Cyclooxygenase and prostaglandins in somatic cell populations of the testis

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Abstract

Prostaglandins (PGs) are synthesized through the action of the rate-limiting enzyme cyclooxygenase (COX) and further specific enzymes. The development of Cox-deficient mice in the 1990s gave insights into the reproductive roles of PGs. Female Cox-knockout mice were subfertile or infertile. Interestingly, fertility was not affected in male mice deficient in Cox, suggesting that PGs may not be critical for the functioning of the testis. However, this conclusion has recently been challenged by observations of important roles for PGs in both physiological and pathological processes in the testis. The two key somatic cell types in the testis, Leydig and Sertoli cells, express the inducible isoenzyme COX2 and produce PGs. Testicular COX2 expression in these somatic cells is regulated by hormonal input (FSH, prolactin (PRL), and testosterone) as well as by IL1β. PGs modulate steroidogenesis in Leydig cells and glucose uptake in Sertoli cells. Hence, the COX2/PG system in Leydig and Sertoli cells acts as a local modulator of testicular activity, and consequently may regulate spermatogenic efficiency. In addition to its expression in Leydig and Sertoli cells, COX2 has been detected in the seminiferous tubule wall, and in testicular macrophages and mast cells of infertile patients. These observations highlight the possible relevance of PGs in testicular inflammation associated with idiopathic infertility. Collectively, these data indicate that the COX2/PG system plays crucial roles not only in testicular physiology (i.e., development, steroidogenesis, and spermatogenesis), but more importantly in the pathogenesis or maintenance of infertility status in the male gonad. Further studies of these actions could lead to new therapeutic approaches to idiopathic male infertility.

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Introduction

Prostaglandins (PGs) are bioactive lipid substances derived from arachidonic acid. Arachidonic acid is generated from phospholipid hydrolysis catalyzed by combined phospholipase A2 (PLA2) and cyclooxygenase (COX) or lipoxygenase activities. Arachidonic acid can also be generated from diacylglycerol (DAG) by the action of a DAG lipase (Harnett & Goodrigde 2005).

PGs, which are found in most tissues and organs, are produced by almost all nucleated cells. They were discovered in the 1930s and named prostaglandins because they were originally thought to be prostatic products (Goldblatt 1933, Von Euler 1935).

PGs are involved in a diversity of physiological and pathological systems such as regulation of inflammatory and immune responses, cell growth, intraocular pressure, calcium movement, contraction and relaxation of vascular smooth muscle cells, aggregation and disaggregation of platelets, glomerular filtration rate in the kidney, sensitivity of spinal neurons to pain, body temperature in response to fever, and parturition (Narumiya 2007).

The biosynthetic pathway of PGs is initiated when COX catalyzes two sequential reactions, cyclooxygenation of arachidonic acid to PGH and a subsequent peroxidation in which PGH is reduced to PGGH. The resulting PGH is converted to other bioactive PG isomers by the action of synthases and ketoreductases, reactions of dehydration, and non-enzymatic isomerization (Fig. 1; Simmons et al. 2004, Frungieri et al. 2006). The majority of the biologically active PGs belong to series 2, characterized by the presence of two double bonds in...
Arachidonic acid

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\begin{align*}
\text{COX} & \quad \rightarrow \quad \text{PGG}_2 \\
\text{COX} & \quad \rightarrow \quad \text{PGH}_2 \\
\text{Dehydration} & \quad \rightarrow \quad \text{PGD}_2 \\
\text{11-Keto-reductase} & \quad \rightarrow \quad \text{PGF}_{2\alpha} \\
\text{15–deoxy-\(\Delta^{12,14}\)-PGJ}_2 &
\end{align*}
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Figure 1 Schematic representation of the prostaglandin (PG) biosynthetic pathway. The process is initiated by the action of the cyclooxygenase (COX) enzyme, which catalyzes both the conversion of arachidonic acid into PGG2, and the subsequent reduction of PGG2 to PGH2. Afterward, PGH2 is the common precursor for the synthesis of the remaining major PGs.

the hydrocarbon structure (Simmons et al. 2004, Frungieri et al. 2006).

COX, the rate-limiting enzyme of PG biosynthesis, is also known as prostaglandin H synthase (PGHS) or prostaglandin endoperoxide synthase (PTGS). COX is present in two distinct isoforms, types 1 and 2, encoded by separate genes (Smith & Langenbach 2001, Simmons et al. 2004). COX1, commonly known as the constitutive isoform, is found in most cell types, while COX2, the inducible form, appears to be expressed only during early stages of cell differentiation or replication, in response to varying stimuli such as cytokines and mitogenic factors. COX2 expression has been described in physiological and pathological processes including inflammation, angiogenesis, bone absorption, gastric ulceration, kidney diseases, brain disorders, and female genital tract disorders (Katori & Majima 2000). Furthermore, COX2 is overexpressed in many types of cancer, including breast, colon, lung, and prostate cancers (Harris 2009).

Depending on the biological process, COX isoenzymes can act individually, in concert, or in cases where one isoenzyme is lacking, in a compensatory manner (Smith & Langenbach 2001). Recently, new variants of COX have been discovered, such as COX3 and PCOX1, splice variants that affect the coding region of COX1, as well as a number of alternatively polyadenylated transcripts of COX and single nucleotide polymorphisms (SNPs; Simmons et al. 2004). COX variants and mutants are likely to yield altered or expanded biological function.

