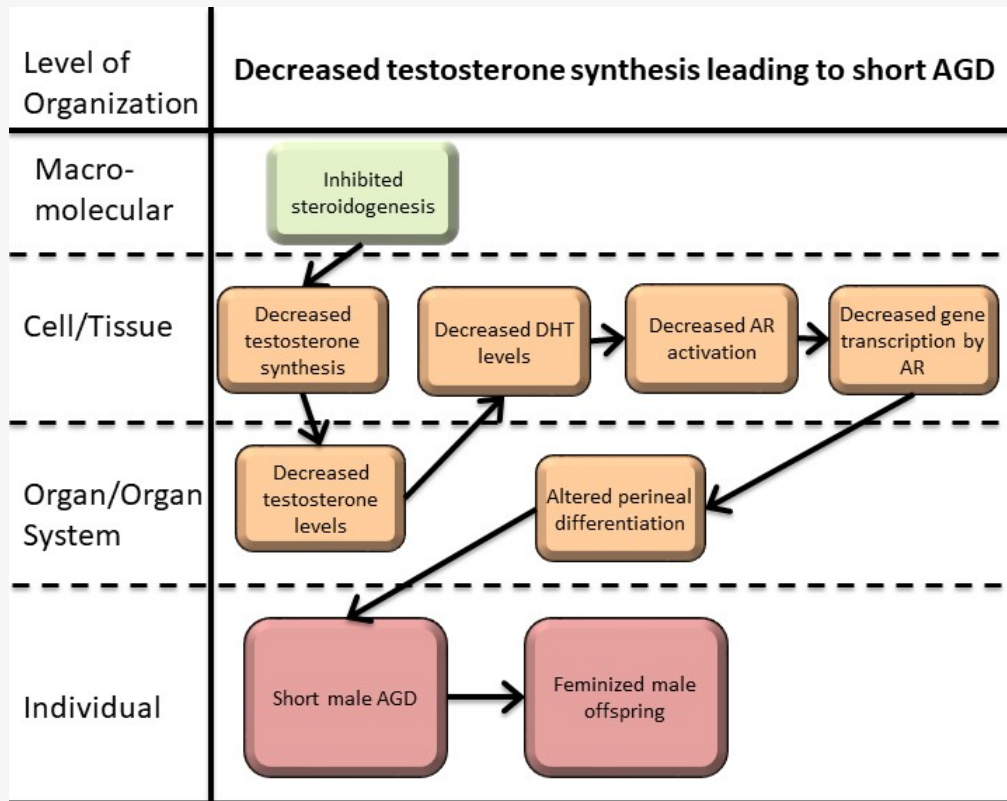


AOP ID and Title:

AOP 307: Decreased testosterone synthesis leading to short anogenital distance (AGD) in male (mammalian) offspring

Short Title: Decreased testosterone synthesis leading to short AGD

Graphical Representation**Authors**

Terje Svengen; National Food Institute, Technical University of Denmark, Kongens Lyngby, 2800 Denmark

Status**Author status**

Under development: Not open for comment. Do not cite

OECD status

Under Development

OECD project

1.90

SAAOP status

Included in OECD Work Plan

Abstract

This AOP links decreased testosterone synthesis by fetal Leydig cells with short anogenital distance (AGD) in male offspring. A short AGD around birth is a marker for feminization of male fetuses and is associated with male reproductive disorders, including reduced fertility in adulthood. Although a short AGD is not necessarily 'adverse' from a human health perspective, it is considered an 'adverse outcome' in OECD test guidelines; AGD measurements are mandatory in specific tests for developmental and reproductive toxicity in chemical risk assessment (TG 443, TG 421/422, TG 414).

Testosterone is primarily synthesized by fetal Leydig cells of the fetal testes by the process of steroidogenesis. The precursor molecule cholesterol is converted to testosterone via several enzymatic steps and includes for instance key CYP enzymes, CYP11 and CYP17. Following synthesis, testosterone is released into the circulation and transported to target tissues and organs where it initiates masculinization processes. Under normal physiological conditions, testosterone produced by the testicles, is converted in peripheral tissues by 5 α -reductase into DHT, which in turn binds AR and activates downstream target genes. AR signaling is necessary for masculinization of the developing fetus, including differentiation of the levator ani/bulbocavernosus (LABC) muscle complex in males. The LABC complex does not develop in the absence, or low levels of, androgen signaling, as in female fetuses.

The key events in this pathway is inhibition of testosterone synthesis in the fetal Leydig cells. In turn, this results in reduced circulating testosterone levels and less DHT (converted by 5 α -reductase). Low DHT fails to properly activate AR in target tissues, including the developing perineal region, which leads to failure to properly masculinize the perineum/LABC complex and ultimately a short AGD.

Summary of the AOP

Events

Molecular Initiating Events (MIE), Key Events (KE), Adverse Outcomes (AO)

Sequence	Type	Event ID	Title	Short name
	KE	413	Reduction, Testosterone synthesis in Leydig cells	Reduction, Testosterone synthesis in Leydig cells
	KE	1690	reduction, testosterone levels	reduction, testosterone levels
	KE	1613	Decrease, dihydrotestosterone (DHT) level	Decrease, DHT level
	KE	1614	Decrease, androgen receptors (AR) activation	Decrease, AR activation
	KE	286	Altered, Transcription of genes by AR	Altered, Transcription of genes by AR
	AO	1688	decrease, male anogenital distance	short male AGD

Key Event Relationships

Upstream Event	Relationship Type	Downstream Event	Evidence	Quantitative Understanding
Reduction, Testosterone synthesis in Leydig cells	adjacent	reduction, testosterone levels	High	Moderate
reduction, testosterone levels	adjacent	Decrease, dihydrotestosterone (DHT) level	Moderate	Low
Decrease, dihydrotestosterone (DHT) level	adjacent	Decrease, androgen receptors (AR) activation	High	Moderate
Decrease, androgen receptors (AR) activation	adjacent	Altered, Transcription of genes by AR	High	Moderate
Altered, Transcription of genes by AR	adjacent	decrease, male anogenital distance	Moderate	Moderate
reduction, testosterone levels	non-adjacent	Decrease, androgen receptors (AR) activation	Moderate	Moderate

Stressors

Name	Evidence
Dibutyl phthalate	High

Name	Evidence
Bis(2-ethylhexyl) phthalate	High

Overall Assessment of the AOP

Domain of Applicability

Life Stage Applicability

Life Stage	Evidence
Foetal	High
Pregnancy	High

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
human	Homo sapiens	Moderate	NCBI
rat	Rattus norvegicus	High	NCBI
mouse	Mus musculus	Moderate	NCBI

Sex Applicability

Sex	Evidence
Male	High

References

1. Schwartz CL, Christiansen S, Vinggaard AM, Axelstad M, Hass U and **Svingen T** (2019), Anogenital distance as a toxicological or clinical marker for fetal androgen action and risk for reproductive disorders. *Arch Toxicol* 93: 253-272.

