Misleading and reliable markers to differentiate between primate testis-derived multipotent stromal cells and spermatogonia in culture

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BACKGROUND: Several studies have reported the generation of spermatogonia-derived pluripotent stem cells from human testes. The initial aim of the present study was the derivation of equivalent stem cells from an established and experimentally accessible non-human primate model, the common marmoset monkey (Callithrix jacchus). However, an essential prerequisite in the absence of transgenic reporters in primates and man is the availability of validated endogenous markers for the identification of specific cell types in vitro.

METHODS AND RESULTS: We cultured marmoset testicular cells in a similar way to that described for human testis-derived pluripotent cells and set out to characterize these cultures under different conditions and in differentiation assays applying established marker panels. Importantly, the cells emerged as testicular multipotent stromal cells (TMSCs) instead of (pluripotent) germ cell-derived cells. TMSCs expressed many markers such as GFRα, GPR125, THY-1 (CD90), ITGA6, SSEA4 and TRA-1-81, which were considered as spermatogonia specific and were previously used for the enrichment or characterization of spermatogonia. Proliferation of TMSCs was highly dependent on basic fibroblast growth factor, a growth factor routinely present in germ cell culture media. As reliable markers for the distinction between spermatogonia and TMSCs, we established VASA, in combination with the spermatogonia-expressed factors, MAGEA4, PLZF and SALL4.

CONCLUSIONS: Marmoset monkey TMSCs and spermatogonia exhibit an overlap of markers, which may cause erroneous interpretations of experiments with testis-derived stem cells in vitro. We provide a marker panel for the unequivocal identification of spermatogonia providing a better basis for future studies on primate, including human, testis-derived stem cells.

Key words: testis / germ line stem cell / spermatogonia / multipotent stromal cell / non-human primate

Introduction

Pluripotent stem cells are of great interest for regenerative medicine as they are able to generate all cell types of the adult body. The classic source of pluripotent cells is the inner cell mass of blastocysts. For many years now researchers have tried to derive pluripotent cells also from the adult body. Besides the generation of genetically modified induced pluripotent stem cells (Takahashi et al., 2007), the derivation of pluripotent stem cells from unipotent adult human spermatogonia seems to be very promising. For the mouse, this has been demonstrated convincingly (Guan et al., 2006; Seandel et al., 2007; Kanatsu-Shinohara et al., 2008; Ko et al., 2009, 2010a). In recent years, several research groups have also published data suggesting the derivation of pluripotent (Conrad et al., 2008; Golestaneh et al., 2009; Kossack et al., 2009) or multipotent stem cells (Mizrak et al., 2010) from adult human spermatogonia. However, these cells, recently termed hES-like cells (Chikhovskaya et al., 2012), for human testis-derived embryonic stem cell-like cells, are under debate since their developmental potential as well as their origin from spermatogonial stem cells (SSCs) remains unclear (Ko et al., 2010b, 2011; Tapia et al., 2011; Chikhovskaya et al., 2012).

Another adult stem cell type, the multipotent stromal cells (MSCs), is very prevalent in mammals. MSCs are located within the connective tissue of many adult organs and also in the human testis (Gonzalez et al., 2009). Both, MSCs and pluripotent stem cells are known for their great capacity to self-renew. While pluripotent stem cells can differentiate into all cell types of an organism, MSCs display differentiation restricted to cell types of the connective/myoid tissue such as...
osteoblasts, adipocytes, chondrocytes and myocytes (Phinney and Prockop, 2007). In contrast to pluripotent cells, MSCs do not express the transcription factors octamer-binding transcription factor 4 (OCT4, also POU5F1) or sex-determining region Y-box 2 (SOX2) and they are not able to generate teratomas when injected into immuno-deficient nude mice. In cell culture, MSCs minimally have to meet the following criteria: (i) adherence to plastic, (ii) the expression of specific cell surface markers, including CD90 (THY-1), CD105 and CD166 and (iii) potential to differentiate into osteoblasts, adipocytes and chondroblasts (Dominici et al., 2006).

