM         | Dulbecco’s modified eagle medium               |
| DSP          | daily sperm production                         |
| EBs          | embryoid bodies                                |
| EGF          | epidermal growth factor                        |

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http://dx.doi.org/10.5772/intechopen.73505
EGFP enhanced green fluorescence protein
ESCs embryonic stem cells
FACS fluorescence-activated cell sorting
FCS fetal calf serum
GDNF glial cell line-derived neurotrophic factor
GSCs germline stem cells
ICSI intra cytoplasmic sperm injection
iPSCs induced pluripotent stem cells
LIF leukemia inhibitory factor
MACS magnetic-activated cell sorting
miRNA microRNA
MSCs mesenchymal stem cells
PGCs primordial germ cells
RA retinoic acid
SPCs spermatogonial progenitor cells
SSCs spermatogonial stem cells
TESE testicular sperm extraction
3D culture three-dimensional culture

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References

[1] Esteves SC, Agarwal A. The azoospermic male: Current knowledge and future perspectives. Clinics. 2013;68:1-4

[2] Songa HW, Wilkinson MF. In vitro spermatogenesis. Spermatogenesis. 2012;2:38-244

[3] Hamada AJ, Esteves SC, Agarwal A. A comprehensive review of genetics and genetic testing in azoospermia. Clinics. 2013;68:39-60
[4] Gohbara A, Katagiri K, Sato T, Kubota Y, Kagechika H, Araki Y, Araki Y, Ogawa T. *In vitro* murine spermatogenesis in an organ culture system. Biology of Reproduction. 2010;83:261-267

[5] Ketkar AA, Reddy KVR. Expression pattern of OCT-4 and PLZF transcription factors during the early events of spermatogenesis in mice. Journal of Cell Science and Therapy. 2012;3. DOI: 10.4172/2157-7013.1000120

[6] Caires K, Broady J, McLean D. Maintaining the male germline: Regulation of spermatogonial stem cells. Journal of Endocrinology. 2010;205:133-145

[7] Huckins C. The spermatogonial stem cell population in adult rats. Cell and Tissue Kinetics. 1971;4:313-334

[8] Moens PB, Hugenholtz AD. The arrangement of germ cells in the rat seminiferous tubule: An electron microscope study. Journal of Cell Science. 1975;19:487-507

[9] Phillips BT, Gassei K, Orwig KE. Spermatogonial stem cell regulation and spermatogenesis. Philosophical Transactions of the Royal Society. 2010;365:1663-1678

[10] Hermann BP, Phillips BT, Orwig KE. The elusive spermatogonial stem cell marker? Biology of Reproduction. 2011;85:221-223

[11] Ehmcke J, Wistuba J, Schlatt S. Spermatogonial stem cells: Questions, models and perspectives. Human Reproduction Update. 2006;12:275-282

[12] Chan F, Oatley MJ, Kaucher AV, Yang QE, Bieberich CJ, Shashikant CH, Oatley JM. Functional and molecular features of the Id4+ germline stem cell population in mouse testes. Genes & Development. 2014;28:1351-1362

[13] Wu Z, Fallciatori I, Molyneux LA, Richardson TE, Chapman KM, Hamra FK. Spermatogonial culture medium: An effective and efficient nutrient mixture for culturing rat spermatogonial stem cells. Biology of Reproduction. 2009;81:77-86

[14] Nayernia K, Adham I, Kremllng H, Reim K, Schlicker M, Schluter G, Engel W. Stage and developmental specific gene expression during mammalian spermatogenesis. The International Journal of Developmental Biology. 1996;40:379-383

[15] Dadoune JP, Siffroi JP, Alfonso MF. Transcription in haploid male germ cells. International Review of Cytology. 2004;237:1-56

[16] Egger GF, Witter K. Peritubular contractile cells in testis and epididymis of the dog, *Canis lupus familiaris*. Acta Veterinaria Brono. 2009;78:3-11