DP, EP, FP, IP, and TP are serpentine plasma membrane-localized prostanoid receptors that bind PGD, PGE, PGF, PGI, and thromboxane respectively. In addition, several prostanoids, of which 15-deoxy-\(\Delta^{12,14}\)-PGJ2 (15d-PGJ2) is the most potent, may activate the peroxisome proliferator-activated receptor gamma (PPARγ) members of the steroid/thyroid family of nuclear hormone receptors, which act as transcription factors and may thus directly influence gene transcription (Simmons et al. 2004, Narumiya 2007).

COX and PGs in the human testis

In the 1990s, the development of Cox1- and Cox2-deficient mice yielded insights into the reproductive roles of PGs. While female Cox2 knockout mice are infertile, those deficient in Cox1 have difficulties with parturition but produce litters with normal weight. In contrast, fertility is not affected in male mice deficient in Cox1 or Cox2 (Langenbach et al. 1999). These early reports suggested that PGs may not be critical to testicular function. However, this view has recently been challenged by novel observations. It has been reported that paracetamol and some nonsteroidal anti-inflammatory drugs (NSAIDs) such as aspirin and indomethacin induce endocrine disturbances in the human fetal testis capable of interfering with testicular descent (Mazaud-Guittot et al. 2013). Furthermore, PGD2 influences male germ cell differentiation in the fetal mouse testis (Moniot et al. 2014), and it has been proposed that the hematopoietic PGD2 synthase participates in the SOX9 nuclear translocation necessary for the process of Sertoli cell differentiation (Rossitto et al. 2015).

PG receptors have been described in Leydig cells (i.e., EP1, DP, FP, TP, and PPARγ receptors; Walch et al. 2003, Frungieri et al. 2006, Schell et al. 2007, Kowalewski et al. 2009, Pandey et al. 2009), Sertoli cells (e.g., EP1, EP2, EP3, EP4, DP, IP, FP, and PPARγ receptors; Ishikawa & Morris 2006, Winnal et al. 2007, Kristensen et al. 2011, Matzkin et al. 2012a), and the seminiferous tubule wall (PPARγ receptors; Frungieri et al. 2002a). DP prostanoid receptors have also been detected in germ cells of the fetal mouse testis (Moniot et al. 2014), whereas functional PPARγ and PGE receptors have been found in sperm (Schaefer et al. 1998, Santoro et al. 2013).

PGs, mainly those from the PGE and 19-hydroxy-PGE series, are present in human seminal plasma. Several reports have claimed that there is a correlation between PG levels in semen and otherwise unexplained male infertility (Kelly 1978). The lipocalin and hematopoietic PGD2 synthases are also detected in seminal plasma and their concentrations are lower in oligozoospermic men than in normozoospermic men (Tokugawa et al. 1998). PGs in human seminal plasma are mostly secreted from the seminal vesicles. Nevertheless, testicular secretions also contribute up to 5% of the composition of the semen (Thibodeau & Patton 2012).

Data from our group revealed that COX is not detectable by immunohistochemistry in normal adult human testes without morphological abnormalities.
However, the inducible isoenzyme COX2 is expressed by several cell types in testicular biopsies of men with impaired spermatogenesis and infertility (Frungieri et al. 2002a, Welter et al. 2011). They include Leydig cells, Sertoli cells, and cells of the tubular wall that present an altered morphology (Figs 2 and 3; Schell et al. 2008, Matzkin et al. 2010). COX2 was also found in testicular immune cells, namely mast cells and macrophages (Matzkin et al. 2010, Welter et al. 2011, Rossi et al. 2014).

Similarly, Hase et al. (2003) did not detect COX expression in the normal human testis, but described induction of COX1 and COX2 in testicular cancer. Additionally, lipocalin and hematopoietic PGD2 syntheses are expressed in testes from patients with impaired spermatogenesis (Schell et al. 2007).

These data suggest that, in pathological situations, the human testis is capable of synthesizing PGs. In this regard, we have recently described the presence of the PG metabolite, 15d-PGJ2, in biopsies of patients suffering from idiopathic infertility (Kampfer et al. 2012).

Overall, the wide distribution of PG receptors and synthesizing enzymes in the testis emphasizes the plethora of functions and potential key roles exerted by these bioactive lipid substances on testicular development, steroidogenesis, sperm maturation, and male fertility.

Physiological studies cannot be performed using human testicular biopsies. In the search for an appropriate model, our laboratory turned to the Syrian hamster. It was chosen as the experimental model because the exposure of male adult animals to 12.5 h of light/day for 3–4 months results in a severe testicular regression with morphological features resembling those observed in biopsies of patients suffering from hypospermatogenesis and germ cell arrest. For instance, seminiferous tubules in photoperiodically regressed hamster testes contain mostly Sertoli cells, spermatogonia, and a few primary spermatocytes (Fig. 4; Sinha Hikim et al. 1988, Rossi et al. 2014).

