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Fetal programming of adult Leydig cell function by androgenic effects on stem/progenitor cells


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Fetal growth plays a role in programming of adult cardiometabolic disorders, which in men, are associated with lowered testosterone levels. Fetal growth and fetal androgen exposure can also pre-determine testosterone levels in men, although how is unknown, because the adult Leydig cells (ALCs) that produce testosterone do not differentiate until puberty. To explain this conundrum, we hypothesized that stem cells for ALCs must be present in the fetal testis and might be susceptible to programming by fetal androgen exposure during masculinization. To address this hypothesis, we used ALC ablation/regeneration to identify that, in rats, ALCs derive from stem/progenitor cells that express chicken ovalbumin upstream promoter transcription factor II. These stem cells are abundant in the fetal testis of humans and rodents, and lineage tracing in mice shows that they develop into ALCs. The stem cells also express androgen receptors (ARs). Reduction in fetal androgen action through AR KO in mice or dibutyl phthalate (DBP)-induced reduction in intratesticular testosterone in rats reduced ALC stem cell number by ∼40% at birth to adulthood and induced compensated ALC failure (low/normal testosterone and elevated luteinizing hormone). In DBP-exposed males, this failure was probably explained by reduced testicular steroidogenic acute regulatory protein expression, which is associated with increased histone methylation (H3K27me3) in the proximal promoter. Accordingly, ALCs and ALC stem cells immunoexpressed increased H3K27me3, a change that was also evident in ALC stem cells in fetal testes. These studies highlight how a key component of male reproductive development can fundamentally reprogram adult hormone production (through an epigenetic change), which might affect lifetime disease risk.

Evidence that altered fetal growth/development can fundamentally alter the risk of health disorders in adulthood and perhaps, future generations continues to grow (1). Such fetal programming applies to common disorders encapsulated in the metabolic syndrome (2), which are interlinked in adult men with low testosterone levels (3). Large studies from the United States (4) and Europe (5, 6) also show that testosterone levels in men of all ages are declining with later year of birth. Aging is itself associated with declining testosterone levels and a high incidence of primary/compensated hypogonadism (7–9). Because low testosterone levels are also associated with generalized proinflammatory changes (10, 11), frailty, and risk of dying in aging men (12), what determines an adult man’s testosterone level is of fundamental importance.

There is also evidence from human (13, 14) and animal experimental (15) studies that fetal programming can influence adult testosterone levels, particularly that reduced fetal androgen exposure leads to lower adult male testosterone levels (14, 15). This data fits with growing evidence that subtle deficiency in fetal androgens is a major determinant of adult male reproductive disorders, such as low sperm production (16, 17), and might explain why low sperm counts are often associated with compensated Leydig cell failure in men (18). However, the mechanisms through which fetal events could influence adult testosterone levels are unknown.

Adult Leydig cells, the main source of blood testosterone in adult males, do not develop until puberty; the only Leydig cells present in the fetal testis are a different fetal generation (19–21). Consequently, adult Leydig cells must develop from stem/progenitor cells (22, 23). Numerous studies in rodents have investigated how adult Leydig cells differentiate from progenitor cells at puberty and have identified a number of factors involved (19, 22, 24–29). However, such studies focus around the period when stem/progenitor cells have started along the differentiation pathway into adult Leydig cells. What might affect the stem/progenitor cells before this point, such as during fetal life, has not been studied, primarily because there is no agreed defining marker for such cells before they commence differentiation. In this regard, Qin et al. (30) showed that inducible KO of chicken ovalbumin upstream promoter transcription factor II (Coup-tfII; also termed Nr2f2) in prepubertal male mice resulted in failure of adult Leydig cells to develop. We, therefore, hypothesized that Coup-tfII–expressing non-Leydig interstitial cells in the testis may be the stem cells for adult Leydig cells and that effects

Significance

Men are defined by androgens (testosterone), which drive fetal masculinization (male development) and puberty and maintain masculinity in adulthood, including sex drive, erectile function, and fertility. Moreover, Western cardiometabolic diseases are all associated with lowered testosterone levels in men. Therefore, influences on testosterone levels in adulthood have pervasive importance for masculinity and health. Our study shows, for the first time, to our knowledge, that testosterone levels during fetal masculinization can (re)program adult testosterone levels through effects on stem cells, which develop into adult Leydig cells (the source of testosterone) after puberty. These stem cells are present in fetal testes of humans and animals, and using the latter, we show how these cells are reprogrammed to affect adult testosterone levels.


The authors declare no conflict of interest.

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on these cells might explain how fetal events can impact adult testosterone levels (adult Leydig cell function).