[17] Hu J, Chenb YX, Wang D, Qia X, Lia TG, Haoa J, Mishinac Y, Garbersa DL, Zhaoa GQ. Developmental expression and function of Bmp4 in spermatogenesis and in maintaining epididymal integrity. Developmental Biology. 2004;276:158-171

[18] Whelly S, Johnson S, Powell J, Borchardt C, Hastert MC, Cornwall GA. Nonpathological extracellular amyloid is present during normal epididymal sperm maturation. PLoS One. 2012;7:1371-1378

[19] Cooper HW, Bausek N. Evolution and spermatogenesis. Philosophical Transactions of the Royal Society B. 2010;365:1465-1480
[20] Chenoweth PJ, Lorton SP, editors. Animal Andrology: Theories and Applications. 1st ed. Croydon: CAB International; 2014. pp. 11-33.

[21] Li XC, Barringer BC, Barbash BA. The pachytene checkpoint and its relationship to evolutionary patterns of polyploidization and hybrid sterility. Heredity. 2009;102:24-30.

[22] Amann RP. The cycle of the seminiferous epithelium in humans: A need to revisit? Journal of Andrology. 2008;29:469-487.

[23] Rooij DG. Proliferation and differentiation of spermatogonial stem cells. Reproduction. 2001;121:347-354.

[24] Iwamori N. Regulation of spermatogonial stem cell compartment in the mouse testis. Fukuoka Acta Medica. 2014;105:1-10.

[25] Koshimizu U, Watanabe D, Sawada K, Nishimune YA. Novel stage-specific differentiation antigen is expressed on mouse testicular germ cells during early meiotic prophase. Biology of Reproduction. 1993;49:875-884.

[26] Bechtol KB. Characterization of a cell-surface differentiation antigen of mouse spermatogenesis: Timing and localization of expression by immunohistochemistry using a monoclonal antibody. Journal of Embryology and Experimental Morphology. 1984;81:93-104.

[27] West FD, Rios MIR, 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. Human Reproduction. 2010;25:168-178.

[28] Kaplan OL. In vivo and in vitro differentiation of male germ cells in the mouse. Reproduction. 2004;128:147-152.

[29] Hobbs RM, Fagoonee S, Papa A, Webster K, Altruda F, Nishinakamura R, Chai L, Pandolfi PP. Functional antagonism between Sal4 and Plzf defines germline progenitors. Cell Stem Cell. 2012;10:284-298.

[30] Seandel M, James D, Shmelkov SV, Falcatori I, Kim J, Chavala S, Scherr DS, Zhang F, Torres R, Gale NW, Yancopolous GD, Murphy A, Valenzuela DM, Hobbs RM, Pandolfi PP, Rafii S. Generation of functional multipotent adult stem cells from GPR125+ germline progenitors. Nature. 2007;20:346-350.

[31] Aloisio GM, Nakada Y, Saatcioglu HD, Peña CG, Baker MD, Tarnawa ED, Mukherjee J, Manjunath H, Bugde A, Sengupta AL, Amatruda JF, Cuevas I, Hamra FK, Castrillon DH. PAX7 expression defines germline stem cells in the adult testis. Journal of Clinical Investigations. 2014;124:3929-3944.

[32] Kumar TR. The quest for male germline stem cell markers: PAX7 gets ID’d. The Journal of Clinical Investigation. 2014;124:4219-4222.