While MSCs are multipotent and located within connective tissue, SSCs are a potential source for pluripotent cells. When mouse SSCs are injected into a germ cell-depleted recipient mouse testis, they re-colonize the testis and re-establish spermatogenesis (Brinster and Zimmermann, 1994). This transplantation assay is the gold standard for demonstrating the presence of SSCs. However, when human SSCs are injected into mouse testis they re-colonize the stem cell niche but no SSC proliferation and thus no spermatogenesis occurs (Nagano et al., 2002; Lim et al., 2010; Izadyar et al., 2011). Yet, during both cell culture experiments and heterologous transplantation assays, researchers rely on a set of markers that is endogenously expressed by the primate or human cells of interest. Published markers for spermatogonia include the cell surface markers G-protein-coupled receptor 125 (GPR125), GDNF family receptor alpha-1 (GFR-α), THY-1 (CD90), integrin alpha 6 (ITGA6 or CD49f), stage-specific embryonic antigen 4 (SSEA-4) and tumor rejection antigen 1-81 (TRA-1-81) as well as the intracellular markers Sall-like 4 (SALL4), promyelocytic leukemia zinc finger (PLZF) and melanoma-associated antigen 4 (MAGEA4) (Conrad et al., 2008; Golestaneh et al., 2009; Sadri-Ardekani et al., 2009; He et al., 2010; Izadyar et al., 2011).

The histological and spatial organization of the male germinal epithelium of the non-human primate Callithrix jacchus (common marmoset monkey) is very similar to the human. Therefore, the common marmoset is a suitable and attractive model for the study of aspects of human germ cell development and spermatogenesis (Millar et al., 2000; Mitchell et al., 2008; Mueller et al., 2008; Albert et al., 2010; Eidermann et al., in press). Thus, we use this new-world primate species to investigate primate-specific aspects of testicular function and organization. However, studies aiming at the isolation and characterization of testicular stem cells rely on the specificity of endogenous markers. The recent literature suggests THY-1 (CD90) and ITGA6 (CD49f) as specific markers for spermatogonia (Lee et al., 2006; He et al., 2010), but, importantly, they are also expressed by MSCs (Dominici et al., 2006; Semon et al., 2010). This fact in combination with the discovery that MSCs can also be derived from adult human testis (Gonzalez et al., 2009; Chikhovskaya et al., 2012) suggests that at least 2-cell types within the human testis express these markers. Hence, the question arises of which proteins are really unequivocal markers for different testicular cell types. In the present study, we demonstrate the culture and characterization of marmoset monkey testicular multipotent stromal cells (TMSCs) and spermatogonia and investigate the expression of frequently used spermatogonia markers in both cell types. We show that VASA, in combination with PLZF or SALL4 or MAGEA4, respectively, allows specific labeling of cultured spermatogonia. In contrast, other ‘spermatogonial markers’ such as SSEA-4, TRA-1-81, GPR125 or GFR-α were also expressed by TMSCs and thus may cause serious misinterpretations of testis cell culture data.

**Materials and Methods**

**Marmoset monkey testis tissue samples**

All experiments were performed according to the German Animal Protection Law. Animals were housed according to the standard German Primate Centre practice for common marmoset monkeys. Thirteen adult marmoset monkey (older than 2 years) testes were used for the experiments (Licence numbers AZ10/0063 and AZ11/0395). All data on TMSCs were obtained from three independent primary cultures derived from three individual animals.

**Cell culture**

**Derivation and culture of TMSCs**

Testes were kept on ice in Dulbecco’s modified Eagle’s medium (DMEM)/F-12 immediately after recovery and further processed in a sterile environment. After removing capsule and epididymis, the tubules were digested using DMEM/F-12 containing 1 mg/ml hyaluronidase (Sigma), 1 mg/ml collagenase (Sigma) and 15 U/ml DNase (Roche) for 35–40 min at 37°C under constant mild rotation. Resulting single cells were seeded at a cell density of 2 × 10^5 cells/cm^2 to plastic culture dishes. TMSC-culture medium was based on a 1:1 mixture of DMEM (GIBCO) and F-12 nutrient mixture (GIBCO) which was supplemented with 10% fetal bovine serum (GIBCO), 100 U/l Penicillin–Streptomycin (GIBCO), 0.25 μg/ml Fungizone® Antimycotic (GIBCO) and 5 ng/ml recombinant human basic fibroblast growth factor (bFGF) (ProSpecTany). Following overnight incubation any cells that did not adhere to the plastic ( suspension P0) were re-seeded to a new dish and cultured for an additional 4 days. Adherent cells from the initial cell suspension ( termed ‘adherent 1 passage 0’) and from overnight suspension cells that adhered after an additional 6 days ( termed ‘adherent 2 passage 0’) were passaged upon confluency with 0.05% trypsin in phosphate-buffered saline (PBS) (GIBCO). Adherent cells from the first passage onwards were termed TMSCs. Passaging was performed every 3–5 days at a 1:3 or 1:5 dilution. Generally TMSCs were cultured at 37°C under 5% CO₂ and the medium was exchanged every 2–3 days. A scheme of the different enrichment steps is provided in Supplementary data, Fig. S1.