**Figure 2** Immunohistochemical images of consecutive testicular sections of a patient with hypospermatogenesis immunostained for 3β-hydroxysteroid dehydrogenase (3β-HSD) and cyclooxygenase 2 (COX2). Most, but not all, 3β-HSD-immunoreactive Leydig cells found in the human testis are also positively stained for COX2. A polyclonal rabbit anti-COX2 serum (Oxford Biomedical Research, Oxford, UK, 1:200) and a polyclonal rabbit anti-3β-HSD serum (kindly provided by Prof. Dr J I Mason, University of Edinburgh Centre of Reproductive Biology, Scotland, 1:2000) were used. Bar: 100 μm.

**Figure 3** Using laser capture microdissection, androgen receptor (AR)-immunoreactive peritubular (A) and Sertoli (B) cells (arrows) were isolated from a testicular biopsy of a patient suffering from germ cell arrest, and then subjected to RT-PCR studies. (A) Each panel depicts the same specimen before laser microdissection (left), after u.v. laser delimitation of AR-immunoreactive peritubular cells (arrows; middle), and after IR laser microdissection (right) of target cells. A polyclonal rabbit anti-AR serum (Santa Cruz Biotechnology, Inc., 1:200) was used. Bar, 50 μm. (B) Each panel depicts the same specimen before laser microdissection (left), after u.v. laser delimitation of AR-immunoreactive Sertoli cells (arrows; middle), and after IR laser microdissection (right) of target cells. A polyclonal rabbit anti-AR serum (Santa Cruz Biotechnology, Inc., 1:200) was used. Bar, 50 μm. (C) COX2 mRNA expression was detected in human peritubular and Sertoli cells by RT-PCR assays performed with oligonucleotide primers from Matzkin et al. (2010). PCR products were separated on 2% agarose gels and visualized with ethidium bromide. The identity of the cDNA products was confirmed by sequencing, using a fluorescence-based dideoxy sequencing reaction and an automated sequence analysis on an ABI 373A DNA sequencer.

**Figure 4** Using laser capture microdissection, AR-immunoreactive peritubular (A) and Sertoli (B) cells (arrows) were isolated from a testicular biopsy of a patient suffering from germ cell arrest, and then subjected to RT-PCR studies. (A) Each panel depicts the same specimen before laser microdissection (left), after u.v. laser delimitation of AR-immunoreactive peritubular cells (arrows; middle), and after IR laser microdissection (right) of target cells. A polyclonal rabbit anti-AR serum (Santa Cruz Biotechnology, Inc., 1:200) was used. Bar, 50 μm. (B) Each panel depicts the same specimen before laser microdissection (left), after u.v. laser delimitation of AR-immunoreactive Sertoli cells (arrows; middle), and after IR laser microdissection (right) of target cells. A polyclonal rabbit anti-AR serum (Santa Cruz Biotechnology, Inc., 1:200) was used. Bar, 50 μm. (C) COX2 mRNA expression was detected in human peritubular and Sertoli cells by RT-PCR assays performed with oligonucleotide primers from Matzkin et al. (2010). PCR products were separated on 2% agarose gels and visualized with ethidium bromide. The identity of the cDNA products was confirmed by sequencing, using a fluorescence-based dideoxy sequencing reaction and an automated sequence analysis on an ABI 373A DNA sequencer.

**COX and PGs in Leydig cells**

We initiated the investigation of COX expression in Syrian hamster testes, and although COX1-immunoreactive cells were not detected, immunoperoxidase staining revealed the presence of COX2 in the cytoplasm of interstitial cells, showing the characteristic punctate chromatin pattern of Leydig cells in peripubertal, pubertal, and adult hamster testes. Surprisingly, testicular
expression of COX2 was barely detectable when adult hamsters were exposed to light-deprivation conditions (Frungieri et al. 2006). Thus, although testes from regressed hamsters are histologically similar to biopsies of infertile patients, they are deficient in COX2 expression, a typical feature of Leydig cells in the pathological human testis. This discrepancy may imply that PGs play distinctly different roles in testes of different species (Frungieri et al. 2006). Thus, COX2 and PGs may have a biological relevance in the pathogenesis or maintenance of infertility states in men. Conversely, considering that COX2 levels are much more abundant in Leydig cells of reproductively active hamsters than in testes of photoperiodically regressed animals, we propose that PGs could act as physiological mediators involved in the modulation of steroidogenic cell function in seasonal breeders.

In contrast to our observations in testes of reproductively active hamsters, we failed to detect COX2 by immunohistochemistry in testes from other species (i.e., rhesus monkeys, pigs, BALBc mice, Wistar rats, and Sprague–Dawley rats; Frungieri et al. 2006). However, Parillo et al. (2011) have recently described COX immunoreactivity in Leydig cells of the alpaca Lama pacos. Furthermore, some authors (Wang et al. 2005, Balaji et al. 2007, Winnal et al. 2007) have reported COX2 expression in mouse and rat Leydig cells using more sensitive assays such as western blot, quantitative PCR, and enzyme activity assays. These data allow us to speculate about the existence of species-specific levels of COX2 expression in Leydig cells, which may be explained by the evolutionary divergence in testicular coding sequences (Oduru et al. 2003) and/or the existence of a marked variation between different species in the regulation of testicular COX2 expression and PG production.