We presently show, through ablation/regeneration models, that adult Leydig cells in rats/mice do, indeed, derive from COUP-TFI1-expressing stem cells that are numerous in the fetal testes of humans, marmosets, and rodents. We show that these stem cells express androgen receptors (ARs) and that experimental reduction of androgen production/action in fetal life in mice/rats through transgenic and chemical manipulations results in corresponding reductions in stem cell numbers in adulthood, which are accompanied by compensated adult Leydig cell failure. We also show a potential mechanism through which this programming of compensated adult Leydig cell failure might occur, namely altered histone methylation (H3K27me3) at the gene promoter for steroidogenic acute regulatory protein (StAR).

Thus, our findings show how fetal androgen deficiency can adversely program adult Leydig cell function, which in a human context, has implications for aging, general wellbeing, and longevity of men.

**Result**

**Identification of Adult Leydig Stem Cells by Ablation/Regeneration.**

Before we could investigate how fetal events might program adult Leydig cell function, we had to have a means of identifying the stem/progenitor cells from which adult Leydig cells derive. To do so, we used ethane dimethane sulfonate (EDS)-induced ablation and regeneration of Leydig cells, an established model for studying adult Leydig cell differentiation in rats (31, 32). After complete adult Leydig cell ablation by EDS (Fig. 1) and the consequent reduction in blood testosterone and elevation of blood luteinizing hormone (LH) levels (Fig. S1), there was regeneration of identifiable new adult Leydig (3β-HSD+) cells from ~14 d post-EDS, with recovery to normal adult Leydig cell numbers by 5 wk (Fig. 1). In controls, most adult Leydig (3β-HSD+) cells expressed COUP-TFI in their nuclei as did regenerating adult Leydig cells (Fig. 1). Up to 1 wk post-EDS, when no identifiable adult Leydig cells were present, abundant cells with mainly spindle-shaped nuclei that expressed COUP-TFI were present. We hypothesized that adult Leydig cells regenerated from these presumptive stem cells. The number of putative stem (COUP-TFI+/3β-HSDneg) cells declined significantly over the 5-wk period post-EDS, consistent with some differentiating into adult Leydig cells (Fig. 1). However, there are other cell types present in or bordering the interstitium, such as macrophages, pericytes, endothelial cells, and peritubular myoid cells, which are alternative sources of regenerating adult Leydig cells, although of these cell types, only the peritubular myoid cells express COUP-TFI (33).

We, therefore, used immunohistochemistry for cell-selective markers of macrophages (CD68), pericytes (CD146), endothelial cells (CD31), and peritubular myoid cells [smooth muscle actin (SMA)] plus staining for COUP-TFI and 3β-HSD at day 6 after EDS injection. We found no evidence that regenerating adult Leydig cells coexpressed any of these cell-selective markers other than COUP-TFI (Fig. S2). We then compared the expression profile of adult Leydig cells (in controls) with the adult Leydig stem cells using a range of factors expressed in adult Leydig cells and/or reported in immature adult Leydig cells. However, of the factors investigated, only COUP-TFI and AR were shared by adult Leydig cells and their stem cells (Fig. S2).

Platelet-derived growth factor-α action through its receptor (PDGFRα) is important in adult Leydig cell differentiation from progenitors (27, 29). We found PDGFRα expression in occasional COUP-TFI+ stem cells at 6 d after EDS (Fig. S3), but in control adult (Fig. S3) and fetal testes (Fig. 3), expression of PDGFRα in COUP-TFI+ stem cells was rare. We examined expression of GATA4, which is essential for fetal Leydig cell development (34) and expressed in mouse (35) and human (36) adult Leydig cells. At 6–14 d after EDS, a proportion of adult Leydig stem/progenitor cells (COUP-TFI1), located in peritubular or other regions, coexpressed GATA4, whereas such cells (COUP-TFI1/GATA4+) were rarely evident in control testes (Fig. 2). At 14–21 d after EDS, these GATA4-expressing stem/progenitor cells differentiated into adult Leydig cells, which was indicated by coexpression of 3β-HSD (Fig. 2). We confirmed that this sequence mimicked normal puberty (Fig. 2). Thus, at age 10 d (before puberty), virtually all adult Leydig stem cells (COUP-TFI1) were GATA4neg, but at initiation of puberty (day 15), GATA4 expression...
Leydig Cell Regeneration

