Pathogenesis of polycystic ovary syndrome: multifactorial assessment from the foetal stage to menopause

Anderson Sanches de Melo1, Sabrine Vilan Dias1, Ricardo de Carvalho Cavalli1, Viviane Cunha Cardoso2, Heloisa Bettiol2, Marco Antonio Barbieri2, Rui Alberto Ferriani1 and Carolina Sales Vieira1

1Unit of Human Reproduction and Gynecological Endocrinology, Department of Gynecology and Obstetrics and 2Department of Paediatrics, Medical School of Ribeirão Preto, University of São Paulo, Avenida Bandeirantes, 3900 – Campus Universitário – Monte Alegre, CEP: 14049-900, Ribeirão Preto, São Paulo, Brazil

Correspondence should be addressed to A S Melo; Email: doctor_asmelo@yahoo.com.br

Abstract

Polycystic ovary syndrome (PCOS) is a multifactorial disorder that arises from interactions between genetic, environmental and intra-uterine factors. Small-for-gestational-age (SGA) babies and the daughters of mothers with PCOS represent possible postnatal clinical targets for developmental programming by steroid excess. The presence of excess glucocorticoids and/or androgens during foetal organogenesis and growth might promote changes in gene expression, and these changes might be related to an increase in the risk of PCOS-like reproductive and metabolic disorders in postnatal life, such as rapid growth and weight gain during the first 2 years of life (only in SGA babies), hyperinsulinaemia, adipocyte dysfunction and childhood visceral obesity, premature pubarche and adrenarche (only in SGA babies) and PCOS. In the fourth decade of life, women who have PCOS may be at higher risk for type 2 diabetes mellitus, dyslipidaemia and systemic arterial hypertension, which suggests that these women are also at higher risk for cardiovascular disease during menopause. However, PCOS can also occur in women who were born at appropriate weight for GA or in newborns of women without PCOS, which suggests that genetic variation and environmental factors play important roles in the development and maintenance of PCOS in a population. Genome-wide association studies based on adequate population samples have shown a higher frequency of genetic polymorphisms of the LHCGR, THADA and DENND1A genes in women with PCOS. Genetic studies of PCOS have also included analyses of structural changes in the chromosome based on an assessment of telomere length in single, cross-sectional evaluations, and these studies have produced controversial results. The present narrative review assesses the multifactorial origins of PCOS (including environmental, genetic and intra-uterine factors) and the development of conditions associated with this disorder. It is concluded that although PCOS might originate in the intra-uterine environment through developmental programming by steroid excess, the interaction between genetic and environmental factors is crucial for its appearance. Follow-up studies should be conducted to assess the same populations over their entire lifespans while taking into account different aspects of the pathogenesis of PCOS.


Introduction

Polycystic ovary syndrome (PCOS) is a heterogeneous and complex endocrine disorder with an estimated prevalence of 5–13.9% in women of reproductive age (Norman et al. 2007, Melo et al. 2010). In addition to causing reproductive disorders (anovulation and infertility), PCOS may or may not have a clinical and metabolic impact that varies according to ethnicity and geographic region (Tian et al. 2006, Norman et al. 2007).

Although the clinical manifestations of PCOS appear in adolescence, it has been suggested that the disease has its origins in the intra-uterine environment (de Zegher & Ibáñez 2006). Experimental studies in animals (Abbott et al. 2002, 2005) and clinical observations in human subjects (Melo et al. 2010) lend support to the hypothesis that developmental programming by steroid excess plays a role in the development of PCOS and its associated disorders at various stages of life (Jaquet et al. 2005) (Fig. 1). However, because the interaction between postnatal environmental factors and genetic predisposition are crucial for its occurrence, PCOS clearly has a multifactorial aetiology.

The developmental programming of PCOS represents changes in gene expression that occur following exposure to steroids (mainly glucocorticoids and/or androgens) during critical periods of foetal development. Some evidence suggests that this phenomenon is associated with variable PCOS-related metabolic and reproductive phenotypes in extra-uterine life and that these phenotypes are associated with the stage of
pregnancy during which the foetus was exposed to excess steroids (Padmanabhan & Veiga-Lopez 2011, Reynolds et al. 2012).