Revisiting the issue of COX2 expression in hamster Leydig cells, this isoenzyme is detected mainly in reproductively active pubertal and adult hamsters with increasing circulating concentrations of luteinizing hormone (LH), prolactin (PRL), and androgens (Frungieri et al. 2006, Matzkin et al. 2009, 2012b). On the other hand, in adult hamsters exposed to a short-day photoperiod and also in prepubertal hamsters, testicular COX2 is barely detected, coinciding with low serum concentrations of LH, PRL, and androgens (Frungieri et al. 2006, Matzkin et al. 2009, 2012b). These results suggest that some hormones (LH, PRL, and/or androgens) could be involved in the regulation of testicular COX2 expression and PG production.

The unique expression of PGD synthase in adult Leydig cells had already been described (O’Shaughnessy et al. 2002, Schell et al. 2007). However, to our knowledge, the potential role of COX2 as a marker of mature active Leydig cells during cell development has not previously been suggested.

In vitro experiments performed in Leydig cells purified from reproductively active adult hamsters incubated in the presence or absence of LH/human chorionic gonadotropin (hCG) and testosterone, and with or without the addition of bicalutamide (a pure non-steroidal antiandrogen) to the incubation medium, showed an up-regulation of COX2 expression and PGF2α production. This LH action is not derived from a direct mechanism but rather from its stimulatory role in testosterone synthesis (Matzkin et al. 2009). In fact, testosterone effects in hamster Leydig cells are exerted via androgen receptors (ARs; Matzkin et al. 2009). The classical mechanism of testosterone action involves binding of this steroid to the cytoplasmic AR, translocation of the newly formed complex into the nucleus, its binding to specific DNA regulatory elements, and, finally, gene transcription regulation. In addition to this classical pathway, there is growing evidence indicating that androgens can trigger cellular processes through rapid, non-genomic mechanisms (Foradori et al. 2008). In this context, the stimulatory effect of testosterone on COX2/PGF2α in hamster Leydig cells takes place via a non-classical mechanism that involves phosphorylation of ERK1/2 (Matzkin et al. 2009).
On the other hand, PRL also mediates up-regulation of COX2 expression and stimulation of PGD2 and PGF2 production in hamster Leydig cells through activation of p38–MAPK and JAK2 (Matzkin et al. 2012b). Post-translational modifications of the PRL molecule including glycosylation, tyrosine sulfation, phosphorylation, and deamination may well represent a key mechanism for creating diversity in the biological actions of this hormone (Sinha 1992). In particular, pituitaries from reproductively active hamsters contain PRL charge analogs with pI of 5.16, 4.61, and 4.34. The exposure of adult hamsters to a short-day photoperiod of 6 h light/day results in a decline in PRL pituitary levels and in the presence of less acidic PRL charge analogs with a pI of 5.44. Interestingly, the more acidic PRL charge analogs present in the pituitaries of reproductively active hamsters strongly induce COX2 expression in hamster Leydig cells. By contrast, the less acidic analogs detected in the pituitaries of regressed animals have no effect (Matzkin et al. 2012b). The stimulatory effect of more acidic PRL charge analogs on COX2 expression in hamster Leydig cells takes place through a mechanism that involves the pro-inflammatory cytokine IL1b (Matzkin et al. 2012b). It has been shown that IL1b induces COX2 expression and PGD2 and PGF2 production in mouse TM3 Leydig cells (Matzkin et al. 2010). The expression of the IL1R1 functional receptor of IL1b in Leydig cells has been described not only in rodents (hamsters and mice) but also in humans (Matzkin et al. 2010, 2012b).

The prostaglandin receptors DP and FP have been described in both hamster and Leydig cells (Frungeriet al. 2006, Schell et al. 2007). While PGD2 has a stimulatory effect on basal testosterone production in hamster Leydig cells (Schell et al. 2007), PGF2α exerts an inhibitory effect on the expression of the StAR protein and the 17β-hydroxysteroid dehydrogenase (17β-HSD or HSD17B1) enzyme, as well as on the synthesis of testosterone induced by hCG/LH (Frungeriet al. 2006).

It is therefore tempting to assume that, at least in hamster Leydig cells, there exists a regulatory loop in which testosterone induces COX2 expression and PGF2α production. In turn, PGF2α inhibits StAR and HSD17B1 expression and, consequently, testosterone production, thereby setting a brake on testicular steroidogenesis (Fig. 5; Frungeri et al. 2006, Matzkin et al. 2009).

In agreement with our findings in hamsters, it has been reported that PGF2α reduced hCG-stimulated testosterone secretion in rat Leydig cells (Romanelli et al. 1995). Additionally, other authors (Saksena et al. 1973, Didolkar et al. 1981, Sawada et al. 1994) have shown that PGF2α decreases plasma testosterone levels in male rats. On the contrary, injection of PGF2α to male rhesus monkeys is followed by an abrupt rise in serum testosterone (Kimball et al. 1979).