Control

EDS + 6d

EDS + 14d

EDS + 21d

Puberty

Pnd 15

Pnd 25

Fig. 2. Expression of GATA4 in COUP-TFII+ Leydig stem cells is an early step in their differentiation into adult Leydig cells. Results are shown during Leydig cell regeneration (Top and Middle) after EDS and (Bottom) during normal puberty. (Top Left) In adult controls, GATA4 expression (red) is confined to nuclei of Sertoli cells (asterisk) and 3β-HSD+ (blue) Leydig cells (white arrowheads). COUP-TFII-expressing Leydig stem cells (green) are GATA4+neg. (Top Right) Six days after EDS, Leydig cells are absent, but GATA4 has switched on in some Leydig stem cells (yellow arrows; coexpression of green and red in nuclei). (Middle Left) At EDS + 14 d, some of the GATA4+ stem cells have switched on 3β-HSD (blue), and (Middle Right) by day 21, they have differentiated into adult Leydig cells. Cells coexpressing GATA4, 3β-HSD, and COUP-TFII are labeled with white arrows, but note that, for technical reasons, COUP-TFII expression in mature adult Leydig cells is often not evident in these images, whereas it is in other images that do not involve double immunostaining for GATA4 (Fig. 1). (Bottom Left) At the start of normal puberty (Pnd15), coexpression of GATA4 in COUP-TFII+ Leydig stem cells is common (yellow arrows), and (Bottom Right) by Pnd25, many of these cells are also 3β-HSD+ (white arrows). Images are representative of three to five animals for three independent experiments. Insets show higher magnifications of protein expression changes in Leydig stem cells during their differentiation into Leydig cells.

was evident in a proportion of them; by day 25, they had begun to transform into adult Leydig (3β-HSD+β cells (Fig. 2). In contrast, virtually no COUP-TFII+ stem cells in the fetal testis expressed GATA4, which was confined to the nuclei of Sertoli and fetal Leydig cells (Fig. 3). These studies confirmed our hypothesis that COUP-TFII-expressing non-Leydig interstitial cells must be the stem cell population from which adult Leydig cells differentiate.

was reduced, resulting in a distorted LH to testosterone ratio compared with controls, indicative of compensated Leydig cell failure based on gross distortion of their blood LH to testosterone ratio compared with controls (Fig. 5). In contrast, cell-selective KO of Ar in Sertoli (SCArKO) or peritubular myoid cells (PTM/ArKO) had no significant effect on adult Leydig stem cell numbers (Fig. S4). Although these findings suggest that androgen action on adult Leydig stem cells is important for their normal development, Ar is deleted in other cell types, and all testes are cryptorchid in ArKO mice, which are confounding factors. Therefore, we used a rat model in which intratesticular testosterone in the fetus was experimentally reduced (33) and investigated if similar effects on adult Leydig cell/stem cell development occurred, which was evident in ArKOS.

Discussion

Reduction in Fetal Intratesticular Testosterone Impairs Development of Adult Leydig Stem Cells. Treatment of pregnant rats from embryonic (e)13.5 to e21.5 with 500 mg/kg per day dibutylnitrate (DBP) suppresses intratesticular testosterone (ITT) by 50–70% between e17.5 and e21.5 (33), which is confirmed presently at e21.5 (Fig. 6). This suppression was associated with a ~40% reduction in adult Leydig stem cell number at e21.5 compared with controls, a deficit maintained through postnatal life into adulthood (Fig. 6). In contrast to ArKOS, DBP treatment did not alter final adult Leydig cell number (Fig. 6). Despite normal Leydig cell numbers and significantly raised blood LH levels in DBP-exposed males in adulthood, blood testosterone levels were significantly reduced, resulting in a distorted LH to testosterone ratio compared with controls, indicative of compensated Leydig cell failure (Fig. 6). These results suggest that fetal ITT affects adult Leydig stem cell number and their functional competence when they differentiate into adult Leydig cells. Regarding the former, the number of adult Leydig stem cells (COUP-TFII+3β-HSD+β cells) increased 17-fold from e17.5 [0.16 ± 0.03 × 106 (mean ± SEM),
Potential Mechanism for Fetal Programming of Compensated Adult Leydig Cell Failure. We used the rat DBP model to investigate expression of six genes in the steroidogenic pathway in the adult testis (Fig. 7). Because we used scrotal and cryptorchid testes from DBP-exposed animals for these studies, we used a control gene (Sox9) expressed specifically in Sertoli cells to correct expression of the target genes, because Leydig cell mRNAs would be overrepresented in cryptorchid vs. scrotal testes because of massive germ cell loss in the former. Sox9 was chosen, because adult Sertoli cell number is unchanged in DBP-exposed animals, irrespective of whether testes are scrotal or cryptorchid (41). In DBP-exposed animals, expression of Lhgc, Cyp11a1, Cyp17a1, and 17β-hsd3 were unchanged, whereas expression of StAR and 3β-hsd were both significantly reduced compared with controls (Fig. 7). Because StAR is one of the factors involved in cholesterol transport into the mitochondrion (42), which is rate-limiting for steroidogenesis (43, 44), this change was considered the most significant.