Appendix 1

List of Key Events in the AOP

[Event: 413: Reduction, Testosterone synthesis in Leydig cells](#)

Short Name: Reduction, Testosterone synthesis in Leydig cells

Key Event Component

Process	Object	Action
testosterone biosynthetic process	testosterone	decreased

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:51 - PPARα activation leading to impaired fertility in adult male rodents	KeyEvent
Aop:18 - PPARα activation in utero leading to impaired fertility in males	KeyEvent
Aop:64 - Glucocorticoid Receptor (GR) Mediated Adult Leydig Cell Dysfunction Leading to Decreased Male Fertility	KeyEvent
Aop:307 - Decreased testosterone synthesis leading to short anogenital distance (AGD) in male (mammalian) offspring	KeyEvent

Biological Context

Level of Biological Organization

Cellular

Cell term**Cell term**

testosterone secreting cell

Domain of Applicability**Taxonomic Applicability**

Term	Scientific Term	Evidence	Links
rat	Rattus norvegicus	High	NCBI
human	Homo sapiens	High	NCBI
mice	Mus sp.	Low	NCBI

Key enzymes needed for testosterone production first appear in the common ancestor of amphioxus and vertebrates (Baker 2011). Consequently, this key event is applicable to most vertebrates, including humans.

Key Event Description**Biological state**

Testosterone is a steroid hormone from the androgen group and is found in humans and other vertebrates.

Biological compartments

In humans and other mammals, testosterone is secreted primarily by the testicles of males and, to a lesser extent, the ovaries of females and other steroidogenic tissues (e.g., brain, adipose). It either acts locally /or is transported to other tissues via blood circulation. Testosterone synthesis takes place within the mitochondria of Leydig cells, the testosterone-producing cells of the testis. It is produced upon stimulation of these cells by Luteinizing hormone (LH) that is secreted in pulses into the peripheral circulation by the pituitary gland in response to Gonadotropin-releasing hormone (GnRH) from the hypothalamus. Testosterone and its aromatized product, estradiol, feed back to the hypothalamus and pituitary gland to suppress transiently LH and thus testosterone production. In response to reduced testosterone levels, GnRH and LH are produced. This negative feedback cycle results in pulsatile secretion of LH followed by pulsatile production of testosterone (Ellis, Desjardins, and Fraser 1983), (Chandrashekar and Bartke 1998).

General role in biology

Testosterone is the principal male sex hormone and an anabolic steroid. Male sexual differentiation depends on testosterone (T), dihydrotestosterone (DHT), and the expression of androgen receptors by target cells (Manson and Carr 2003). During the development secretion of androgens by Leydig cells is essential for masculinization of the foetus (Nef 2000). The foetal Leydig cells develop in utero. These cells become competent to produce testosterone in rat by gestational day (GD) 15.5, with increasing production thereafter. Peak steroidogenic activity is reached just prior to birth, on GD19 (Chen, Ge, and Zirkin 2009). Testosterone secreted by foetal Leydig cells is required for the differentiation of the male urogenital system late in gestation (Huhtaniemi and Pelliniemi 1992). Foetal Leydig cells also play a role in the scrotal descent of the testis through their synthesis of insulin-like growth factor 3 (InsI3), for review see (Nef 2000).

In humans, the first morphological sign of testicular differentiation is the formation of testicular cords, which can be seen between 6 and 7 weeks of gestation. Steroid-secreting Leydig cells can be seen in the testis at 8 weeks of gestation. At this period, the concentration of androgens in the testicular tissue and blood starts to rise, peaking at 14-16 weeks of gestation. This increase comes with an increase in the number of Leydig cells for review see (Rouiller-Fabre et al. 2009).

Adult Leydig cells, which are distinct from the foetal Leydig cells, form during puberty and supply the testosterone required for the onset of spermatogenesis, among other functions. Distinct stages of adult Leydig cell development have been identified and characterized. The stem Leydig cells are undifferentiated cells that are capable of indefinite self-renewal but also of differentiation to steroidogenic cells. These cells give rise to progenitor Leydig cells, which proliferate, continue to differentiate, and give rise to the immature Leydig cells. Immature Leydig cells synthesize high levels of testosterone metabolites and develop into terminally differentiated adult Leydig cells, which produce high levels of testosterone. With aging, both serum and testicular testosterone concentrations progressively decline, for review see (Nef 2000).

Androgens play a crucial role in the development and maintenance of male reproductive and sexual functions. Low levels of circulating androgens can cause disturbances in male sexual development, resulting in congenital abnormalities of the male reproductive tract. Later in life, this may cause reduced fertility, sexual dysfunction, decreased muscle formation and bone mineralisation, disturbances of fat metabolism, and cognitive dysfunction. Testosterone levels decrease as a process of ageing: signs and symptoms caused by this decline can be considered a normal part of ageing.

How it is Measured or Detected

OECD TG 456 [1] is the validated test guideline for an in vitro screen for chemical effects on steroidogenesis, specifically the production of 17 β -estradiol (E2) and testosterone (T). The testosterone synthesis can be measured in vitro cultured Leydig cells. The methods for culturing Leydig cells can be found in the Database Service on Alternative Methods to animal experimentation (DB-ALM): Leydig Cell-enriched Cultures [2], Testicular Organ and Tissue Culture Systems [3].

Testosterone synthesis in vitro cultured cells can be measured indirectly by testosterone radioimmunoassay or analytical methods such as LC-MS.

References

Chandrashekar, V, and A Bartke. 1998. "The Role of Growth Hormone in the Control of Gonadotropin Secretion in Adult Male Rats." *Endocrinology* 139 (3) (March): 1067–74. doi:10.1210/endo.139.3.5816.

Ellis, G B, C Desjardins, and H M Fraser. 1983. "Control of Pulsatile LH Release in Male Rats." *Neuroendocrinology* 37 (3) (September): 177–83. Huhtaniemi, I, and L J Pelliniemi. 1992. "Fetal Leydig Cells: Cellular Origin, Morphology, Life Span, and Special Functional Features." *Proceedings of the Society for Experimental Biology and Medicine*. Society for Experimental Biology and Medicine (New York, N.Y.) 201 (2) (November): 125–40.

Manson, Jeanne M, and Michael C Carr. 2003. "Molecular Epidemiology of Hypospadias: Review of Genetic and Environmental Risk Factors." *Birth Defects Research. Part A, Clinical and Molecular Teratology* 67 (10) (October): 825–36. doi:10.1002/bdra.10084.

Nef, S. 2000. "Hormones in Male Sexual Development." *Genes & Development* 14 (24) (December 15): 3075–3086. doi:10.1101/gad.843800.

Rouiller-Fabre, Virginie, Vincent Muczynski, Romain Lambrot, Charlotte Lécureuil, Hervé Coffigny, Catherine Pairault, Delphine Moison, et al. 2009. "Ontogenesis of Testicular Function in Humans." *Folia Histochemica et Cytobiologica / Polish Academy of Sciences, Polish Histochemical and Cytochemical Society* 47 (5) (January): S19–24. doi:10.2478/v10042-009-0065-4.