To analyze the effect of bFGF on proliferation and cell morphology, TMSCs were cultured in medium containing from 0 to 50 ng/ml bFGF. Cells were seeded in 6-well culture plates at a cell density of 1 × 10^5 cells/cm^2. After TMSCs had been allowed to adhere overnight without bFGF, the growth factor concentration was changed to 0, 1, 5, 10 or 50 ng/ml, respectively. Each condition was analyzed in three independent biological replicates. Cell morphology was documented using a ZEISS cell observer microscope. After 7 days of culture, all samples were trypsinized and counted using a hemocytometer.

**Differentiation of TMSCs**

The differentiation capacity of TMSCs was assayed using the human mesenchymal stem cell differentiation kit from StemPro® (Invitrogen Life Technologies, Darmstadt, Germany). The differentiation into chondrocytes and osteoblasts was analyzed after 21 days while adipocyte differentiation was performed for 7 days.

**Derivation and short-term culture of spermatogonia**

Spermatogonia were enriched by differential plating and cultured for 3 days on γ-irradiated TMSCs at 34°C. The spermatogonia culture medium (Supplementary data, Table SII) was a slightly modified version of the
StemPro(R)-34 serum-free medium (Life Technologies, Darmstadt, Germany) based medium that has previously been described to support the growth of mouse spermatores (Ko et al., 2009). Two days prior to the isolation of spermatores, 5 x 10^5 3000-rad irradiated TMSCs were seeded into 48-well culture plates in TMSC-medium without bFGF. Following overnight incubation at 37°C, the medium was replaced with spermatores medium and cultured at 34°C. For the derivation of spermatores, a testicular single cell suspension was seeded in spermatores medium and cultured at 34°C for 3 and up to 14 days at 34°C.

Characterization of cells

**Immunofluorescence staining**

Cells were grown in 48-well plastic plates and fixed for 30 min in 4% paraformaldehyde (PFA). For the detection of intracellular antigens, the cells were permeabilized with 0.04% Triton X-100. Primary antibodies (Supplementary data, Table SII) were diluted in PBS/5% bovine serum albumin (BSA) and incubated for 30 min at 37°C. The appropriate Alexa fluor (AF) 488-linked secondary antibody (Supplementary data, Table SII) was diluted in PBS/5% BSA and applied for 30 min at room temperature in the dark. For double staining, both primary antibodies and subsequently both secondary antibodies, linked to AF488 and AF594, respectively, were applied at the same time. Controls were performed by omitting the primary antibody and by using the corresponding non-specific IgG fraction. Counter staining was performed with 4',6-diamidin-2-phenylindol and images were taken on a Axio Observer Z1 fluorescence microscope from Zeiss (Germany).

**Fluorescence-activated cell sorting**

The staining procedure for fluorescence-activated cell sorting (FACS) analysis of cell surface antigens was performed according to the manufacturer’s recommendations (Human Multipotent Mesenchymal Stromal Cell Marker Antibody Panel, R&D Systems). Each staining was performed three times using cells from three different animals. FACS analysis was performed with a BD LSR II device and the FACS DIVA software. Data were evaluated with the FlowJo software.

**Immunohistochemistry**

Immunohistochemistry (IHC) on Bouin’s solution fixed, paraffin-embedded common marmoset testes tissue sections was performed as previously described (Eildermann et al., in press) using the LSAB Plus-Kit from Dako-Cytomation (CA, USA). All pictures were taken using a Zeiss microscope and the Nuance™ multispectral camera.

**Van Kossa silver staining: detection of osteoblasts**

Calcium deposits indicating osteogenesis were detected by van Kossa silver staining, which was performed as described (Romis, 2010), with slight modifications. In brief, cultured cells were fixed in 4% PFA, washed three times and then incubated for 1 h in 5% aqueous silver nitrate solution in the dark. After rinsing the cells in distilled water, they were incubated in formaldehyde–sodium carbonate solution [5 g sodium carbonate, 25 mL formaldehyde (35–40%), 75 mL distilled water] for 2 min. Following an additional washing step, the staining was fixed in 5% sodium thiosulfate solution for 5 min. Nuclei were stained with 0.1% nuclear fast red solution for 5 min. Sites of calcification appear dark brown and nuclei appear red.

**Oil Red O staining: detection of adipocytes**

Fatty acid incorporations can be detected with the Oil Red O staining procedure. The cells were fixed with 4% PFA. After rinsing with water, the cells were incubated with 0.3% Oil red solution (0.3% Oil red in 60% isopropyl alcohol) for 1 h. Then, the cells were rinsed once with 60% isopropyl alcohol and several times with distilled water. Fatty acids appear bright pink.