Syntin et al. (2001) and Wang et al. (2005) have described that the COX2/PG system represents a potential key factor in the age-related reduction in testosterone production, as up-regulation of COX2 expression in Brown Norway rats during aging is accompanied by decreased testicular production of testosterone. In this context, COX2 inhibition enhances steroidogenesis and Star gene expression in MA-10 mouse Leydig cells, whereas its overexpression leads to the opposite (Wang et al. 2003). Furthermore, production of testosterone by decapsulated mouse testes is significantly inhibited by adding some PGs (PGA1, PGA2, and PGE1) to the incubation medium (Bartke et al. 1976). On the other hand, COX2 seems to be involved in aromatase post-translational activation and increased cell proliferation in the rat Leydig tumor cell line R2C (Sirianni et al. 2009).

From the aforementioned data, it is clear that Leydig cells express the inducible isoenzyme COX2 and produce

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**Figure 5** Summary view of COX2 expression/PG synthesis regulation, and the modulatory effect of some PGs on steroidogenesis in hamster Leydig cells. Based on experimental results, PRL induces COX2 expression as well as PGD2 and PGF2 production in Leydig cells through activation of p38–MAPK and JAK2/STAT5. In addition, testosterone via androgen receptors (ARs) and a non-classical mechanism that involves phosphorylation of ERK1/2 also increases COX2 expression and PGs production. While PGD2 through DP receptors stimulates testosterone production under basal conditions, PGF2α via FP receptors inhibits StAR and HSD17B1 expression and consequently testosterone production in the presence of LH/hCG, thus setting a brake on testicular steroidogenesis.
PGs with age-, photoperiod-, and species-specific differences. In addition to its regulation by PRL and IL1β, COX2 expression is also regulated by testosterone through a non-genomic mechanism. The existence of a COX2/PG system in Leydig cells serves as a local modulator of steroid hormone production.

**COX and PGs in Sertoli cells**

Spermatogenesis is dependent upon adequate Sertoli cell function (Griswold 1998). The expression of COX, production of PGE₂, PGF₂α, and PGL₂, as well as the existence of the prostanoid receptors (i.e., EP1, EP2, EP3, EP4, IP, and FP) has been reported in Sertoli cells of immature and juvenile rodents (Ishikawa & Morris 2006, Winnal et al. 2007, Kristensen et al. 2011).

Studies are usually limited to Sertoli cells isolated from immature rodents to avoid germ cell contamination during the purification procedure. Consequently, data obtained from adult Sertoli cells are scarce. As only Sertoli cells, spermatagonia, and a few primary spermatocytes are observed in tests of photoperiodically regressed adult Syrian hamsters (Fig. 4; Bartke 1985, Sinha Hikim et al. 1988, Rossi et al. 2014), this species becomes a useful and available experimental model for isolation of Sertoli cells from adult animals.

Follicle-stimulating hormone (FSH) and testosterone are the two major hormones that act in the testis to regulate spermatogenesis. Sertoli cells transduce signals from FSH and testosterone into the synthesis of factors that are required for spermatogenesis. These actions take place through FSH receptors and ARs located in Sertoli cells (Walker & Cheng 2005, Matzkin et al. 2009, 2012a).

In recent studies carried out on Sertoli cells purified from tests of adult hamsters exposed to a short-day photoperiod, we have demonstrated that FSH exerts a stimulatory effect on COX2 expression, as well as on 15d-PGJ₂ and PGF₂α production through a mechanism that involves ERK1/2 phosphorylation (Matzkin et al. 2012a). Supporting our results, Jannini et al. (1994) have shown FSH-stimulated eicosanoid generation dependent upon the activation of the COX pathway in immature rat Sertoli cells. Moreover, both stimulatory and inhibitory actions of FSH on ERK1/2 phosphorylation were described in rodent Sertoli cells (Crepieux et al. 2001, Meroni et al. 2004).

Testosterone also induces COX2 expression and increases 15d-PGJ₂ production in adult hamster Sertoli cells via ARs most probably located on the cell surface (Matzkin et al. 2012a). The existence of testosterone-binding sites in the plasma membrane has been previously reported for Sertoli cells (Fix et al. 2004). Using the plasma membrane-impermeable testosterone–BSA, we observed that both COX2 expression and 15d-PGJ₂ production are enhanced in adult hamster Sertoli cells, via a non-classical androgen action associated with the activation of the ERK1/2 signaling pathway (Matzkin et al. 2012a). Supporting these data, members of the MAPK pathway have been shown to form complexes with ARs on molecular scaffolds anchored to the plasma membrane (Pedram et al. 2007). Moreover, using an immunofluorescence technique, Cheng et al. (2007) have found that upon testosterone stimulation of rat Sertoli cells, a population of ARs is localized, in a transient manner, in the plasma membrane.

Among Sertoli cell functions that may be important to germ cell development is the provision of adequate levels of energy substrates such as lactate. In this context, the transport of glucose through the plasma membrane is the rate-limiting step in glucose metabolism and, consequently, in lactate production (Riera et al. 2001, 2009). Glucose enters the cell by carrier proteins called glucose transporters (known as GLUTs or SLC2A). Thus far, expression of SLC2A1, SLC2A3, and SLC2A8 transporters has been demonstrated in Sertoli cells (Carosa et al. 2005, Galardo et al. 2008). In adult hamster Sertoli cells, FSH and testosterone induce the uptake of [2,6-3H]-2-deoxy-D-glucose, a non-metabolizable glucose analog. In accordance with these data, an increased FSH-mediated glucose uptake has been described in immature rat Sertoli cells (Riera et al. 2001).