[33] Carломagno G, van Bragt MPA, Korver CM, Repping S, de Rooij DG, Van Pelt AMM. BMP4-induced differentiation of a rat spermatogonial stem cell line causes changes in its cell adhesion properties. Biology of Reproduction. 2010;83:742-749.
[34] Kee K, Angeles VT, Flores M, Nguyen HN, Pera RAR. Human DAZL, DAZ and BOULE genes modulate primordial germ cell and haploid gamete formation. Nature. 2009;462:222-225

[35] Jia W, Cheng D, Chen S, Lei L, Wang H. Retinoic acid induces myoblasts transdifferentiation into premeiotic Stra8-positive cells. Cell Biology International. 2011;35:365-372

[36] Sabour D, Arauzo-Bravo MJ, Hubner K, Ko K, Greber B, Gentile L, Stehling M, Scholer HR. Identification of genes specific to mouse primordial germ cells through dynamic global gene expression. Human Molecular Genetics. 2010;20:115-125

[37] Liu Y, Niu M, Yao C, Hai T, Yuan O, Liu Y, Guo Y, Li Z, He Z. Fractionation of human spermatogenic cells using STA-PUT gravity sedimentation and their miRNA profiling. Scientific Reports. 2015;5. DOI: 10.1038/srep08084

[38] Bhartiya SD, Kasiviswanathan S, Unni SK, Pethe P, Dhabalia JV, Patwardhan S, Tongaonkar HB. Newer insights into premeiotic development of germ cells in adult human testis using Oct-4 as a stem cell marker. Journal of Histochemistry & Cytochemistry. 2010;58:1093-1106

[39] He Z, Kokkinaki M, Jiang J, Dobrinski I, Isolation DM. Characterization, and culture of human spermatogonia. Biology of Reproduction. 2010;82:363-372

[40] Liu S, Tang Z, Xiong T, Tang W. Isolation and characterization of human spermatogonial stem cells. Reproductive Biology and Endocrinology. 2011;9:141-149

[41] Valli H, Sukhwani M, Dovey SL, Peters KA, Donohue J, Castro CA, Chu T, Marshall GR, Orwig KE. Fluorescence and magnetic activated cell sorting strategies to isolate and enrich human spermatogonial stem cells. Fertility and Sterility. 2014;102:566-580

[42] Bowles J, Koopman P. Retinoic acid, meiosis and germ cell fate in mammals. Development. 2007;134:3401-3411

[43] Pellegrini M, Siena SD, Claps G, Cesare SD, Dolci S, Rossi P, Geremia R, Grimaldi P. Microgravity promotes differentiation and meiotic entry of postnatal mouse male germ cells. PLoS One. 2010;5:1371-1380

[44] Itman C, Loveland KL. SMAD expression in the testis: An insight into BMP regulation of spermatogenesis. Developmental Dynamics. 2008;237:97-111

[45] Luetjens CM, Xu EY, Pera RAR, Kamischke A, Nieschlag E, Gromoll J. Association of meiotic arrest with lack of BOULE protein expression in infertile men. The Journal of Clinical Endocrinology & Metabolism. 1993;89:1926-1933

[46] Kostova E, Yeung CH, Luetjens CM, Brune M, Nieschlag E, Gromoll J. Association of three isoforms of the meiotic BOULE gene with spermatogenic failure in infertile men. Molecular Human Reproduction. 2007;13:85-93

[47] Zanganeh BM, Rastegar T, Roudkenar MH, Kashani IR, Amidi F, Abolhasani F, Barbarestani M. Co-culture of spermatogonial stem cells with sertoli cells in the presence of microgravity.
of testosterone and FSH improved differentiation via up-regulation of post meiotic genes. Acta Medica Iranica. 2013;51:1-11

[48] Peschon JJ, Behringer RR, Brinster RL, Palmiter RD. Spermatid-specific expression of protamine 1 in transgenic mice. Developmental Biology. 1987;84:5316-5319

[49] Ravel C, Bastaraud SC, Houate BE, Berthaut I, Verstraete L, De Larouziere V, Lourenc D, Dumaine A, Antoine JM, Mandelbaum J, Siffroi JP, Mc Elreavey K. Mutations in the protamine 1 gene associated with male infertility. Molecular Human Reproduction. 2007;13:461-464