**Alcian blue staining: detection of chondrocytes**

Chondrocytes are characterized by the production of proteoglycans, which can be detected with alcian blue. The staining was performed as described in the manual of the StemPro Chondrogenesis Differentiation Kit (StemPro #A10582) with slight modifications. In brief, cell accumulations were fixed in 4% PFA, embedded in Paraffin and sectioned at 5 μm. Following deparaffinization and rehydration, sections were incubated in 1% alcian blue (in 0.1 M HCl) for 1 h and washed three times with 0.1 M HCl. After rinsing with water and 2 min of incubation in isopropyl alcohol, slides were transferred to xylol and covered in Eukitt® (Sigma). Proteoglycans appear blue.

**Reverse transcription-polymerase chain reaction**

Specific common marmoset mRNA sequences were derived from http://www.ensembl.org/Callithrix_jacchus/Info/Index and confirmed using the marmoset genomic database available at the UCSC homepage (http://genome.ucsc.edu/cgi-bin/hgGateway?db=caljac1). Sequencespecific primers (if possible intron-spanning) were designed using the CLC DNA workbench and the Primer3 software (Supplementary data, Table SIV). RNA was isolated with the RNeasy mini kit from Qiagen (Hilden, Germany; #74106) and reverse transcription was performed using 1 μg of the total RNA and the Omniscript reverse transcriptase from Qiagen (Hilden, Germany). For negative control negative reverse transcription (RT) samples, no reverse transcriptase was added to the reaction. All polymerase chain reactions (PCRs) were performed on cDNA and the according negative control RT sample using Chrimson Taq polymerase (New England Biolabs). ACTB was analyzed with 25 PCR cycles; all other genes were tested using 32 cycles. PCR products were separated and visualized using the QiAexc multicapillary electrophoresis device (Qiagen, Hilden, Germany). The optical output of this analyzer is a digitalized graph based on the detected fluorescence in the microcapillaries over time instead of conventional agarose gels. The method of presentation used in this study can be interpreted with regard to signal intensity in the same way as that used for conventional images of electrophoresed DNA within agarose gels. The identity of all PCR products has been confirmed by sequencing (LCG-genomics, Berlin, Germany).

**Quantitative RT–PCR**

Relative quantitative (q)RT–PCR was performed on common marmoset testicular cells and testis material with at least three samples. Design and testing of all qRT–PCR primers (Supplementary data, Table SV) as well as the qRT–PCR procedure was performed as previously described (Eildermann et al., in press). In brief, 2 μg testicular RNA were reverse transcribed, using random hexamers and Superscript II (Invitrogen, Karlsruhe) to obtain cDNA. For each 20 μL PCR reaction, 2 μL of 1:2 diluted cDNA was used with Power SYBR Green Mastermix (Applied Biosystems), and different primer concentrations ranging between 50 and 900 nM. The extent of fluorescence of the Power SYBR green dye was detected and analyzed using the 2^(-ΔΔCt) method and the ABI Prism® 7000 SDS software (Applied Biosystems). Each sample was assayed in triplicate and normalized to glyceraldehyde-3-phosphate dehydrogenase (GAPDH) expression.
## Results

### Multipotent cells from testis emerge as stromal cells

We initially set out to isolate and culture marmoset spermatogonia. However, our culture mainly contained a cell type morphologically resembling mesenchymal cells. Therefore, we tested these Marmoset testis-derived cells (hereafter called TMSCs) according to the minimum criteria for adult MSCs (Dominici et al., 2006): (i) adherence to plastic, (ii) expression of specific cell surface antigens, (iii) differentiation into osteogenic-, adipogenic- and chondrogenic cells. The first criterion was fulfilled by deriving TMSCs through their adherence to plastic. To test the second criterion, i.e. marker expression, we performed FACS and immunofluorescence (IF) using a human MSC-marker antibody panel (R&D Systems, Minneapolis). Conventional IF revealed the presence of the MSC-positive markers CD105, CD90, CD166 and CD44 in the majority of TMSCs, while only a sub-fraction of cells expressed, yet very intensely, STRO-1 (Fig. 1A). The MSC-negative markers CD19 and CD45 did not display signals in IF. FACS revealed that CD105 and CD90 were expressed in over 95% of the cells (Fig. 1B). In contrast to these robust markers, the percentage of CD44-positive cells varied from 64 to 92% and STRO-1 was present in only 8–26% of the cells (Fig. 1B). The MSC-absent markers CD19 and CD45 were detected in 4–54% of the cells by FACS (Fig. 1B). Additionally, RT–PCR indicated the expression of the MSC markers, VCAM1 and CD166, in TMSCs (Fig. 1C, illustrated as QIAcube software gel picture). To test the third criterion, i.e. differentiation capacity, we applied the Tissue-Specific Cytokine (StemPro®) (Data not shown). bFGF stimulation led to a fibroblast-like appearance and very low proliferation rates. This morphology was maintained at 1 ng/ml bFGF, while proliferation strongly increased. When cultured with 5 and 10 ng/ml bFGF, TMSCs formed a cohesive monolayer and the cells became more spindle-shaped. The proliferation rates increased up to a bFGF concentration of 10 ng/ml. At 50 ng/ml proliferation declined and large spaces separated individual TMSCs. All cells appeared vital and no signs of apoptosis were detected.