The nuclear PPARγ receptor is present in hamster Sertoli cells (Matzkin et al. 2012a), suggesting a potential autocrine action of its natural ligand 15d-PGJ₂. In fact, 15d-PGJ₂ inhibits glucose uptake in adult hamster Sertoli cells via the nuclear PPARγ receptor (Matzkin et al. 2012a). The participation of arachidonic acid, precursor in PG biosynthesis, in the regulation of Sertoli cell function has recently been addressed (Meroni et al. 2004).

These results therefore have led to the suggestion that testosterone and FSH induce glucose uptake, COX2 expression, and 15d-PGJ₂ production in Sertoli cells. Subsequently, 15d-PGJ₂ acts via the nuclear PPARγ receptor to impair glucose entry. Therefore, the COX2/15d-PGJ₂/PPARγ system may serve as a local autocrine modulator of Sertoli cell activity and, consequently, spermatogenic efficiency (Fig. 6).

Harmful actions of COX/PGs have also been described in Sertoli cells. Elevated testicular temperature in cryptorchidism decreases the expression of the cystic fibrosis transmembrane conductance regulator (CFTR), resulting in overexpression of COX2 and excessive PG₂ production in rodent Sertoli cells, which in turn lead to further damage of inter-Sertoli cell tight junctions and defective spermatogenesis (Chen et al. 2012). In contrast, toxic xenobiotics such as nonylphenol, commonly used as a detergent, up-regulate COX2 in TM4 immature mouse Sertoli cells (Liu et al. 2014).

In summary, Sertoli cells express COX2 and produce PGs in response to FSH and a non-classical mechanism triggered by testosterone. PGs serve as local autocrine modulators of Sertoli cell function, and thus indirectly regulate sperm maturation.
**COX and PGs in the seminiferous tubule wall**

Depending on the species, the seminiferous tubule wall can be either a simple structure or a rather complex one. For instance, in rodents, the tubular wall is composed of a single cell layer and a tiny extracellular matrix. However, in the human testis, the seminiferous tubule wall is composed of the following components: an internal acellular basal membrane adjacent to the germinal epithelium containing collagen fibers, laminin, glycoproteins, and hyaluronic acid; a middle cellular zone made of spindle-shaped and contractile cells (called myoid cells or myofibroblasts); and an external cellular zone consisting of collagen-producing fibroblasts (Pop et al. 2011, Mayerhofer 2013). Disturbances in testicular function and decreased or no spermatogenic activity are associated with a thickening of the seminiferous tubule wall, which becomes fibrotically remodeled. Fibroblasts, together with smooth muscle cells, mediate tissue fibrosis and collagen deposition (Mayerhofer 2013). This frequent change is observed irrespective of the causes of male infertility and is regarded as a hallmark of male infertility (Frunieri et al. 2002a, Weinbauer et al. 2010). Different human cellular models have been used to study tubular fibrosis, the involvement of the local COX/PG system and its regulation. For instance, we used human fetal foreskin fibroblast cells (HFFF2), which show increased COX2 protein levels, PG (PGF2α and 15d-PGJ2) production, and cell proliferation in the presence of the serine protease trypstatse (Frunieri et al. 2002a). Tryptase is a mast cell product known to cause proliferation of fibroblasts and fibrosis (Frunieri et al. 2002a). The effect of tryptase was tested in HFFF2 because increased numbers of tryptase-immunoreactive mast cells are detected in the seminiferous tubule wall in the testes of infertile men (Meineke et al. 2000). Furthermore, the amount of testicular tryptase-immunoreactive mast cells correlates with the fibrotic thickening of the tubular wall in patients with impaired spermatogenesis or Sertoli-cell-only (SCO) syndrome (Meineke et al. 2000). When the COX2 antagonist meloxicam was added to the incubation media, the proliferative action of the mast cell product tryptase on HFFF2 was blocked, implying that PGs derived from COX2 activity are crucially involved in this action. On the other hand, the nuclear PPARγ receptor is expressed in the seminiferous tubule wall of infertile patients as well as in HFFF2 cells, and its natural ligand 15d-PGJ2 directly increases fibroblast proliferation (Frunieri et al. 2002a). Thus, there is a signaling pathway linked to fibroblast proliferation that involves the mast cell product tryptase, its receptor PAR2, induction of COX2, synthesis of 15d-PGJ2, and its action through PPARγ. The initial events of the tryptase/PAR2 signaling pathway leading to COX2 induction and fibroblast proliferation involve up-regulation of the immediate-early genes C-JUN and C-FOS, and phosphorylation of ERK1/2 (Frunieri et al. 2005).