[50] Zhao GQ, Liaw L, Hogan BLM. Bone morphogenetic protein 8A plays a role in the maintenance of spermatogenesis and the integrity of the epididymis. Development. 1998;125:1103-1112

[51] Seandel M, Falcicatori I, Shmelkov SV, Kim J, James D, Rafii S. Spermatogonial progenitors marked by GPR125. Cell Cycle. 2008;15:135-140

[52] Calvel P, Rolland AD, Je’gou B, Pineau C. Testicular post genomics: Targeting the regulation of spermatogenesis. Philosophical Transactions of the Royal Society B. 2010;365:1481-1500

[53] West FD, Shirazi R, Mardanpour P, Ozcan S, Dinc G, Hodges DH, Lichaei HRS, Nayernia K. In Vitro derived gametes from stem cells. Seminars in Reproductive Medicine. 2013;31:33-38

[54] Aponte PM, Schlatt S, de Franca LR. Biotechnological approaches to the treatment of aspermatogenic men. Clinics. 2013;68:157-167

[55] Steinberger A, Steinberger E, Perloff WH. Mammalian testes in organ tubules. Experimental Cell Research. 1964;36:19-27

[56] Nagano MC. Techniques for culturing spermatogonial stem cells continue to improve. Biology of Reproduction. 2011;84:5-6

[57] Tesarik J, Guido M, Mendoza C, Greco E. Human spermatogenesis in vitro: Respective effects of follicle-stimulating hormone and testosterone on meiosis, spermiogenesis, and sertoli cell apoptosis. The Journal of Clinical Endocrinology and Metabolism. 1998;83:4467-4473

[58] Sani RN, Tajik P, Yousefi MH, Movahedin M, Panahi BQ, Shafiei S, Hamedani MA. Follicle stimulating hormone increases spermatogonial stem cell colonization during in vitro coculture. Veterinary Research Forum. 2012;4:37-41

[59] Goharbakhsh L, Mohazzab A, Salehkhoo S, Heidari M, Zarnani AH, Parivar K, Akhondi MM. Isolation and culture of human spermatogonial stem cells derived from testis biopsy. Avicenna Journal of Medical Biotechnology. 2013;5:54-61

[60] Ardekani HS, Mizrak SC, van Daalen SKM, Korver CM, Gajadien HLR, Koruji M, Hovingh G, de Reijke TM, de la Rosette JJMCH, van der Veen F, de Rooij DG, Repping S, van Pelt AMMM. Propagation of human spermatogonial stem cells in vitro. Journal of American Medical Association. 2009;302:2127-2134
[61] Stukenborg JB, Schlatt S, Simoni M, Yeung CH, Elhija MA, Luetjens CM, Huleihel M, Wistuba J. New horizons for \textit{in vitro} spermatogenesis? An update on novel three-dimensional culture systems as tools for meiotic and post-meiotic differentiation of testicular germ cells. Molecular Human Reproduction. 2009;15:521-529

[62] 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 \textit{in vitro} co-culture system. European Journal of Medical Research. 2015;20. DOI: 10.1186/s40001-014-0080-6

[63] Miryounesi M, Nayernia K, Dianatpour M, Mansouri F, Modarressi MH. Co-culture of mouse embryonic stem cells with Sertoli cells promote \textit{in vitro} generation of germ cells. Iranian Journal of Basic Medical Science. 2013;16:779-783

[64] Nayernia K, Lee JH, Drusenheimer N, Nolte J, Wulf G, Dressel R, Gromoll J, Engel W. Derivation of male germ cells from bone marrow stem cells. Laboratory Investigation. 2006;86:654-663

[65] Park TS, Galic Z, Conway AE, Lindgren A, Van Handel BJ, Magnusson M, Richter L, Teitell MA, Mikkola HKA, Lowry WE, Plath K, Clark AT. Derivation of primordial germ cells from human embryonic and induced pluripotent stem cells is significantly improved by co-culture with human fetal gonadal cells. Cells. 2009;27:783-795