Event: 1690: reduction, testosterone levels

Short Name: reduction, testosterone levels

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:307 - Decreased testosterone synthesis leading to short anogenital distance (AGD) in male (mammalian) offspring	KeyEvent

Biological Context

Level of Biological Organization

Tissue

Event: 1613: Decrease, dihydrotestosterone (DHT) level

Short Name: Decrease, DHT level

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:288 - Inhibition of 17α-hydrolase/C 10.20-lyase (Cyp17A1) activity leads to birth reproductive defects (cryptorchidism) in male (mammals)	KeyEvent
Aop:289 - Inhibition of 5α-reductase leading to impaired fecundity in female fish	KeyEvent
Aop:305 - 5α-reductase inhibition leading to short anogenital distance (AGD) in male (mammalian) offspring	KeyEvent

Aop:307 - Decreased testosterone synthesis leading to short anogenital distance (AGD) in male (mammalian) offspring	Event Type
AOP ID and Name	
Biological Context	
Level of Biological Organization	
Cellular	
Key Event Description	
Reduction in DHT synthesis leads to a reduction in DHT circulating levels. ¹²	
How it is Measured or Detected	
DHT levels in a sample can be measured by (High Performance) Liquid Chromatography. After sample fractionation, DHT can be identify by comparison with internal standards spectrum. Quantification of DHT levels can be performed using hormones measurements kits (ELISA), instrumental techniques (LC-MS) or liquid scintillation spectrometry (after radiolabeling). ³	
References	
¹ Miller Walter L. (1988) Molecular Biology of Steroid Hormone Synthesis. Endocrine Reviews, 9(3): 295-318. https://doi.org/10.1210/edrv-9-3-295	
² Miller W.L. and Auchus R.J. (2011) The Molecular Biology, Biochemistry, and Physiology of Human Steroidogenesis and Its Disorders. Endocrine Reviews, 32(1): 81-151. https://doi.org/10.1210/er.2010-0013	
³ Shiraishi S., Lee P.W., Leung A., Goh V.H., Swerdloff R.S. and Wang C. (2008) Simultaneous measurement of serum testosterone and dihydrotestosterone by liquid chromatography-tandem mass spectrometry. Clinical chemistry, 54(11): 1855-63. https://doi.org/10.1373/clinchem.2008.103846	
Event: 1614: Decrease, androgen receptors (AR) activation	
Short Name: Decrease, AR activation	
AOPs Including This Key Event	
AOP ID and Name	Event Type
Aop:288 - Inhibition of 17α-hydrolase/C 10,20-lyase (Cyp17A1) activity leads to birth reproductive defects (cryptorchidism) in male (mammals)	KeyEvent
Aop:305 - 5α-reductase inhibition leading to short anogenital distance (AGD) in male (mammalian) offspring	KeyEvent
Aop:306 - Androgen receptor (AR) antagonism leading to short anogenital distance (AGD) in male (mammalian) offspring	KeyEvent
Aop:307 - Decreased testosterone synthesis leading to short anogenital distance (AGD) in male (mammalian) offspring	KeyEvent
Aop:344 - Androgen receptor (AR) antagonism leading to nipple retention (NR) in male (mammalian) offspring	KeyEvent
Aop:372 - Androgen receptor antagonism leading to testicular cancer	KeyEvent
Biological Context	
Level of Biological Organization	
Cellular	

Key Event Description

Androgen receptor activation is regulated by the binding of androgens. AR activity can be decreased by either a lack of steroidal ligands (testosterone, DHT) or the presence of antagonist compounds.¹²

How it is Measured or Detected

Significance of AR signaling in fetal development can be studied through a conditional deletion of the androgen receptor using a Cre/loxP approach. The recommended animal model for reproductive study is the mouse.³

Also, epidemiological case-studies following mouse or humans expressing a complete androgen insensitivity allow to directly assess the effects of a lack of AR activation on the development.⁴

Enzyme immunoassay (ELISA) kits for in vitro quantitative measurement of AR activity are available. Androgen receptors activity can be measured using bioassay such as the (Anti-)Androgen Receptor CALUX reporter gene assay.⁵

References

- ¹ Davey R.A and Grossmann M. (2016) Androgen Receptor Structure, Function and Biology: From Bench to Bedside. Clinical Biochemist Reviews, 37(1): 3-15. PCM4810760
- ² Gao W., Bohl C.E. and Dalton J.T. (2005) Chemistry and Structural Biology of Androgen Receptor. Chemical Reviews 105(9): 3352-3370 <https://doi.org/10.1021/cr020456u>
- ³ Kaftanovskaya E.M., Huang Z., Barbara A.M., De Gendt K., Verhoeven G., Ivan P. Gorlov, and Agoulnik A.I. (2012) Cryptorchidism in Mice with an Androgen Receptor Ablation in Gubernaculum Testis. Molecular Endocrinology, 26(4): 598-607. <https://doi.org/10.1210/me.2011-1283>
- ⁴ Hutson J.M. (1985) A biphasic model for the hormonal control of testicular descent. Lancet, 24;2(8452): 419-21 [http://dx.doi.org/10.1016/S0140-6736\(85\)92739-4](http://dx.doi.org/10.1016/S0140-6736(85)92739-4)
- ⁵ van der Burg B., Winter R., Man HY., Vangenechten C., Berckmans P., Weimer M., Witters M. and van der Linden S. (2010) Optimization and prevalidation of the in vitro AR CALUX method to test androgenic and antiandrogenic activity of compounds. Reproductive Toxicology, 30(1):18-24 <https://doi.org/10.1016/j.reprotox.2010.04.012>

Event: 286: Altered, Transcription of genes by AR

Short Name: Altered, Transcription of genes by AR

Key Event Component

Process	Object	Action
regulation of gene expression	androgen receptor	decreased

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:19 - Androgen receptor antagonism leading to adverse effects in the male fetus (mammals)	KeyEvent
Aop:307 - Decreased testosterone synthesis leading to short anogenital distance (AGD) in male (mammalian) offspring	KeyEvent
Aop:344 - Androgen receptor (AR) antagonism leading to nipple retention (NR) in male (mammalian) offspring	KeyEvent
Aop:345 - Androgen receptor (AR) antagonism leading to decreased fertility in females	KeyEvent
Aop:305 - 5α-reductase inhibition leading to short anogenital distance (AGD) in male (mammalian) offspring	KeyEvent

Stressors

Name

Name

Bicalutamide
 Cyproterone acetate
 Epoxiconazole
 Flutamide
 Flusilazole
 Prochloraz
 Propiconazole
 Stressor:286 Tebuconazole
 Triticonazole
 Vinclozalin

Biological Context

Level of Biological Organization

Cellular

Cell term

Cell term

eukaryotic cell

Evidence for Perturbation by Stressor

Bicalutamide

Using analysis of androgen-regulated gene expression in the LNCaP prostate cancer cell line (Ngan et al. 2009).

Cyproterone acetate

Using analysis of androgen-regulated gene expression in the LNCaP prostate cancer cell line (Ngan et al. 2009) and using the AR-CALUX reporter assay in antagonism mode, cyproterone acetate showed an IC50 of 7.1 nM (Sonneveld et al. 2005).

Epoxiconazole

Using transiently AR-transfected CHO cells, epoxiconazole showed a LOEC of 1.6 mM and an IC50 of 10 mM (Kjærstad et al. 2010).

Flutamide

Analysis of androgen-regulated gene expression in the LNCaP prostate cancer cell line (Ngan et al. 2009) and using the AR-CALUX reporter assay in antagonism mode, flutamide showed an IC50 of 1.3 μ M (Sonneveld et al. 2005).