For fetal androgen action on stem cells to alter subsequent adult Leydig cell function through repression of StAR transcription, we considered an epigenetic mechanism likely. Altered methylation of the proximal-1 promoter region of StAR is crucial for regulating its expression (45–47) and conserved across species (48). Because H3K27me3 is an established transcriptional repressor (49–51), including of StAR (47), we investigated if the level of H3K27me3 upstream of the coding region of StAR was altered using a ChIP assay (47, 51).

Our ChIP results showed a significant increase in H3K27me3 localization to the StAR proximal promoter in adult testes of DBP-exposed animals compared with controls (Fig. 8). This increase in repressive H3K27me3 could account for reduced StAR expression. Using an antibody against H3K27me3, we showed that a proportion of Leydig cells in DBP-exposed rats at postnatal day 25 (Pnd25) and in adulthood showed expression of H3K27me3 in their nuclei, whereas it was minimal/absent in controls at this antibody dilution (Fig. 9); a similar difference was

Fig. 3. Presence of adult Leydig stem cells (white arrows) expressing COUP-TFII (green) in their nuclei in fetal testes of different species (rows 1 and 2) and their protein expression phenotype (rows 3 and 4). In rows 1 and 2, red indicates 3β-HSD (fetal Leydig cells (LCs)); and blue indicates SMA (asterisks are seminiferous cords). Rows 3 and 4 show that, whereas most adult Leydig stem (COUP-TFII+) cells lack expression of PDGFRα and GATA4 (white arrows), most adult Leydig stem cells coexpress (white arrowheads) the AR (red). In rows 3 and 4, blue indicates 3β-HSD (fetal LC). Yellow arrows show potential PDGFRα− adult Leydig stem cells. Images are representative of three to five animals from three independent experiments. (Scale bars: 20 μm.)

$e_{21.5} (2.81 \pm 0.24 \times 10^6, n = 7)$ in control rats (this study) when ITT is high/increasing (33, 40).

Fig. 4. COUP-TFII is a marker of the adult Leydig stem population, which is evident from the transgenic lineage tracing of adult Leydig cells. (Upper) At birth, the aP2 Cre Recombinase-induced GFP expression (white arrows) is coincident with COUP-TFII expression (yellow arrows). The merged image shows COUP-TFII and GFP colocalization (white arrowheads) in adult Leydig stem cells. (Lower) In adulthood, fetally induced YFP expression (white arrow) is restricted to 3β-HSD−expressing (yellow arrow) adult Leydig cells, which is indicated by their coexpression (white arrowhead in merged image). Images are representative of three to five animals from two independent experiments. (Scale bars: 20 μm.)
found between ArKO and WT adult mice (Fig. 9). This increased H3K27me3 immunoreactivity may not be restricted to StAR, but consistent with the hypothesized fetal origin of the change in H3K27me3 localization to the StAR promoter in testes of DBP-exposed animals, we found localization of H3K27me3 to adult Leydig stem (COUP-TFI*) cells in the fetal testes of DBP-exposed rats, which showed no/minimal expression was detectable in stem cells in controls at this antibody dilution (Fig. 9). In contrast, immunoreactivity of unmodified histone 3 was comparable in control and DBP-exposed animals (Fig. S5). These observations provide a potential mechanism (i.e., H3K27me3) through which deficiency in fetal androgen action on stem cells could reprogram/compromise adult Leydig cell function by altering transcription of StAR.

**Discussion**

Fetal programming of testosterone levels/Leydig cell function in adult men is conceptually important because of its close interrelationship with common diseases that impair quality and length of life in men. Although there is indirect supporting evidence for fetal programming of adult testosterone levels (reviewed in ref. 16), a limiting factor is the absence of direct evidence for a mechanism to explain how adult Leydig cells, which do not appear until puberty, could be affected (programmed) by fetal events. The present findings provide this evidence in animal studies by (i) identifying a population of (COUP-TFI*–HSD*) and (ii) showing that these cells are numerous in the fetal testis and conserved across species, (iii) showing that these cells are androgen targets, and (iv) showing that fetal deficits in intratesticular levels/action impair development of these stem cells, resulting in impaired function of the adult Leydig cells that differentiate from them. An epigenetic mechanism that might explain this long-range programming through altered H3K27me3 of the StAR promoter is also shown.