It is important to bear in mind that PAR2 receptors are expressed in interstitial cells, while PPARγ receptors are found in the peritubular cells of the human testis. Furthermore, mast cells containing tryptase accumulate in testes showing abnormal spermatogenesis, and COX2 is mostly detected in biopsies of patients with idiopathic infertility (Frunieri et al. 2002a). Thus, the fact that all components involved in the tryptase/COX2/15d-PGJ2/PPARγ-induced proliferation of HFFF2 cells are also present in the testes of infertile patients showing fibrotic thickening in the wall of the seminiferous tubules implies that COX2 and some PGs could be of relevance for human diseases linked to fibrotic disorders.

To further investigate the wall of the seminiferous tubules in health and disease, a new and more reliable experimental model has recently been developed.
Human testicular peritubular cells were isolated from very small testicular tissue samples from adult patients with obstructive azoosperma but normal spermatogenesis (HTPCs), as well as from biopsies of men with non-obstructive azoosperma, impaired spermatogenesis, and testicular fibrosis (HTPCFs) (Albrecht et al. 2006, Schell et al. 2008, 2010, Spinnler et al. 2010, Mayerhofer 2013).

Tumor necrosis factor alpha (TNFα), a cytokine with pleiotropic actions, which is known to be released from human testicular macrophages (Frungieri et al. 2002b), induces inflammatory markers in HTPCs such as COX2 and PGD2 (Schell et al. 2008). Previously, a PGD2 system had been identified in the human testis (Schell et al. 2007). This system includes the expression of PGD2 synthases and the existence of the prostanoid receptor DP in the testes of men suffering from spermatogenic damage and infertility (Schell et al. 2007).

On the other hand, 15d-PGJ2, via the generation of reactive oxygen species (ROS), strongly influences cultured HTPCs and HTPCFs (Kampfer et al. 2012). Upon 15d-PGJ2 treatment, cells become hypertrophic and show a diminished expression of smooth muscle cell markers (e.g., smooth muscle actin, MYH11, and calponin) as well as a reduced ability to contract. Interestingly, upon removal of 15d-PGJ2, cells spontaneously revert to the normal phenotype, an indication of a high intrinsic degree of cellular plasticity (Schell et al. 2010, Welter et al. 2013, Mayerhofer 2013). HTPCFs express higher levels of the H2O2-metabolizing enzyme catalase than HTPCs, circumstantial evidence for increased ROS levels in the tubular wall of infertility patients (Kampfer et al. 2012). Thus, it is possible to speculate that up-regulation of COX2/15d-PGJ2 and generation of ROS are interconnected events, forcing smooth muscle-like peritubular cells to adapt and change their phenotype, and finally, to lose contractility (Mayerhofer 2013). As contractility of the tubular wall is crucial for sperm transport and fertility, COX2/15d-PGJ2 could be, to date, an overlooked factor that contributes to male infertility.

Hence, results obtained from cellular studies and parallel examinations of human testicular biopsies provide insights into the roles played by PGs in tubular fibrosis and contractility. Consequently, PGs may be crucial factors for the active transportation of immotile sperm that takes place in the seminiferous tubules. Furthermore, these bioactive lipid substances might be key players in the paracrine interactions taking place between peritubular cells and other testicular somatic cells such as Leydig and Sertoli cells.

COX and PGs in testicular immune cells

The testis is one of a small number of so-called immunologically privileged tissues of the body. In fact, the production, differentiation, and presence of germ cells represent inimitable challenges to the immune system, because these cells appear long after the maturation of the immune system and formation of systemic self-tolerance (Fijak & Meinhardt 2006). The blood-testis barrier represents an essential element for local immunosuppression. However, the existence of the blood-testis barrier does not mean that the lymphatic drainage of the testis is deficient or that immune cells are unable to access germ cells (Hedger 2002). Actually, immune cells are observed in the capsule, interstitium, and seminiferous tubules of the testis. In particular, large numbers of macrophages are found in the testis. Significant amounts of testicular mast cells, dendritic cells, as well as effector, regulatory, and natural killer T lymphocytes have also been reported (Itoh et al. 1995, Tompkins et al. 1998, Meineke et al. 2000, Frungieri et al. 2002b, Hedger 2002, Jacobo et al. 2009).

Testicular immunoregulation depends on a delicate equilibrium between immunoprivilege and inflammation in which immune cells play a dual role. Under physiological conditions, antigen-specific autoimmune responses are prevented by systemic and local tolerance mechanisms involving the actions of dendritic cells and regulatory T lymphocytes, as well as immunosuppressor cytokines mainly secreted by resident macrophages. Breakdown of immune homeostasis in the testis leads to inflammation (Pérez et al. 2013). It is known that male genital tract inflammations are relevant co-factors in infertility. Human testicular macrophages from infertile patients secrete pro-inflammatory cytokines such as IL1β and TNFα (Frungieri et al. 2002b). The numbers of macrophages and mast cells are markedly increased in testes of patients, indicating impaired spermatogenesis (Meineke et al. 2000, Frungieri et al. 2002b). Furthermore, the distribution pattern and morphology of these immune cells are altered in pathological states. For instance, there is a significant shift in the location of macrophages and mast cells from the interstitium to the tubular compartment in the testes of infertile men (Meineke et al. 2000, Frungieri et al. 2002b). In samples with normal spermatogenesis, these immune cells are round and located mainly in the interstitial spaces close to Leydig cells. In pathological conditions, mast cells and macrophages are heterogeneous, with not only rounded but also elongated shapes and signs of degranulation (Meineke et al. 2000, Frungieri et al. 2002b). In contrast to men, it has been described that mast cells are located almost exclusively in the capsule adjacent to testicular blood vessels in the testes of rodents, including hamsters (Frungieri et al. 1999, Rossi et al. 2014).