### bFGF affects proliferation and morphology of TMSCs

The bFGF concentration strongly influenced proliferation and TMSC morphology (Fig. 2). Absence of bFGF led to a fibroblast-like appearance and very low proliferation rates. This morphology was maintained at 1 ng/ml bFGF, while proliferation strongly increased. When cultured with 5 and 10 ng/ml bFGF, TMSCs formed a cohesive monolayer and the cells became more spindle-shaped. The proliferation rates increased up to a bFGF concentration of 10 ng/ml. At 50 ng/ml proliferation declined and large spaces separated individual TMSCs. All cells appeared vital and no signs of apoptosis were detected.

### TMSCs originate in testicular connective tissue

Mammalian testis function relies on the presence of characteristic cell types, including germ cells, Sertoli cells, Leydig cells and peritubular cells. To define the cellular origin and identity of marmoset TMSCs, we screened them for markers that are specifically expressed in different testicular cell types (Fig. 3). Vimentin, in situ expressed in Sertoli-, peritubular-, endothelial- and interstitial cells (Fig. 3A), was detected at different intensities in TMSCs by IF (Fig. 3B) and qRT–PCR (Fig. 3C). Both techniques also demonstrated the presence of alpha smooth muscle actin (ACTA2), a marker for peritubular, some interstitial and vascular cells, but not for Sertoli- or Leydig cells. The presence of Vimentin and ACTA2 in TMSCs has also been confirmed by western blot (data not shown). Androgen receptor (AR), a marker for Sertoli-, Leydig- and peritubular cells (Fig. 3A) was not detected in TMSCs, neither using IF (Fig. 3B) nor RT–PCR (Fig. 3D). qRT–PCR revealed the absence of the Sertoli cell markers, SOX9, follicle-stimulating hormone receptor (FSHR) and the Leydig cell marker, luteinizing hormone receptor (LHR) and conventional RT–PCR demonstrated the absence of the Leydig cell marker, insulin like 3 (INSL3). Importantly, a germ cell identity of TMSCs was excluded through the lack of VASA expression at the protein and mRNA levels (see below).

### TMSCs express the cell surface markers SSEA-4, TRA-1-81, GFR-α, GPR125, THY-1 (CD90) and ITGA6

We tested the expression of SSEA-4, TRA-1-81, GFR-α, GPR125, THY-1 (CD90), ITGA6 (CD49f) and the cytoplasmic protein PGP9.5 on the protein and/or the mRNA level in the adult testis and TMSCs. SSEA-4, TRA-1-81, GPR125 and PGP9.5 labeled spermatogonia in testis sections (Fig. 4A). While the GPR125 and the SSEA-4 antibody additionally detected another intracellular structure in later germ cell stages, there was apparently no other cell type stained using the TRA-1-81 antibody. IHC for PGP9.5 localized the protein to spermatogonia and to a few interstitial cells (Fig. 4A, inset). Importantly, IHC demonstrated the presence of SSEA4, TRA-1-81, GPR125, PGP9.5 and GFR-α also in TMSCs (Fig. 4B) and conventional RT–PCR confirmed the expression of GFR-α and GPR125 (Fig. 4C) and conventional RT–PCR confirmed the expression of GFR-α, ITGA6, PGP9.5 and THY-1 (CD90) in TMSCs (Fig. 4D).