Flusilazole

Using hAR-EcoScreen Assay, triticonazole showed a LOEC for antagonisms of 0.8 mM and an IC50 of 2.8 ($\pm$ 0.1) mM (Draskau et al. 2019)

Prochloraz

Using gene expression analysis of the androgen-regulated genes ornithine decarboxylase, prostatic binding protein C3 as well as insulin-like growth factor I. Gene expression levels were reduced in ventral prostates of male Wistar pups at postnatal day 16 following *in utero* and lactational exposure from maternal perinatal dosing with prochloraz (50 and 150 mg/kg/day) from gestational day 7 to postnatal day 16 (Laier et al. 2006). Also, using transiently AR-transfected CHO cells, prochloraz showed a LOEC of 6.3 mM and an IC50 of 13 mM (Kjærstad et al. 2010).

Propiconazole

Using transiently AR-transfected CHO cells, propiconazole showed a LOEC of 12.5 mM and an IC50 of 18 mM (Kjærstad et al. 2010).

Stressor:286 Tebuconazole

Using transiently AR-transfected CHO cells, tebuconazole showed a LOEC of 3.1 mM and an IC50 of 8.1 mM (Kjærstad et al. 2010).

Triticonazole

Using hAR-EcoScreen Assay, triticonazole showed a LOEC for antagonisms of 0.2 mM and an IC50 of 0.3 (± 0.01) mM (Draskau et al. 2019).

Vinclozalin

Using the AR-CALUX reporter assay in antagonism mode, vinclozolin showed an IC50 of 1.0 μ M (Sonneveld et al. 2005).

Domain of Applicability

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
human	Homo sapiens	High	NCBI
rat	Rattus norvegicus	High	NCBI
mouse	Mus musculus	High	NCBI

Life Stage Applicability

Life Stage	Evidence
Foetal	High
Adult, reproductively mature	High

Sex Applicability

Sex	Evidence
Mixed	High

Both the DNA-binding and ligand-binding domains of the AR are highly evolutionary conserved, whereas the transactivation domain show more divergence, which may affect AR-mediated gene regulation across species (Davey and Grossmann 2016). Despite certain inter-species differences, AR function mediated through gene expression is highly conserved, with mutation studies from both humans and rodents showing strong correlation for AR-dependent development and function (Walters et al. 2010).

This KE is applicable for both sexes, across developmental stages into adulthood, in numerous cells and tissues and across taxa.

Key Event Description

The Androgen Receptor and its function

Androgens act by binding to the Androgen receptor (AR) in androgen-responsive tissues (Davey and Grossmann 2016). Human AR mutations and mouse knockout models have established the fundamental role of AR in masculinization and spermatogenesis (Maclean et al.; Walters et al. 2010; Rana et al. 2014). The AR is also expressed in many other tissues such as bone, muscles, ovaries and within the immune system (Rana et al. 2014).

Altered transcription of genes by the AR as a Key Event

The AR belongs to the steroid hormone nuclear receptor family. It is a ligand-activated transcription factor with three domains; the N-terminal domain, the DNA-binding domain, and the ligand-binding domain with the latter being the most evolutionary conserved (Davey and Grossmann 2016). Upon activation by ligand-binding, the AR translocate from the cytoplasm to the cell nucleus, dimerizes, binds to androgen response elements in the DNA to modulate gene transcription (Davey and Grossmann 2016). The transcriptional targets varies between different cells and tissues, as well as with developmental stages and is, for instance, dependent on available co-regulators (Bevan and Parker 1999; Heemers and Tindall 2007).

Several known and proposed target genes of AR canonical signaling have been identified by analysis of gene expression following treatments with AR agonists (Bolton et al. 2007; Ngan et al. 2009) and can for instance be found in the Androgen-Responsive Gene Database (Jiang et al. 2009).

How it is Measured or Detected

In vitro

Decreased transcription of genes by the AR can be measured by measuring the transcription level of known downstream target genes by RT-qPCR or other transcription analyses approaches, eg transcriptomics.

Indirect approaches include the use of transient or stable transactivation assays including the validated OECD test guideline assay, Test No. 458: *Stably Transfected Human Androgen Receptor Transcriptional Activation Assay for Detection of Androgenic Agonist and Antagonist Activity of Chemicals* (OECD 2016). The stably transfected AR-EcoScreen™ cell line is freely available for the Japanese Collection of Research Bioresources (JCRB) Cell Bank under reference number JCRB1328. These cell-based transcriptional activation assays are typically used to detect AR agonists and antagonists. However, these types of assays are well suited to measure this KE as what they measure is exactly AR transcriptional activity. Other assays along this line include the AR-CALUX reporter gene assay that is derived from human U2-OS cells stably transfected with the human AR and an AR responsive reporter gene (van der Burg et al. 2010).

In vivo

Known downstream target gene transcription level can be measured in tissues by RT-qPCR or other gene expression analyses approaches.

References

- Bevan C, Parker M (1999) The role of coactivators in steroid hormone action. *Exp. Cell Res.* 253:349–356
- Bolton EC, So AY, Chaivorapol C, et al (2007) Cell- and gene-specific regulation of primary target genes by the androgen receptor. *Genes Dev* 21:2005–2017. doi: 10.1101/gad.1564207
- Davey RA, Grossmann M (2016) Androgen Receptor Structure, Function and Biology: From Bench to Bedside. *Clin Biochem Rev* 37:3–15
- Draskau MK, Boberg J, Taxvig C, et al (2019) In vitro and in vivo endocrine disrupting effects of the azole fungicides triticonazole and flusilazole. *Environ Pollut* 255:113309. doi: 10.1016/j.envpol.2019.113309
- Estrada M, Espinosa A, Müller M, Jaimovich E (2003) Testosterone Stimulates Intracellular Calcium Release and Mitogen-Activated Protein Kinases Via a G Protein-Coupled Receptor in Skeletal Muscle Cells. *Endocrinology* 144:3586–3597. doi: 10.1210/en.2002-0164
- Heemers H V., Tindall DJ (2007) Androgen receptor (AR) coregulators: A diversity of functions converging on and regulating the AR transcriptional complex. *Endocr. Rev.* 28:778–808
- Jiang M, Ma Y, Chen C, et al (2009) Androgen-Responsive Gene Database: Integrated Knowledge on Androgen-Responsive Genes. *Mol Endocrinol* 23:1927–1933. doi: 10.1210/me.2009-0103
- Kjærstad MB, Taxvig C, Nellemann C, et al (2010) Endocrine disrupting effects in vitro of conazole antifungals used as pesticides and pharmaceuticals. *Reprod Toxicol* 30:573–582. doi: 10.1016/J.REPROTOX.2010.07.009
- Laier P, Metzдорff SB, Borch J, et al (2006) Mechanisms of action underlying the antiandrogenic effects of the fungicide prochloraz. *Toxicol Appl Pharmacol* 213:160–71. doi: 10.1016/j.taap.2005.10.013
- Maclean HE, Chu S, Warne GL, Zajack JD Related Individuals with Different Androgen Receptor Gene Deletions
- MacLeod DJ, Sharpe RM, Welsh M, et al (2010) Androgen action in the masculinization programming window and development of male reproductive organs. In: *International Journal of Andrology*. Blackwell Publishing Ltd, pp 279–287
- Ngan S, Stronach EA, Photiou A, et al (2009) Microarray coupled to quantitative RT–PCR analysis of androgen-regulated genes in human LNCaP prostate cancer cells. *Oncogene* 28:2051–2063. doi: 10.1038/onc.2009.68
- OECD (2016) Test No. 458: Stably Transfected Human Androgen Receptor Transcriptional Activation Assay for Detection of Androgenic Agonist and Antagonist Activity of Chemicals, OECD Guide. OECD Publishing
- Rana K, Davey RA, Zajack JD (2014) Human androgen deficiency: Insights gained from androgen receptor knockout mouse models. *Asian J. Androl.* 16:169–177
- Sonneveld E, Jansen HJ, Riteco JAC, et al (2005) Development of Androgen-and Estrogen-Responsive Bioassays, Members of a Panel of Human Cell Line-Based Highly Selective Steroid-Responsive Bioassays. *Toxicol Sci* 83:136–148. doi: 10.1093/toxsci/kfi005