Our initial goal, inspired by the KO studies by Qin et al. (30), was to identify if COUP-TFI–expressing non-Leydig interstitial cells were stem cells for adult Leydig cells. Using EDS-induced adult Leydig cell ablation, we show that the new generation of adult Leydig cells differentiates from among the population of COUP-TFI–expressing, undifferentiated, spindle-shaped interstitial cells. These cells, which we have termed adult Leydig stem cells, do not express classical Leydig cell markers (LH receptor, steroidogenic factor-1, steroidogenic enzymes, and INSL3) but express COUP-TFI and AR, which they share with adult Leydig cells (although neither of these markers is Leydig cell specific). Based on comparative phenotyping of the stem cells and newly differentiating Leydig cells after EDS, switching on of the transcription factor GATA4 and probably, PDGFRα seems to be a key early differentiation step, and thereafter, these GATA4*/COUP-TFI* cells switch on classic Leydig cell markers, such as β3-HSD and INSL3. We show that this differentiation pattern recapitulates what happens during normal puberty in the rat. GATA4 is important for differentiation of fetal Leydig cells (34), which also derive from COUP-TFI–expressing interstitial cells (33). GATA4 may also be imperative for development of adult Leydig cells (52), because it induces expression of steroidogenic factor-1 and StAR (53). Our findings are consistent with previous reports of GATA4 expression in adult Leydig cells in humans and rats (27, 35, 36) as well as in adult Leydig stem cells (27). Expression of PDGFRα was not explored in detail in our studies, but our findings and previous studies (27, 29) point to a similar pattern and timing of expression in the adult Leydig stem cells, which was detailed for GATA4. Our interpretation is that
and GATA4 are switched on in the stem cells only when ∼expressing stem cells during puberty is after EDS.

Fig. 7. Effect of prenatal DBP exposure on adult Leydig cell function as monitored by expression of Leydig cell-specific genes in the steroidogenic pathway. The testosterone synthesis cascade is shown at the top starting with the LH receptor (Lhcgr) and finishing with 17β-hydroxysteroid dehydrogenase type 3 (17β-hsd3). (A) Lhcgr, (B) Star, (C) Cyp11a1, (D) 3β-hsd, (E) Cyp17a1, (F) 17β-hsd2. Because testis cellular composition was affected by treatment (loss of germ cells and their mRNA in cryorghini testes) in some DBP-exposed animals, gene expression has been expressed relative to Sox9 expression in the same testis (in the text). Values are means ± SEMs for n = 11–12 rats in each group. *P < 0.05, **P < 0.01 compared with respective (control) vehicle.

PDGFRα and GATA4 are switched on in the stem cells only when they commence differentiation down the adult Leydig cell pathway (i.e., become progenitors), because few, if any, of the (COUP-TFI1) stem cells in the fetal testes express either GATA4 or PDGFRα. It is unclear if the complete population of COUP-TFI1-expressing stem cells can develop into adult Leydig cells or only a subpopulation, because only a proportion of the stem cells switched on GATA4 or PDGFRα after EDS.

Previous studies suggested that adult Leydig cells could originate from other interstitial cell types, such as peritubular myoid cells, pericytes, endothelial cells, or macrophages (24, 29, 54–56). Using specific markers for these cell types and the EDS model, we found no evidence for coexpression of COUP-TFI1 in these cell types. Therefore, because the majority of normal and regenerating adult Leydig cells expresses COUP-TFI1, we concluded that development of adult Leydig cells from these other cell types, although possible, is probably not the main mechanism. This conclusion is supported by our lineage tracing experiment. In keeping with earlier studies (27, 29, 57), we noted that adult Leydig cells commonly derive from (COUP-TFI1) cells that border the seminiferous tubules, although in contrast to other studies (29), we did not find any cells coexpressing the peritubular myoid (PTM) cell marker SMA, COUP-TFI1, and early Leydig cell markers. However, our findings do not exclude the possibility that, after EDS treatment, regenerating adult Leydig cells could also derive from interstitial cells that have dedifferentiated (e.g., pericytes that have switched off CD146 or PTM cells that have switched off SMA) and then either switched on COUP-TFI1 (pericytes) or maintained their COUP-TFI1 expression (PTM cells).

Our results show an abundance of adult Leydig stem cells in the fetal testes of four species, including humans, and that most of these cells coexpress AR; similar cells are present in the adult testes of these species together with COUP-TFI1-expressing adult Leydig cells. Our data show that, in fetal life, these stem cells increase >17-fold in number from e15.5 to e21.5 in rats when intratesticular testosterone levels are high/increasing (33, 40). Moreover, KO of AR in this cell type (and in all other cells; ARKOs) in mice or experimental lowering of intratesticular testosterone in rats throughout this period (DBP exposure) both resulted in ∼40% reduction in numbers of adult Leydig stem cells around birth. This finding suggests that androgens positively regulate proliferation of the stem cells. In both of our experimental situations involving deficient fetal androgen action, the resulting decrease in stem cell number persisted through to adulthood, despite the fact that puberty was associated with a marked and parallel increase in stem cell number in control and treated rats and mice. This observation indicates that factors other than androgens play an important role during puberty in determining adult Leydig stem cell proliferation/number. The increase in COUP-TFI1-expressing stem cells during puberty is consistent with an earlier study that quantified mesenchymal non-Leydig interstitial cells based on morphology (22).