### PLZF, SALL4 and MAGEA4 are expressed by spermatogonial markers but not by TMSCs

VASA protein is present within all germ cells except elongating spermatids (Fig. 3A). SALL4 and PLZF specifically labeled the nuclei of a sub-fraction of spermatogonial, namely spermatogonial stem and progenitor cells (Phillips et al., 2010; Eildermann et al., in press), while the MAGEA4 antibody labeled all spermatogonial cells (Fig. 5A) and also early spermatocytes with lower intensities. This demonstrates the in situ specificity of the proteins for germ cells and spermatogonia (and in case of MAGEA4 also for spermatocytes), respectively. IF on TMSCs with the same antibodies resulted in no staining for VASA (Fig. 3) and very weak, probably non-specific signals for PLZF and SALL4. VASA, SALL4 and PLZF were also undetectable in TMSCs by western blot, while these proteins were detected in the positive...
Figure 1 Characterization of TMSCs. (A) Immunofluorescence analysis of the cell surface markers of MSCs. Scale bar: 100 μm. (B) FACS analysis of MSC markers, n = 3. (C) RT–PCR on testis and two TMSC samples for MSC markers CD166 and VCAM1. (D) Hematoxylin–eosin staining of differentiated TMSCs. Von Kossa silver staining demonstrates osteoblasts, oil red-o staining demonstrates adipocytes and alcian blue staining demonstrates chondrocytes. Scale bar: 250 μm. (E) Morphology of a TMSC colony (arrow). (F) Contractile myoid structures within differentiated TMSCs.
controls, i.e. testis or embryonic stem cell (ESCs) (Mueller et al., 2009), respectively (data not shown). IF staining of TMSCs with MAGEA4 was completely blank (Fig. 5B). However, it is important to note that the PLZF, SALL4 and MAGEA4 antibodies robustly stained cultured cells in other experimental settings (see below). These protein data were verified at the mRNA level by qRT–PCR (Fig. 5C) and by conventional RT–PCR. As TMSCs express neither the germ cell marker VASA nor the spermatogonial markers PLZF, SALL4, nor MAGEA4, which is expressed in spermatogonia and early spermatocytes, these genes represent a marker panel which, in combination, is useful for the identification of spermatogonial stem and progenitor cells in culture.

Detection of spermatogonia and somatic cell types within adherent and suspension fractions

We used the markers SALL4, PLZF, MAGEA4 and VASA to screen different plastic-adhering and non-adhering cell factions for the presence of spermatogonia (Fig. 6A; see also Supplementary data, Fig. S1). All markers were present in both suspension cell fractions, indicating the enrichment of germ cells in the suspension fraction. While SALL4 and MAGEA4 were never detected in the adhering cells, weak signals for PLZF and VASA suggested the presence of some germ cells including spermatogonia also in the adhering cell fraction. However, cells from the second adherence fraction completely lacked germ cell markers. We screened the same fractions for the presence of somatic cell types and found that AR, labeling Sertoli-, Leydig- and peritubular but not vascular cells, was present mainly in adherent cells. Insl3, expressed by Leydig cells, was detected in P0 adherent cells and the suspension cell fractions, indicating that Leydig cells have only a limited affinity to plastic.

VASA in combination with spermatogonial markers clearly distinguishes spermatogonia from TMSCs

The presence of VASA and PLZF within the first adherent cell fraction (Fig. 6A) led to the idea that TMSCs might support spermatogonia. To test this, suspension cells (exhibiting spermatogonia markers) were seeded onto irradiated, i.e. proliferation-arrested TMSCs. Using the germ cell-specific marker VASA, we detected single and paired germ cells that were attached to the feeder (Fig. 6B). The VASA-positive cells were morphologically indistinguishable from the feeder cells (Fig. 6B). To analyze whether those VASA-positive germ cells were spermatogonia, we performed double staining using several spermatogonia-expressed proteins. As demonstrated above, GFR-α, GPR125, PGP9.5, SSEA4 and TRA-1-81 were expressed also by the feeder layer, while PLZF, SALL4 and MAGEA4 were not. Importantly,
the expression of all markers in spermatogonia was robust and the distribution within their respective cellular compartments was steady (Fig. 7). This was in contrast to the distribution of the respective molecules within TMSCs, where they appeared rather heterogeneous and spotty (compare spermatogonia and TMSCs in Fig. 7D–H). All SALL4-positive cells and all MAGEA4-positive cells were also robustly VASA positive, clearly indicating a germ cell identity of SALL4-stained and MAGEA4-stained cells (Fig. 7B and C). The strongest signals for PLZF were seen in VASA^low cells (Fig. 7A, orange arrow). Only a sub-

Figure 3 Analysis of the cellular origin of TMSCs. (A) Immunohistochemical detection of Vimentin, AR, ACTA2 and VASA in marmoset testis. Scale bar: 50 μm (B) Immunofluorescence detection of Vimentin, ACTA2, AR and VASA in TMSCs. (C) qRT–PCR for Vimentin, ACTA2, SOX9, FSHR, LHR and VASA using marmoset adult testis and TMSC cDNA. Mean value of n = 2 samples. (D) RT–PCR detecting AR, INSL3 and VASA in marmoset testis and TMSCs.
expression (Fig. 7A, white arrows). Spermatogonia can be maintained on irradiated TMSCs for at least 14 days (Fig. 7I).