[66] Li Y, Wang X, Feng X, Liao L, Zhang D, Cui X, Gao F, Han C. Generation of male germ cells from mouse induced pluripotent stem cells \textit{in vitro}. Stem Cell Research. 2014;12:517-530

[67] Easley CA, Phillips BT, McGuire MM, Barringer JM, Valli H, Hermann BP, Simerly CR, Rajkovic A, Miki T, Orwig KE, Schatten GP. Direct differentiation of human pluripotent stem cells into haploid spermatogenic cells. Cell Reports. 2012;27:440-446

[68] Aflatoonian B, Ruban L, Jones M, Aflatoonian R, Fazeli A, Moore HD. \textit{In vitro} post-meiotic germ cell development from human embryonic stem cells. Human Reproduction. 2009;24:3150-3159

[69] Panula S, Medrano JV, Kee K, Bergström R, Nguyen HN, Byers B, Wilson KD, Wu JC, Simon C, Hovatta O, Pera RAR. Human germ cell differentiation from fetal- and adult-derived induced pluripotent stem cells. Human Molecular Genetics. 2011;20:752-762

[70] Wei W, Qing T, Ye X, Liu H, Zhang D, Yang W, Deng H. Primordial germ cell specification from embryonic stem cells, PLoS ONE. 2008;3, doi: 10.1371/journal.pone.0004013

[71] Silva C, Wood JR, Salvador L, Kostetskii I, Williams CJ, Strauss JF. Expression profile of male germ cell-associated genes in mouse embryonic stem cell cultures treated with all-trans retinoic acid and testosterone. Molecular Reproduction and Development. 2009;76:11-21

[72] Fuchs E, Green H. Regulation of terminal differentiation of cultured human keratinocytes by vitamin A. Cell. 1981;25:617-625
[73] Aflatoonian B, Moore H. Germ cells from mouse and human embryonic stem cells. Reproduction. 2006;132:699-707

[74] Childs AJ, Saunders PTK, Anderson RA. Modelling germ cell development in vitro. Molecular Human Reproduction. 2008;14:501-511

[75] Mari AIM, Kaplan OL, Medrano LV, Pellicer A, Simon C. Differentiation of germ cells and gametes from stem cells. Human Reproduction Update. 2009;15:379-390

[76] Zhou GB, Meng QG, Li N. In vitro derivation of germ cells from embryonic stem cells in mammals. Molecular Reproduction & Development. 2010;77:586-594

[77] Kubota H, Brinster RL. Technology insight: in vitro culture of spermatogonial stem cells and their potential therapeutic uses. Endocrinology & Metabolism. 2006;2:99-108

[78] Sato Y, Taniguchi M, Otoi T. Studying spermatogenesis by using in vivo and in vitro models: Advantages and disadvantages of these models for practical use. Journal of Veterinary Science and Technology. 2012;3. DOI: 10.4172/2157-7579.1000115

[79] Lue Y, Erkkila K, Liu PY, Ma K, Wang C, Hikim AS, Swerdloff RS. Fate of bone marrow stem cells transplanted into the testis. The American Journal of Pathology. 2007;170:899-908

[80] Mehrabani D, Hassanshahi MA, Tamadon A, Zare S, Keshavarz S, Rahmanifar F, Dianatpour M, Khodabandeh Z, Jahromi IR, Tanideh N, Ramzi M, Aqababa H, Hoseinabadi OK. Adipose tissue-derived mesenchymal stem cells repair germinal cells of seminiferous tubules of busulfan-induced azoospermic rats. Journal of Human Reproductive Sciences. 2015;8:103-110

[81] Toyooka Y, Tsunekawa N, Akasu R, Noce T. Embryonic stem cells can form germ cells in vitro. PNAS. 2003;100:11457-11462