van der Burg B, Winter R, Man H yen, et al (2010) Optimization and prevalidation of the in vitro AR CALUX method to test androgenic and antiandrogenic activity of compounds. Reprod Toxicol 30:18–24. doi: 10.1016/j.reprotox.2010.04.012

Walters KA, Simanainen U, Handelsman DJ (2010) Molecular insights into androgen actions in male and female reproductive function from androgen receptor knockout models. Hum Reprod Update 16:543–558. doi: 10.1093/humupd/dmq003

List of Adverse Outcomes in this AOP

[Event: 1688: decrease, male anogenital distance](#)

Short Name: short male AGD

Key Event Component

Process	Object	Action
androgen receptor signaling pathway	Musculature of male perineum	disrupted

AOPs Including This Key Event

AOP ID and Name	Event Type
Aop:305 - 5α-reductase inhibition leading to short anogenital distance (AGD) in male (mammalian) offspring	AdverseOutcome
Aop:306 - Androgen receptor (AR) antagonism leading to short anogenital distance (AGD) in male (mammalian) offspring	AdverseOutcome
Aop:307 - Decreased testosterone synthesis leading to short anogenital distance (AGD) in male (mammalian) offspring	AdverseOutcome

Stressors

Name
Butylparaben
p,p'-DDE
Bis(2-ethylhexyl) phthalate
Dexamethasone
Fenitrothion
Finasteride
Flutamide
Ketoconazole
Linuron
Prochloraz
Procymidone
Triticonazole
Vinclozolin
di-n-hexyl phthalate
Dicyclohexyl phthalate
butyl benzyl phthalate
monobenzyl phthalate
di-n-heptyl phthalate

Biological Context

Level of Biological Organization

Tissue

Organ term**Organ term**

perineum

Evidence for Perturbation by Stressor**Butylparaben**

Butylparaben has been shown to cause decreased male AGD in rats following intrauterine exposure to 500 and 1000 mg/kg bw/day ([Boberg et al. 2016](#); [Zhang et al. 2014](#)). A separate study using 600 mg/kg bw/day did not see an effect on male AGD ([Boberg et al. 2008](#)).

p,p'-DDE

p,p,DDE has been shown to cause decreased male AGD in rats following intrauterine exposure to 100-200 mg/kg bw/day ([Loeffler & Peterson, 1999](#); [Wolf et al. 1999](#)).

Bis(2-ethylhexyl) phthalate

DEHP has been shown to cause decreased male AGD in rats following intrauterine exposure to 300-1500 mg/kg bw/day ([Christiansen et al. 2010](#); [Gray et al. 2000](#); [Howdeshell et al. 2007](#); [Jarfelt et al. 2005](#); [Kita et al. 2016](#); [Li et al. 2013](#); [Lin et al. 2009](#); [Moore et al. 2001](#); [Nardelli et al. 2017](#); [Saillenfait et al. 2009](#); [Wolf et al. 1999](#)).

Dexamethasone

Dexamethasone has been shown to cause decreased male AGD in rats following intrauterine exposure to 0.1 mg/kg bw/day ([Van den Driesche et al. 2012](#)).

Fenitrothion

Fenitrothion has been shown to cause decreased male AGD in rats following intrauterine exposure to 25 mg/kg bw/day ([Turner et al. 2002](#)).

Finasteride

Finasteride has been shown to cause decreased male AGD in rats following intrauterine exposure to 100 mg/kg bw/day ([Bowman et al. 2003](#)).

Flutamide

Flutamide has been shown to cause decreased male AGD in rats following intrauterine exposure to doses between 16-100 mg/kg bw/day ([Foster & Harris. 2005](#); [Hass et al. 2007](#); [Kita et al. 2016](#); [McIntyre et al. 2001](#); [Mylchreest et al. 1999](#); [Scott et al. 2007](#); [Welsh et al. 2007](#)).

Ketoconazole

Ketoconazole has been shown to cause decreased male AGD in rats following intrauterine exposure to 50 mg/kg bw/day in one study ([Taxvig et al. 2008](#)), but no effect in another study using same dose ([Wolf et al. 1999](#)).

Linuron

Linuron has been shown to cause decreased male AGD in rats following intrauterine exposure to 50-100 mg/kg bw/day ([Hotchkiss et al. 2004](#); [McIntyre et al. 2002](#); [Wolf et al. 1999](#)).

Prochloraz

Prochloraz has been shown to cause decreased male AGD in rats following intrauterine exposure to 150-250 mg/kg bw/day ([Laier et al. 2006](#); [Noriega et al. 2005](#)).

Procymidone

Procymidone has been shown to cause decreased male AGD in rats following intrauterine exposure to doses between 50-150 mg/kg bw/day ([Hass et al. 2012](#); [Hass et al. 2007](#); [Wolf et al. 1999](#)).

Triticonazole

Triticonazole has been shown to cause decreased male AGD in rats following intrauterine exposure to 150 and 450 mg/kg bw/day ([Draskau et al. 2019](#)).

Vinclozolin

Vinclozolin has been shown to cause decreased male AGD in rats following intrauterine exposure to doses between 50-200 mg/kg bw/day ([Christiansen et al. 2009](#); [Gray et al. 1994](#); [Hass et al. 2007](#); [Matsuura et al. 2005](#); [Ostby et al. 1999](#); [Schneider et al. 2011](#); [Wolf et al. 2004](#)).

di-n-hexyl phthalate

DnHP has been shown to cause decreased male AGD in rats following intrauterine exposure to 500-750 mg/kg bw/day ([Saillenfait et al. 2009a](#); [Saillenfait et al. 2009b](#)).

Dicyclohexyl phthalate

DCHP has been shown to cause decreased male AGD in rats following intrauterine exposure to 350-750 mg/kg bw/day ([Aydoğan Ahabab & Barlas. 2015](#); [Hoshino et al. 2005](#); [Saillenfait et al. 2009a](#)).

butyl benzyl phthalate

BBP has been shown to cause decreased male AGD in rats following intrauterine exposure to 500-1000 mg/kg bw/day ([Ema & Miyawaki. 2002](#); [Gray et al. 2000](#); [Hotchkiss et al. 2004](#); [Nagao et al. 2000](#); [Tyl et al. 2004](#)).

monobenzyl phthalate

MBeP has been shown to cause decreased male AGD in rats following intrauterine exposure to 375 mg/kg bw/day ([Ema et al. 2003](#)).

di-n-heptyl phthalate

DHPP has been shown to cause decreased male AGD in rats following intrauterine exposure to 1000 mg/kg bw/day ([Saillenfait et al. 2011](#)).