We anticipated that a developmental deficit in adult Leydig stem cells might lead to reduced adult Leydig cell number. Although such a reduction was the case in ARKOs, normal numbers of adult Leydig cells developed in DBP-exposed rats in which androgen levels/action had been reduced just in fetal life. One explanation for this difference in outcome, despite the similarity in shortfall of adult Leydig stem cells, is that KO of AR in other testis cell types in ARKOs caused additional effects on adult Leydig cell differentiation. Indeed, because SACTAR mice (deficient in ScAr) also exhibit a numerical deficit in adult Leydig cells as well as ARKOs (58), it is a potential explanation. Nevertheless, the absence of any significant effect on adult Leydig stem cell numbers in ScArKO or PTM/ArKO (deficient in PTM/Ar) mice [but their reduction in ARKOs (which lack AR also in the adult Leydig stem cells) and DBP-exposed rats] emphasizes the importance of androgen action on the stem cells. In this regard, we cannot exclude the possibility that the fetal reduction in adult Leydig stem cells is secondary to reduced Sertoli cell number (as a result of androgen deficiency); as such, a reduction is evident in both ARKO mice and DBP-exposed rats at birth (59).

In both models in which there was a fetal deficit in androgen levels/action, there was compensated adult Leydig cell failure.

Fig. 8. Effect of prenatal DBP exposure on H3K27me3 in the proximal promoter of StAR. The schematic shows the StAR promoter region targeted (∼85 bp) and amplified by PCR using primers as outlined (167 bp in length). Levels of H3K27me3 were increased at the proximal promoter of StAR, which was analyzed by ChIP (A) and densitometric assessment of PCR products (B). Normal rabbit IgG was used as the negative control. Data were calculated using the percentage total genomic input method. The input DNA threshold cycle value (i.e., DNA that did not undergo immunoprecipitation) was used to normalize the ChIP data. The average threshold cycle for triplicate assays was used in all subsequent calculations. Values are means ± SEMs for n = 3 per group. **P < 0.01 compared with (control) vehicle.
Effect of fetal DBP exposure or Kilcoyne et al. www.pnas.org/cgi/doi/10.1073/pnas.1320735111

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and therefore, our finding has occurred. However, our studies do not ∼ or promoter in adult Leydig stem cells in fetal life would (47, 63, 64), Using ChIP, we showed that H3K27me3 expression is reduced in adulthood in testes of DBP-StAR proximal promoter region in stem cells in fetal life potentially explains the compensated Leydig cell failure of DBP-exposed rats in adulthood. In this regard, two other facts are important. First, H3K27me3 is propagated through cell divisions (61, 62); therefore, it is reasonable to suppose that H3K27me3-induced modification of the StAR promoter in adult Leydig stem cells in fetal life would be transmitted through to adulthood, despite the huge proliferative changes that occur in stem cells pre- and postnatally. Second, LH is a positive regulator of StAR (47, 63, 64), and therefore, we find that StAR expression is reduced in adulthood in testes of DBP-exposed rats, despite elevated blood LH levels (and normal Lhr expression), is additional indirect evidence that altered responsiveness of StAR has occurred. However, our studies do not rule out that other epigenetic factors might be altered that could also lead to altered expression of StAR or 3β-hsd.

Alternative explanations for our observations are possible. For example, fetal phthalate exposure of rats has been shown to alter adrenal function in adulthood (65), which may secondarily alter Leydig cell function (66). We cannot exclude this possibility as a contributory factor in our DBP studies, although it would not explain the similar changes observed in ArKO mice.

Our finding that fetal deficits in androgen action can result in compromised adult Leydig cell function in rodents fits with emerging evidence from humans (14, 16). There is a similar connection between reduced fetal androgens and reduced adult sperm counts/sperm production in men and rats (15, 16). What further ties these observations together is that men with low sperm counts commonly exhibit compensated adult Leydig cell failure, although why is unknown (18, 60, 67). It has been suggested that it may be indicative of a common underlying (fetal) cause (18), and our present animal experimental studies provide direct supporting evidence for this suggestion. This suggested connection has widespread implications, because one in six young men in northern European countries has a low sperm count (<20 million/mL) (68), and testosterone levels in men of all ages are declining (4–6). Moreover, it has implications for morbidities associated with aging and the aging-related decline in testosterone levels (3, 7–9, 69), because ~10% of aging men exhibit compensated Leydig cell failure (7). Our findings also provide a pathway through which fetal androgen exposure lead to a range of adverse changes in reproductive function and disorders in boys/men.