Discussion

Testicular multipotent stromal cells

To culture non-human primate SSCs and eventually derive pluripotent cells, we set out using culture systems that were published previously for human testis-derived pluripotent stem cells (e.g. Conrad et al., 2008). Interestingly, we propagated fibroblast-like cells that upon confluence formed colonies (Fig. 7E) resembling those shown previously (Conrad et al., 2008; Golestaneh et al., 2009; Kossack et al., 2009) and further resembling pluripotent embryonic stem cell colonies. We identified these cells as MSCs (Dominici et al., 2006). MSCs have already been derived from the human testis and were termed mesenchymal stem cells (Chikhovskaya et al., 2012) or gonadal stem cells (GSCs; Gonzalez et al., 2009). However, as the mesenchyme is an embryonic tissue but the cultured cells were derived from adult tissue, the term mesenchymal stem cell seems inappropriate. The abbreviation GSCs has previously also been used for germline stem cells and would be confusing. Therefore, we propose the term TMSCs.
Similar to the equivalent human cells (Gonzalez et al., 2009; Chikhovskaya et al., 2012), the marmoset testicular fibroblast-like cells expressed the MSC-characteristic cell surface antigens CD105, CD166, CD44 and CD90. In contrast to the human cells, where the MSC-negative markers CD45 and CD19 showed no or only low labeling, marmoset TMSCs showed quantitatively moderate expression in FACS analysis (Fig. 1B) while IF demonstrated only weak signals. These inconsistencies in marker expression might be explained by the presence of other not yet fully characterized cell types within our primary culture or by species differences. Nevertheless, the marmoset TMSCs adhered to plastic and differentiated into adipocytes, chondrocytes and osteoblasts. Additionally, they display a great self-renewing capacity as they could be maintained as a primary culture for 15 passages without loss of proliferation. Altogether, these experiments demonstrated MSC identity.

To analyze whether TMSCs were multipotent or pluripotent, we performed a teratoma formation assay (Phillips et al., 2010). However, three attempts to generate teratomas by subcutaneous injection of TMSCs into immuno-deficient mice failed. We also failed to demonstrate the expression of the pluripotency-related transcription factors OCT4 and SOX2 in TMSCs under different culture conditions including ESC medium. We therefore assume that TMSCs are not pluripotent.

**Effect of bFGF on testicular MSCs**

There is a strong effect of the bFGF concentration on the proliferation of TMSCs. This is important with regard to the culture of spermatogonia, where the addition of bFGF to the medium may lead to an overgrowth of TMSCs over spermatogonia. Similar observations regarding bFGF were made by Chikhovskaya et al. (2012). In that study an expansion of human htES-like cells, likely equivalent to the cells described in this study for the marmoset monkey, was only possible in medium containing bFGF. Importantly, in previous studies bFGF was used at concentrations that effectively promoted TMSC proliferation in our experiments [e.g. 25 ng/ml (Mizrak et al., 2010), 10 ng/ml (Kossack et al., 2009; He et al., 2010; Lim et al., 2010) and 4 ng/ml (Conrad et al., 2008)].

**The origin of TMSCs**

The testis contains several functionally important organ-specific cell types. These are the germ- and Sertoli cells within the seminiferous...
tubules, the Leydig cells that are located within the interstitial compartment and the peritubular cells that surround and border the seminiferous tubules. TMSCs lack the expression of the germ cell gene VASA, as well as AR (expressed in Sertoli-, Leydig and myoid cells, respectively), FSHR and SOX9 (both specific for Sertoli cells) and LHR and INSL3 (specific for Leydig cells). We therefore conclude that TMSCs do not arise from any of these testis-specific cell types.

TMSCs express Vimentin and ACTA2, both markers that are expressed not only by peritubular cells but also within the interstitial compartment of the testes and within vascular cells. When we analyzed the expression of the MSC markers CD105, CD44 and STRO-1 on marmoset testis tissue sections, we found CD105 and CD44 exclusively within the interstitial compartment and STRO-1 in the interstitial compartment as well as in some meiotic germ cells (Supplementary data, Fig. S2). Our cells therefore most likely do not represent a testis-specific cell type, but rather derive from the interstitial stroma. Indeed, marmoset adipose tissue-derived MSCs exhibited a similar marker expression pattern (K.E. and R.B., unpublished data).