COX2 is expressed in both testicular mast cells and macrophages of patients suffering from hypospermatogenesis, germ cell arrest, mixed atrophy, or SCO syndrome (Matzkin et al. 2010, Welter et al. 2011, Rossi et al. 2014). Interestingly, few mast cells that do not express COX2 are observed in testes with normal spermatogenesis.
Human testicular macrophages secrete IL1ß, and a positive correlation between IL1ß levels and COX2 expression has been described in the testes of infertile patients (Matzkin et al. 2010).

Thus, mast cells and macrophages increased the population number and secretion of pro-inflammatory cytokines, as well as the acquisition of the capability to produce PG inflammatory mediators seem to play a decisive role in the autoimmune basis of testicular inflammation associated with subfertility and infertility.

Concluding remarks and future perspectives

In contraposition to initial data showing that fertility is not affected in Cox-deficient male mice (Langenbach et al. 1999), and therefore that PGs might not be significant to testicular function, research carried out in recent years describes a plethora of PG functions in the male gonad.

A COX2/PG system has been described in the two key somatic cell types of the testis: Leydig and Sertoli cells. Furthermore, studies have provided new insights into how several hormones and cytokines (i.e., FSH, PRL, testosterone, and IL1ß) modulate COX2 expression and PG production in Leydig and Sertoli cells. Studies performed mainly in rodents indicate that some PGs (i.e., PGD2 and PGF2α) modulate androgen production in Leydig cells, while 15d-PGJ2 regulates glucose transport in Sertoli cells and, consequently, spermatogenic efficiency. Recently, an additional physiological role of COX2 as a protector of germ cells against spermatogenic disturbance has been reported in an experimental cryptorchidism mouse model (Kubota et al. 2011).

Most importantly, besides their action on testicular physiology, PGs seem to be associated with pathogenesis or maintenance of infertility states in men.

For instance, 15d-PGJ2 was associated with the fibrosis and loss of contractility often observed in the wall of the seminiferous tubules in patients suffering from idiopathic infertility. Furthermore, the existence of a COX2/PG system in testicular immune cells (mast cells and macrophages), showing a significant increase in their population number in some pathologies, strongly suggest the importance of PGs in the development of local inflammation that might further compromise testicular function in patients with hypospermatogenesis, germ cell arrest, or SCO syndrome.

Currently, the majority of infertile men present disorders either untreatable or treatable with drugs of questionable effectiveness. In this context, drugs targeting COX, PGs, and prostanoid receptors are being developed or used in clinical practice for a variety of conditions. For example, there are widely marketed and relatively safe drugs such as celecoxib, valdecoxib, and rofecoxib, developed for specific COX2 inhibition, that possess all of the analgesic, antipyretic, and anti-inflammatory activities of the older nonselective NSAIDs (Simmons et al. 2004).

Therefore, the study of COX and PG actions appears to be a promising field of research with a potential impact on male fertility. Further advances in the knowledge of the role played by COX, PGs, and their receptors in the human testis, as well as future investigations concerning the impact of drugs targeting COX/PGs at the testicular level, could lead to new therapeutic approaches in idiopathic male infertility. In this context, non-selective inhibitors of COX usually used as mild analgesics, such as indomethacin, paracetamol, and aspirin, have been shown to display endocrine-disrupting properties in the adult human testis in vitro (Albert et al. 2013). Nevertheless, the beneficial or disadvantageous effects of specific COX2 inhibitors in the infertile human testis have not, to date, been fully explored.

Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the review.

Funding

Studies mentioned in this review were supported by grants from Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Agencia Nacional de Promoción Científica y Técnica (ANPCyT), Ministerio de Ciencia, Tecnología e Innovación Productiva (MINCYT), Facultad de Medicina—Universidad de Buenos Aires, Fundación Antorchas, and Fundación Alberto J. Roemmers of Argentina, and Deutscher Akademischer Austausch Dienst (DAAD) and Deutsche Forschungsgemeinschaft (DFG) of Germany, especially MA1080/21-1 and MA1080/25-1.

Acknowledgements

The authors are grateful to our colleagues, Drs V Ambao, S Campo, M H Carino, S B Cigorraga, B Gonzalez, C R Gonzalez, L Gonzalez, S I Gonzalez-Calvar, O Levalle, L Lustig, F Parborell, E H Pellizarri, P Pomata, R Ponzo, E Puigdomenech, S P Rossi, C Terradas and D Turyn (Buenos Aires, Argentina), and Drs M Albrecht, B Jessberger, C Kampler, M Köhn, C Mayer, V Meineke, R Raemsch, C Schell, J U Schwarzer, S Spillner, K Spinnler, H-J Vogt, S Weidinger, and S Windschuettl (Munich, Germany).

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Received 1 August 2014
First decision 8 October 2014
Revised manuscript received 27 November 2014
Accepted 11 December 2014