Domain of Applicability

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
human	Homo sapiens	Moderate	NCBI
rat	Rattus norvegicus	High	NCBI
mouse	Mus musculus	High	NCBI

Life Stage Applicability

Life Stage	Evidence
Foetal	High

Sex Applicability

Sex	Evidence
Male	High

A short AGD in male offspring is a marker of insufficient androgen action during critical fetal developmental stages ([Schwartz et al. 2019](#); [Welsh et al. 2008](#)). A short AGD is thus a sign of undervirilization, which is also associated with a series of male reproductive disorders, including genital malformations and infertility in humans ([Juul et al. 2014](#); [Skakkebaek et al. 2001](#)).

There are numerous human epidemiological studies showing associations with intrauterine exposure to anti-androgenic chemicals and short AGD in newborn boys alongside other reproductive disorders ([Schwartz et al. 2019](#)). This underscores the human relevance of this AO. However, in reproductive toxicity studies and chemical risk assessment, rodents (rats and mice) are what is tested on. The list of chemicals inducing short male AGD in male rat offspring is extensive, as evidenced by the 'stressor' list and reviewed by ([Schwartz et al. 2019](#)).

Key Event Description

The anogenital distance (AGD) refers to the distance between anus and the external genitalia. In rodents and humans, the male AGD is approximately twice the length as the female AGD ([Salazar-Martinez et al. 2004](#); [Schwartz et al. 2019](#)). This sexual dimorphism is a consequence of sex hormone-dependent development of secondary sexual characteristics ([Schwartz et al. 2019](#)). In males, it is believed that androgens (primarily DHT) activate AR-positive cells in non-myotoc cells in the fetal perineum region to initiate differentiation of the perineal *levator ani* and *bulbocavernosus* (LABC) muscle complex ([Ipulan et al. 2014](#)). This AR-dependent process occurs within a critical window of development, around gestational days 15-18 in rats ([MacLeod et al. 2010](#)). In females, the absence of DHT prevents this masculinization effect from occurring.

The involvement of androgens in masculinization of the male fetus, including the perineum, has been known for a very long time ([Jost. 1953](#)), and AGD has historically been used to, for instance, sex newborn kittens. It is now well established that the AGD in newborns is a proxy readout for the intrauterine sex hormone milieu the fetus was developing. Too low androgen levels in XY fetuses makes the male AGD shorter, whereas excess (ectopic) androgen levels in XX fetuses makes the female AGD longer, in humans and rodents ([Schwartz et al. 2019](#)).

How it is Measured or Detected

The AGD is a morphometric measurement carried out by trained technicians (rodents) or medical staff (humans).

In rodent studies AGD is assessed as the distance between the genital papilla and the anus, and measured using a stereomicroscope with a micrometer eyepiece. The AGD index (AGDi) is often calculated by dividing AGD by the cube root of the body weight. It is important in statistical analysis to use litter as the statistical unit. This is done when more than one pup from each litter is examined. Statistical analyses is adjusted using litter as an independent, random and nested factor. AGD are analysed using body weight as covariate as recommended in Guidance Document 151 ([OECD. 2013](#)).

Regulatory Significance of the AO

In regulatory toxicology, the AGD is mandatory inclusions in OECD test guidelines used to test for developmental and reproductive toxicity of chemicals. Guidelines include 'TG 443 extended one-generation study', 'TG 421/422 reproductive toxicity screening studies' and 'TG 414 developmental toxicity study'.

References

- Aydoğan Ahabab M, Barlas N (2015) Influence of in utero di-n-hexyl phthalate and dicyclohexyl phthalate on fetal testicular development in rats. *Toxicol Lett* **233**: 125-137
- Boberg J, Axelstad M, Svingen T, Mandrup K, Christiansen S, Vinggaard AM, Hass U (2016) Multiple endocrine disrupting effects in rats perinatally exposed to butylparaben. *Toxicol Sci* **152**: 244-256
- Boberg J, Metzдорff S, Wortziger R, Axelstad M, Brokken L, Vinggaard AM, Dalgaard M, Nellemann C (2008) Impact of diisobutyl phthalate and other PPAR agonists on steroidogenesis and plasma insulin and leptin levels in fetal rats. *Toxicology* **250**: 75-81
- Bowman CJ, Barlow NJ, Turner KJ, Wallace DG, Foster PM (2003) Effects of in utero exposure to finasteride on androgen-dependent reproductive development in the male rat. *Toxicol Sci* **74**: 393-406
- Christiansen S, Boberg J, Axelstad M, Dalgaard M, Vinggaard AM, Metzдорff SB, Hass U (2010) Low-dose perinatal exposure to di(2-ethylhexyl) phthalate induces anti-androgenic effects in male rats. *Reprod Toxicol* **30**: 313-321
- Christiansen S, Scholze M, Dalgaard M, Vinggaard AM, Axelstad M, Kortenkamp A, Hass U (2009) Synergistic disruption of external male sex organ development by a mixture of four antiandrogens. *Environ Health Perspect* **117**: 1839-1846
- Draskau MK, Boberg J, Taxvig C, Pedersen M, Frandsen HL, Christiansen S, Svingen T (2019) In vitro and in vivo endocrine disrupting effects of the azole fungicides triticonazole and flusilazole. *Environ Pollut* **255**: 113309
- Ema M, Miyawaki E (2002) Effects on development of the reproductive system in male offspring of rats given butyl benzyl phthalate

during late pregnancy. *Reprod Toxicol* **16**: 71-76

Ema M, Miyawaki E, Hirose A, Kamata E (2003) Decreased anogenital distance and increased incidence of undescended testes in fetuses of rats given monobenzyl phthalate, a major metabolite of butyl benzyl phthalate. *Reprod Toxicol* **17**: 407-412

Foster PM, Harris MW (2005) Changes in androgen-mediated reproductive development in male rat offspring following exposure to a single oral dose of flutamide at different gestational ages. *Toxicol Sci* **85**: 1024-1032

Gray LE, Jr., Ostby J, Furr J, Price M, Veeramachaneni DN, Parks L (2000) Perinatal exposure to the phthalates DEHP, BBP, and DINP, but not DEP, DMP, or DOTP, alters sexual differentiation of the male rat. *Toxicol Sci* **58**: 350-365

Gray LEJ, Ostby JS, Kelce WR (1994) Developmental effects of an environmental antiandrogen: the fungicide vinclozolin alters sex differentiation of the male rat. *Toxicol Appl Pharmacol* **129**: 46-52

Hass U, Boberg J, Christiansen S, Jacobsen PR, Vinggaard AM, Taxvig C, Poulsen ME, Herrmann SS, Jensen BH, Petersen A, Clemmensen LH, Axelstad M (2012) Adverse effects on sexual development in rat offspring after low dose exposure to a mixture of endocrine disrupting pesticides. *Reprod Toxicol* **34**: 261-274

Hass U, Scholze M, Christiansen S, Dalgaard M, Vinggaard AM, Axelstad M, Metzдорff SB, Kortenkamp A (2007) Combined exposure to anti-androgens exacerbates disruption of sexual differentiation in the rat. *Environ Health Perspect* **115 Suppl. 1**: 122-128