Materials and Methods

Animals and Treatments. Selective destruction of Leydig cells in adult Wistar rats used a single i.p. injection of EDS (75 mg EDS/kg in 2 mL/kg DMSO:water (1:3; vol:

defined as normal/reduced blood testosterone in the face of elevated LH and thus, an altered LH to testosterone ratio (7, 60). Because adult Leydig cells develop from the stem cells, this finding implies that the stem cells are modified functionally as well as numerically because of reduced fetal androgen exposure, and this ultimately translates in adulthood into compromised steroidogenesis. Based on results from the DBP rat model, a potential explanation is reduced expression of StAR, which contributes to regulating the import of cholesterol into the mitochondrion, the rate-limiting step for testosterone production (42–44). Expression of other genes involved in Leydig cell steroidogenesis was unaffected by in utero DBP exposure apart from 3β-hsd, which was also decreased, but this change might not be expected to significantly impact steroidogenesis, because it is not considered rate-limiting.

To investigate a potential mechanism for reduced expression of StAR, we hypothesized that it was because of histone modifications in its proximal-1 promoter region, which are important in its regulation (45–47). Using ChIP, we showed that H3K27me3 upstream of the coding region of StAR, which is associated with transcriptional repression (47, 49–51), was increased in testes of DBP-exposed rats. Consistent with this finding, we found increased immunoexpression of H3K27me3 in adult Leydig cells of DBP-exposed rats and their stem cells in fetal life. A similar increase in H3K27me3 immunoexpression in adult Leydig cells of ArKOs is consistent with it being because of (fetal) androgen deficiency rather than DBP exposure. Altered H3K27me3 of the StAR proximal promoter region in stem cells in fetal life potentially explains the compensated Leydig cell failure of DBP-exposed rats in adulthood. In this regard, two other facts are important. First, H3K27me3 is propagated through cell divisions (61, 62); therefore, it is reasonable to suppose that H3K27me3-induced modification of the StAR promoter in adult Leydig stem cells in fetal life would be transmitted through to adulthood, despite the huge proliferative changes that occur in stem cells pre- and postnatally. Second, LH is a positive regulator of StAR (47, 63, 64), and therefore, we find that StAR expression is reduced in adulthood in testes of DBP-exposed rats, despite elevated blood LH levels (and normal Lhr expression), is additional indirect evidence that altered responsiveness of StAR has occurred. However, our studies do not rule out that other epigenetic factors might be altered that could also lead to altered expression of StAR or 3β-hsd.

Alternative explanations for our observations are possible. For example, fetal phthalate exposure of rats has been shown to alter adrenal function in adulthood (65), which may secondarily alter Leydig cell function (66). We cannot exclude this possibility as a contributory factor in our DBP studies, although it would not explain the similar changes observed in ArKO mice.

Our finding that fetal deficits in androgen action can result in compromised adult Leydig cell function in rodents fits with emerging evidence from humans (14, 16). There is a similar connection between reduced fetal androgens and reduced adult sperm counts/sperm production in men and rats (15, 16). What further ties these observations together is that men with low sperm counts commonly exhibit compensated adult Leydig cell failure, although why is unknown (18, 60, 67). It has been suggested that it may be indicative of a common underlying (fetal) cause (18), and our present animal experimental studies provide direct supporting evidence for this suggestion. This suggested connection has widespread implications, because one in six young men in northern European countries has a low sperm count (<20 million/mL) (68), and testosterone levels in men of all ages are declining (4–6). Moreover, it has implications for morbidities associated with aging and the aging-related decline in testosterone levels (3, 7–9, 69), because ~10% of aging men exhibit compensated Leydig cell failure (7). Our findings also provide a pathway through which fetal androgen exposure lead to a range of adverse changes in reproductive function and disorders in boys/men.
Male congenic C57BL/6J mice. Animals were treated with immunogen concentration (Santa Cruz) and killed by CO₂ inhalation and cervical dislocation. In adults, blood was collected by cardiac puncture into a heparinized syringe. Testes were dissected, weighed, and either frozen for RNA analysis or fixed in Bouins (6 h) before processing into paraffin wax (33). Sections (5 μm) were mounted on charged microscope slides (VWR) and dried overnight at 50 °C.

Human, Marmoset, and Mouse Fetal Testis Tissue. Male congeneric C57BL/6J mice hemizygous for an A2P-Cre transgene (37) were mated to homozygous R26R-EYFP females (73). The +AaP2-Cre/+R26R-EYFP and +/+R26R-EYFP (control) male offspring from these matings were genotyped as previously described (38).