[82] Nayernia K, Nolte J, Michelmann HW, Lee JH, Rath sack K, Drusenheimer N, Dev A, Wulf G, Ehrmann IE, Elliott DJ, Okpanyi V, Zechner U, Haaf T, Meinhardt A, Engel W. In vitro-differentiated embryonic stem cells give rise to male gametes that can generate offspring mice. Developmental Cell. 2006;11:125-132

[83] Akhondi MM, Najar RA, Tehrani MJ, Sadeghi MR, Zarnani AH, Rabbani H, Salehkhoo S, Eini L, Hoseinzadeh F, Heidari M. The effect of human chorionic gonadotropin treatment on recipient mouse germ cell proliferation following spermatogonial stem cell transplantation of neonatal donor mice. Avicenna Journal of Medical Biotechnology. 2010;2:23-35

[84] Ruwanpura SM, McLachlan RI, Meachem SJ. Hormonal regulation of male germ cell development. Journal of Endocrinology. 2010;205:117-131

[85] Pelosi E, Forabosco A, Schlessinger D. Germ cell formation from embryonic stem cells and the use of somatic cell nuclei in oocytes. Annals of the New York Academy of Science. 2011;1221:18-26
[86] Linher K, Dyce P, Li J. Primordial germ cell-like cells differentiated in vitro from skin-derived stem cells. PLoS ONE. 2009;4. DOI: 10.1371/journal.pone.0008263

[87] Bucay N, Yebra M, Cirulli V, Afrikanova I, Kaido T, Hayek A, Montgomery AMP. A novel approach for the derivation of putative primordial germ cells and Sertoli cells from human embryonic stem cells. Stem Cells. 2009;27:68-77

[88] Elhija MA, Lunenfeld E, Schlatt S, Huleihel M. Differentiation of murine male germ cells to spermatozoa in a soft agar culture system. Asian Journal of Andrology. 2012;14:285-293

[89] Wu Z, Phelps KL, Bugde A, Molyneux LA, Denard B, Li WH, Süel GM, Garbers DL. Capacity for stochastic self-renewal and differentiation in mammalian spermatogonial stem cells. The Journal of Cell Biology. 2009;187:513-524

[90] Lee JH, Gye MC, Choi KW, Hong JY, Lee YB, Park DW, Lee SJ, Min CK. In vitro differentiation of germ cells from non-obstructive azoospermic patients using three dimensional culture in a collagen gel matrix. Fertility Sterility. 2007;87:824-833

[91] Nayernia K, Li M, Jaroszynski L, Khusainov R, Wulf G, Schwandt I, Korabiowska M, Michelmann HW, Meinhardt A, Engel W. Stem cell based therapeutical approach of male infertility by teratocarcinoma derived germ cells. Human Molecular Genetics. 2004;13:1451-1460

[92] Riboldi M, Rubio C, Pellicer A, Gil-Salom M, Simon C. In vitro production of haploid cells after co-culture of CD49fD with Sertoli cells from testicular sperm extraction in non-obstructive azoospermic patients. Fertility and Sterility. 2012;98:580-590

[93] Mitchell RT, Saunders PTK, Childs AJ, Kojima CC, Anderson RA, Wallace WHB, Kelnar CJH, Sharpe RM. Xenografting of human fetal testis tissue: A new approach to study fetal testis development and germ cell differentiation. Human Reproduction. 2010;25:2405-2414

[94] Hua J, Qiu P, Zhu H, Cao H, Wang F, Li W. Multipotent mesenchymal stem cells (MSCs) from human umbilical cord: Potential differentiation of germ cells. African Journal of Biochemistry Research. 2011;5:113-123

[95] Zhou Q, Wang M, Yuan Y, Wang X, Fu R, Wan H, Xie M, Liu M, Guo X, Zheng Y, Feng G, Shi Q, Zhao XY, Sha J, Zhou Q. Complete meiosis from embryonic stem cell-derived germ cells in vitro. Cell Stem Cell. 2016;18:330-340