Hoshino N, Iwai M, Okazaki Y (2005) A two-generation reproductive toxicity study of dicyclohexyl phthalate in rats. *J Toxicol Sci* **30 Spec No**: 79-96

Hotchkiss AK, Parks-Saldutti LG, Ostby JS, Lambright C, Furr J, Vandenberg JG, Gray LEJ (2004) A mixture of the "antiandrogens" linuron and butyl benzyl phthalate alters sexual differentiation of the male rat in a cumulative fashion. *Biol Reprod* **71**: 1852-1861

Howdeshell KL, Furr J, Lambright CR, Rider CV, Wilson VS, Gray LE, Jr. (2007) Cumulative effects of dibutyl phthalate and diethylhexyl phthalate on male rat reproductive tract development: altered fetal steroid hormones and genes. *Toxicol Sci* **99**: 190-202

Ipulan LA, Suzuki K, Sakamoto Y, Murashima A, Imai Y, Omori A, Nakagata N, Nishinakamura R, Valasek P, Yamada G (2014) Nonmyocytic androgen receptor regulates the sexually dimorphic development of the embryonic bulbocavernosus muscle. *Endocrinology* **155**: 2467-2479

Jarfelt K, Dalgaard M, Hass U, Borch J, Jacobsen H, Ladefoged O (2005) Antiandrogenic effects in male rats perinatally exposed to a mixture of di(2-ethylhexyl) phthalate and di(2-ethylhexyl) adipate. *Reprod Toxicol* **19**: 505-515

Jost A (1953) Problems of fetal endocrinology: The gonadal and hypophyseal hormones. *Recent Prog Horm Res* **8**: 379-418

Juul A, Almstrup K, Andersson AM, Jensen TK, Jorgensen N, Main KM, Rajpert-De Meyts E, Toppari J, Skakkebaek NE (2014) Possible fetal determinants of male infertility. *Nat Rev Endocrinol* **10**: 553-562

Kita DH, Meyer KB, Venturelli AC, Adams R, Machado DL, Morais RN, Swan SH, Gennings C, Martino-Andrade AJ (2016) Manipulation of pre and postnatal androgen environments and anogenital distance in rats. *Toxicology* **368-369**: 152-161

Laier P, Metzдорff SB, Borch J, Hagen ML, Hass U, Christiansen S, Axelstad M, Kledal T, Dalgaard M, McKinnell C, Brokken LJ, Vinggaard AM (2006) Mechanisms of action underlying the antiandrogenic effects of the fungicide prochloraz. *Toxicol Appl Pharmacol* **213**: 2

Li M, Qiu L, Zhang Y, Hua Y, Tu S, He Y, Wen S, Wang Q, Wei G (2013) Dose-related effect by maternal exposure to di-(2-ethylhexyl) phthalate plasticizer on inducing hypospadiac male rats. *Environ Toxicol Pharmacol* **35**: 55-60

Lin H, Lian QQ, Hu GX, Jin Y, Zhang Y, Hardy DO, Chen GR, Lu ZQ, Sottas CM, Hardy MP, Ge RS (2009) In utero and lactational exposures to diethylhexyl-phthalate affect two populations of Leydig cells in male Long-Evans rats. *Biol Reprod* **80**: 882-888

Loeffler IK, Peterson RE (1999) Interactive effects of TCDD and p,p'-DDE on male reproductive tract development in in utero and lactationally exposed rats. *Toxicol Appl Pharmacol* **154**: 28-39

MacLeod DJ, Sharpe RM, Welsh M, Fisk M, Scott HM, Hutchison GR, Drake AJ, van den Driesche S (2010) Androgen action in the masculinization programming window and development of male reproductive organs. *Int J Androl* **33**: 279-287

Matsuura I, Saitoh T, Ashina M, Wako Y, Iwata H, Toyota N, Ishizuka Y, Namiki M, Hoshino N, Tsuchitani M (2005) Evaluation of a two-generation reproduction toxicity study adding endpoints to detect endocrine disrupting activity using vinclozolin. *J Toxicol Sci* **30 Spec No**: 163-168

McIntyre BS, Barlow NJ, Foster PM (2001) Androgen-mediated development in male rat offspring exposed to flutamide in utero: permanence and correlation of early postnatal changes in anogenital distance and nipple retention with malformations in androgen-dependent tissues. *Toxicol Sci* **62**: 236-249

- McIntyre BS, Barlow NJ, Sar M, Wallace DG, Foster PM (2002) Effects of in utero linuron exposure on rat Wolffian duct development. *Reprod Toxicol* **16**: 131-139
- Melching-Kollmuss S, Fussell KC, Schneider S, Buesen R, Groeters S, Strauss V, van Ravenzwaay B (2017) Comparing effect levels of regulatory studies with endpoints derived in targeted anti-androgenic studies: example prochloraz. *Arch Toxicol* **91**: 143-162
- Moore RW, Rudy TA, Lin TM, Ko K, Peterson RE (2001) Abnormalities of sexual development in male rats with in utero and lactational exposure to the antiandrogenic plasticizer Di(2-ethylhexyl) phthalate. *Environ Health Perspect* **109**: 229-237
- Mylchreest E, Sar M, Cattley RC, Foster PM (1999) Disruption of androgen-regulated male reproductive development by di(n-butyl) phthalate during late gestation in rats is different from flutamide. *Toxicol Appl Pharmacol* **156**: 81-95
- Nagao T, Ohta R, Marumo H, Shindo T, Yoshimura S, Ono H (2000) Effect of butyl benzyl phthalate in Sprague-Dawley rats after gavage administration: a two-generation reproductive study. *Reprod Toxicol* **14**: 513-532
- Nardelli TC, Albert O, Lalancette C, Culty M, Hales BF, Robaire B (2017) In utero and lactational exposure study in rats to identify replacements for di(2-ethylhexyl) phthalate. *Sci Rep* **7**: 3862
- Noriega NC, Ostby J, Lambright C, Wilson VS, Gray LE, Jr. (2005) Late gestational exposure to the fungicide prochloraz delays the onset of parturition and causes reproductive malformations in male but not female rat offspring. *Biol Reprod* **72**: 1324-1335
- OECD. (2013) Guidance document in support of the test guideline on the extended one generation reproductive toxicity study No. 151.
- Ostby J, Kelce WR, Lambright C, Wolf CJ, Mann P, Gray CLJ (1999) The fungicide procymidone alters sexual differentiation in the male rat by acting as an androgen-receptor antagonist in vivo and in vitro. *Toxicol Ind Health* **15**: 80-93
- Saillenfait AM, Gallissot F, Sabaté JP (2009a) Differential developmental toxicities of di-n-hexyl phthalate and dicyclohexyl phthalate administered orally to rats. *J Appl Toxicol* **29**: 510-521
- Saillenfait AM, Roudot AC, Gallissot F, Sabaté JP (2011) Prenatal developmental toxicity studies on di-n-heptyl and di-n-octyl phthalates in Sprague-Dawley rats. *Reprod Toxicol* **32**: 268-276
- Saillenfait AM, Sabaté JP, Gallissot F (2009b) Effects of in utero exposure to di-n-hexyl phthalate on the reproductive development of the male rat. *Reprod Toxicol* **28**: 468-476
- Salazar-Martinez E, Romano-Riquer P, Yanez-Marquez E, Longnecker MP, Hernandez-Avila M (2004) Anogenital distance in human male and female newborns: a descriptive, cross-sectional study. *Environ Health* **3**: 8
- Schneider S, Kaufmann W, Strauss V, van Ravenzwaay B (2011) Vinclozolin: a feasibility and sensitivity study of the ILSI-HESI F1-extended one-generation rat reproduction protocol. *Regulatory Toxicology and Pharmacology* **59**: 91-100
- Schwartz CL, Christiansen S, Vinggaard AM, Axelstad M, Hass U, Svingen T (2019) Anogenital distance as a toxicological or clinical marker for fetal androgen action and risk for reproductive disorders. *Arch Toxicol* **93**: 253-272
- Scott HM, Hutchison GR, Mahood IK, Hallmark N, Welsh M, De Gendt K, Verhoeven H, O'Shaughnessy P, Sharpe RM (2007) Role of androgens in fetal testis development and dysgenesis. *Endocrinology* **148**: 2027-2036
- Skakkebaek NE, Rajpert-De Meyts E, Main KM (2001) Testicular dysgenesis syndrome: an increasingly common developmental disorder with environmental aspects. *Hum Reprod* **16**: 972-978
- Taxvig C, Vinggaard AM, Hass U, Axelstad M, Metzдорff S, Nellemann C (2008) Endocrine-disrupting properties in vivo of widely used azole fungicides. *Int J Androl* **31**: 170-177
- Turner KJ, Barlow NJ, Struve MF, Wallace DG, Gaido KW, Dorman DC, Foster PM (2002) Effects of in utero exposure to the organophosphate insecticide fenitrothion on androgen-dependent reproductive development in the Crl:CD(SD)BR rat. *Toxicol Sci* **68**: 174-183
- Tyl RW, Myers CB, Marr MC, Fail PA, Seely JC, Brine DR, Barter RA, Butala JH (2004) Reproductive toxicity evaluation of dietary butyl benzyl phthalate (BBP) in rats. *Reprod Toxicol* **18**: 241-264
- Van den Driesche S, Kolovos P, Platts S, Drake AJ, Sharpe RM (2012) Inter-relationship between testicular dysgenesis and Leydig cell function in the masculinization programming window in the rat. *PLoS one* **7**: e30111
- Welsh M, Saunders PT, Fiskin M, Scott HM, Hutchison GR, Smith LB, Sharpe RM (2008) Identification in rats of a programming window for reproductive tract masculinization, disruption of which leads to hypospadias and cryptorchidism. *J Clin Invest* **118**: 1479-1490
- Welsh M, Saunders PT, Sharpe RM (2007) The critical time window for androgen-dependent development of the Wolffian duct in the rat. *Endocrinology* **148**: 3185-3195