Generation of ArKO Mice. ArKO mice were generated (58) by crossing Arflox/− females with phosphoglycerate kinase-1−/− males. Animals were treated according to the Care and Use of Laboratory Animals of the Catholic University of Leuven with approval by the local ethics committee. Groups of 5–11 WT and ArKO males were killed on Pnd2, -12, -20, -50, and -140.

Tissue Collection and Processing. Animals were killed by CO₂ inhalation and cervical dislocation. In adults, blood was collected by cardiac puncture into a heparinized syringe. Testes were dissected, weighed, and either frozen for RNA analysis or fixed in Bouins (6 h) before processing into paraffin wax (33). Sections (5 μm) were mounted on charged microscope slides (VWR) and dried overnight at 50 °C.

Immunohistochemical Analysis. Immunostaining was for two to three proteins to delineate cell types for analysis using methods and antibodies validated previously (33, 41). Slides were dewaxed and rehydrated and underwent heat-induced antigen retrieval (33). Sections were blocked using 20% normal rabbit serum (vol/vol; Biosera) and 5% BSA (wt/vol; Sigma-Aldrich) in Tris-buffered saline (TBS). Secondary antibodies were diluted 1:500 in sera (Table S1). Slides were incubated for 30 min with Streptavidin-alkaline phosphatase (Vector) at 1:200 in TBS. Fast blue and red were used for protein detection (Perkin-Elmer-TSA-Plus Cyanine3/5 System; Perkin-Elmer Life Sciences) followed by antigen retrieval for 2.5 min on medium heat. Sections were reblocked in protein detection (Perma Blue/Red; Diagnostic BioSystems) followed by phosphatase (Vector) at 1:200 in TBS. Fast blue and red were used for heat-induced antigen retrieval (33). Sections were blocked using 20% normal serum/TBS/BSA as above before application of (second) primary antibody. Sections (5 μm) were washed for 10 min with solutions of low salt (0.1% SDS, 1% Triton-X, 2 mM EDTA, 20 mM Tris·HCl). Chromatin eluate and incubated overnight at 4 °C to reverse cross-links before incubating with salmon sperm DNA/Protein Agarose A (Millipore) for 30 min at 4 °C with rotation and then incubated overnight (with rotation at 4 °C) with H3K27me3 antibody, rabbit IgG (27472; Abcam) as negative control, or anti-human β-HSD antibody (Table S1) as positive control. Samples were incubated with salmon sperm DNA/Protein Agarose A for 4 h at 4 °C. After centrifugation, precipitates were washed for 10 min with solutions of low salt (0.1% SDS, 1% Triton-X, 2 mM EDTA, 20 mM Tris·HCl, 150 mM NaCl), high salt (0.1% SDS, 1% Triton-X, 2 mM EDTA, 20 mM Tris·HCl, 500 mM NaCl), lithium chloride (1 mM EDTA, 10 mM Tris·HCl, 1% Deoxycholic acid, 1% Igepal ca630, 0.25 M LiCl), and Tris-ethylendiaminetetraacetic acid buffer (1 mM EDTA, 10 mM Tris·HCl, 500 mM NaCl). The eluate was added to 200–1,000 bp before diluting 10-fold in immunoprecipitation dilution buffer (0.1% SDS, 1% Triton-X [wt/vol], 1.2 mM EDTA, 16.7 mM Tris·HCl, 167 mM NaCl). An aliquot (1%) was saved for input control. Samples were precleared using salmon sperm DNA/protein Agarose A (Millipore) for 30 min at 4 °C with rotation and then incubated overnight (with rotation at 4 °C) with H3K27me3 antibody, rabbit IgG (27472; Abcam) as negative control, or anti-human β-HSD antibody (Table S1) as positive control. 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Chromatin was eluted in 1% SDS and 0.1 M NaHCO₃, NaCl (8 μL S M) was added to the eluate and incubated overnight at 4 °C to reverse cross-links before incubating with 0.5 M EDTA, 1 M Tris·HCl, and proteinase K for 60 min at 45 °C. Purified DNA from samples, including input control, was recovered (QUIAquick PCR Purification Kit; Qiagen). Primers for the proximal upstream promoter of StAR (167 bp) (Table S2) were used for PCR using SYBR Green Master Mix (Brilliant III Ultrafast; Agilent Technologies). PCR products were visualized by 2% agarose gel electrophoresis followed by densitometric analysis using ImageJ (version 1.46; National Institutes of Health).

Statistical Analysis. Data were analyzed by GraphPad Prism (version 5; GraphPad Software, Inc.) using ANOVA followed by either posthoc Bonferroni or Student t tests as appropriate. Where significant heterogeneity of variance occurred (e.g., plasma testosterone), values were log-transformed before analysis.

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