Markers expressed in spermatogonia and TMSCs

Several markers were published which should allow the identification and the enrichment of spermatogonia (Nagano, 2001; Conrad et al., 2008; Mueller et al., 2008; Maki et al., 2009; Gassei et al., 2010; He et al., 2010; Lim et al., 2010; Reding et al., 2010; Izadyar et al., 2011). We have analyzed marmoset TMSCs for the expression of the cell surface antigens ITGA6, THY-1 (CD90), GFR-α, GPR125, TRA-1-81 and SSEA-4 and found all of them to be expressed. We therefore suggest that none of those markers is suited for the specific isolation of spermatogonia as they are indeed expressed by at least two different testicular cell types, consequently resulting in the enrichment of at least 2-cell populations, TMSCs and spermatogonia. The expression of ITGA6, THY-1 (CD90) and SSEA-4 has been described for MSCs (Dominici et al., 2006; Phinney and Prockop, 2007; Gonzalez et al., 2009; Semon et al., 2010; Chikhovskaya et al., 2012). THY-1 is even considered as an essential characteristic of MSCs (Dominici et al., 2006). However, to our knowledge the present study demonstrates for the first time the expression TRA-1-81, GPR125 and GFR-α by TMSCs. In addition to these cell surface markers, PGP9.5 (UCHL1), a cytoplasmic protein that is widely used to identify spermatogonia (e.g. He et al., 2010), has also only limited use as a spermatogonial marker since it is also present in TMSCs. Using FACS analysis, Chikhovskaya et al. demonstrated that human hiES-like cells lack TRA-1-81, while IF on the same cells displayed the marker (Mizrak et al., 2010). In our hands, TRA-1-81 appears to be rather cytoplasmic and limited to a small population of cells in IF. This might explain the discrepancy using these two different methods.
Characterization of marmoset spermatogonia

The spermatogonia markers SALL4, PLZF, MAGEA4 and the germ cell marker VASA were not expressed by TMSCs. Thus, they represent, when used in specific combinations, good candidates to reliably detect spermatogonia within a mixture of testicular cells. Our experiments indicated that spermatogonia do not adhere to plastic surfaces. However, they do adhere to TMSCs. In order to further characterize spermatogonia on a feeder cell layer consisting of TMSCs, we transferred the plastic non-adherent testicular cell fraction to irradiated

Figure 7 Characterization of marmoset monkey germ cells cultured on irradiated TMSCs. Suspension cells were seeded onto proliferation-inactivated TMSCs and cultured for 3 (A–H) or 14 (I) days. (A–H) Double staining of VASA and the respective spermatogonia markers. (I) Spermatogonia after 14 days of culture expressing SALL4 and VASA. White arrows highlight double-positive cells, yellow arrows cells that were only VASA positive and orange arrows cells that were VASA negative but displayed the second marker.
Human testis-derived pluripotent stem cells

In the recent literature, different human testis-derived stem cell types and cultures have been described (e.g. Conrad et al., 2008; Golestaneh et al., 2009; Kossack et al., 2009; Mizrak et al., 2011), and there is a considerable degree of confusion regarding the identity of these cells. Besides the challenges that were raised by the Schöler group (Ko et al., 2010b; Tapia et al., 2011), novel data published recently by Chikhovskaya et al. (2012) further strengthen the view that those human testis-derived cells that were initially considered as pluripotent germ cell-derivatives capable of producing teratoma-like structures (Conrad et al., 2008; Golestaneh et al., 2009; Kossack et al., 2009) are indeed rather MSCs. Those tissues considered as teratomas in the above-mentioned studies may either derive from MSCs (which have a remarkable differentiation capability) or from invaded tissue of the host. Indeed, the origin (host or graft) of the cells in the teratoma (-like structures) has so far not been analyzed. Altogether, data available to date including that presented in this study may suggest the following scenario for the previous reports on pluripotent germ line-derived human testis. Subsequent sorting of this suspension using VASA and SALL4 might be the most appropriate since double staining for VASA and MAGEA4 may also detect early spermatocytes in addition to spermatogonia, as both latter proteins are also present in some spermatocytes (Fig. 5).

Summary

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Authors’ roles

K.E.: study design, collection and assembly of data; data analysis and interpretation, manuscript writing, final approval of manuscript. J.G.: collection and assembly of data; data analysis and interpretation, final approval of manuscript. R.B.: study design, financial support, data analysis and interpretation, manuscript writing, final approval of manuscript.

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