Wolf CJ, LeBlanc GA, Gray LE, Jr. (2004) Interactive effects of vinclozolin and testosterone propionate on pregnancy and sexual differentiation of the male and female SD rat. *Toxicol Sci* **78**: 135-143

Wolf CJJ, Lambright C, Mann P, Price M, Cooper RL, Ostby J, Gray CLJ (1999) Administration of potentially antiandrogenic pesticides (procymidone, linuron, iprodione, chlozolate, p,p'-DDE, and ketoconazole) and toxic substances (dibutyl- and diethylhexyl phthalate, PCB 169, and ethane dimethane sulphonate) during sexual differentiation produces diverse profiles of reproductive malformations in the male rat. *Toxicol Ind Health* **15**: 94-118

Zhang L, Dong L, Ding S, Qiao P, Wang C, Zhang M, Zhang L, Du Q, Li Y, Tang N, Chang B (2014) Effects of n-butylparaben on steroidogenesis and spermatogenesis through changed E₂ levels in male rat offspring. *Environ Toxicol Pharmacol* **37**: 705-717

Appendix 2

List of Key Event Relationships in the AOP

List of Adjacent Key Event Relationships

Relationship: 2125: Reduction, Testosterone synthesis in Leydig cells leads to reduction, testosterone levels

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Decreased testosterone synthesis leading to short anogenital distance (AGD) in male (mammalian) offspring	adjacent	High	Moderate

Relationship: 2126: reduction, testosterone levels leads to Decrease, DHT level

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Decreased testosterone synthesis leading to short anogenital distance (AGD) in male (mammalian) offspring	adjacent	Moderate	Low

Relationship: 1935: Decrease, DHT level leads to Decrease, AR activation

AOPs Referencing Relationship

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Inhibition of 17α-hydrolase/C 10.20-lyase (Cyp17A1) activity leads to birth reproductive defects (cryptorchidism) in male (mammals)	adjacent	High	High
Decreased testosterone synthesis leading to short anogenital distance (AGD) in male (mammalian) offspring	adjacent	High	Moderate
5α-reductase inhibition leading to short anogenital distance (AGD) in male (mammalian) offspring	adjacent		

Evidence Supporting Applicability of this Relationship

Taxonomic Applicability

Term	Scientific Term	Evidence	Links
mammals	mammals	High	NCBI
human	Homo sapiens	High	NCBI
mouse	Mus musculus	High	NCBI
rat	Rattus norvegicus	High	NCBI

Life Stage Applicability

Life Stage	Evidence
Foetal	High
During development and at adulthood	High

Sex Applicability**Sex Evidence**

Male High

Key Event Relationship Description

Dihydrotestosterone (DHT) is, together with testosterone, a primary ligand for the Androgen receptor (AR). DHT is an endogenous sex hormone that is synthesis from e.g. testosterone by the enzyme 5 α -reductase in selected tissues, not least in the reproductive tracts of both sexes, but also other tissues and organs ([Davey & Grossmann, 2016](#); [Marks, 2004](#)). In the absence of ligand (DHT/testosterone) the AR is localized in the cytoplasm. AR is only activated and translocated into the nucleus to carry out its 'genomic function' upon ligand binding ([Davey & Grossmann, 2016](#)). Hence, AR transcriptional function is directly dependent on the presence of ligands, with DHT being a more potent AR activator (2-fold higher binding affinity) than testosterone ([Grino et al. 1990](#)). Reduced levels of DHT will lead to reduced AR activation.

[Relationship: 2124: Decrease, AR activation leads to Altered, Transcription of genes by AR](#)**AOPs Referencing Relationship**

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Decreased testosterone synthesis leading to short anogenital distance (AGD) in male (mammalian) offspring	adjacent	High	Moderate
Androgen receptor (AR) antagonism leading to nipple retention (NR) in male (mammalian) offspring	adjacent	Moderate	Moderate

[Relationship: 2127: Altered, Transcription of genes by AR leads to short male AGD](#)**AOPs Referencing Relationship**

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Decreased testosterone synthesis leading to short anogenital distance (AGD) in male (mammalian) offspring	adjacent	Moderate	Moderate

List of Non Adjacent Key Event Relationships**[Relationship: 2131: reduction, testosterone levels leads to Decrease, AR activation](#)****AOPs Referencing Relationship**

AOP Name	Adjacency	Weight of Evidence	Quantitative Understanding
Decreased testosterone synthesis leading to short anogenital distance (AGD) in male (mammalian) offspring	non-adjacent	Moderate	Moderate