Developmental programming by glucocorticoid excess might account for the higher risk of PCOS and the associated clinical-metabolic disorders exhibited by small-for-gestational-age (SGA) infants who present compensatory growth. Although women who were born SGA may have an increased risk for developing PCOS, and both PCOS and SGA may lead to a higher risk of cardiovascular disease during old age (Jaquet et al. 2005, Martinez-Aguayo et al. 2007, Bonamy et al. 2008, Anderson et al. 2014), these propositions have not been evaluated in follow-up studies that simultaneously considered subjects who were born SGA and those who had PCOS. Thus, it is possible that individuals born SGA who exhibit compensatory growth, PCOS and cardiovascular and metabolic alterations represent part of a spectrum of abnormalities in developmental programming due to steroid excess.

Developmental programming by androgen excess during pregnancy could occur in women with obesity, type 2 diabetes mellitus (DM), insulin resistance (IR) (Escobar-Morreale et al. 2014), excessive weight gain during pregnancy, PCOS and/or any other situation associated with hyperandrogenism (Sir-Petermann et al. 2009) and could result in an increased risk of PCOS and/or associated clinical and metabolic comorbidities in their offspring (Sir-Petermann et al. 2009, Padmanabhan & Veiga-Lopez 2011, Escobar-Morreale et al. 2014). Experimental studies show that androgen excess during intra-uterine development may also be associated with intra-uterine growth restriction (IUGR) (Beckett et al. 2008), hyperinsulinaemia, visceral obesity and PCOS-like reproductive manifestations in women of reproductive age (Abbott et al. 2005, Padmanabhan & Veiga-Lopez 2011). Notwithstanding this association, individuals who apparently did not undergo developmental programming (subjects with birth weights appropriate for their gestational age (AGA) and daughters of women without hyperandrogenism during pregnancy) can also develop PCOS (Melo et al. 2010). This observation suggests that genetic variation and environmental factors play important roles in the development of PCOS. Genome-wide association studies (GWAS) have shown a higher frequency of genetic polymorphisms of the LHCGR, THADA and DENND1A genes in women with PCOS (Chen et al. 2011, Shi et al. 2012, Louwers et al. 2013). Genetic factors associated with a higher frequency of PCOS also include structural changes in chromosomes that have been analysed in cross-sectional studies by assessing telomere length at a single time point. These analyses have presented controversial results, and additional studies involving the longitudinal assessment of telomere length dynamics in women with PCOS at different stages of life are needed.

Existing studies of the pathogenesis of PCOS have limitations. Because there are three supported definitions of PCOS (Zawadski & Dunaić 1992, Rotterdam ESHRE/ASRM-Sponsored PCOS Consensus Workshop Group 2004, Azziz et al. 2006), comparing the results reported in different publications is somewhat difficult. Whereas some authors use a PCOS diagnosis based on criteria listed by the National Institutes of Health (NIH) (Goodarzi et al. 2012, Jones et al. 2012, Welt et al. 2012, Hwang et al. 2012, Mutharasan et al. 2013), others use the criteria proposed by the American Society of Human Reproduction/European Society of Human Reproduction and Embryology (Chen et al. 2011, Shi et al. 2012, Hwang et al. 2012, Louwers et al. 2013), which thereby intensifies discrepancies in the published work on the genetic analysis of PCOS. Some authors have not even attempted to standardise the diagnosis of PCOS (Davies et al. 2012, Hizli et al. 2012), and they include in their studies women with polycystic ovaries on ultrasonography only, a finding that alone does not increase the risk for PCOS-associated conditions (Cresswell et al. 1997), or they collect retrospective data from medical records that antedate the publication of the first consensus on PCOS by the NIH (Mumm et al. 2013).
The Rotterdam consensus criteria for the diagnosis of PCOS (Rotterdam ESHRE/ASRM-Sponsored PCOS Consensus Workshop Group 2004) defines some non-hyperandrogenic phenotypes (menstrual irregularity plus polycystic ovaries) as non-existent diagnoses according to the criteria formulated by the NIH (Zawadski & Dunaf 1992) and the Androgen Excess Society (Azziz et al. 2006). Because the cardio-metabolic profile of PCOS phenotypes characterised by hyperandrogenism and chronic anovulation is poorer, the inclusion of non-hyperandrogenic phenotypes might favour the occurrence of bias in the assessment of the aetiopathogenesis of PCOS and its relationship to cardiovascular comorbidities during late stages of life (Melo et al. 2011, Daan et al. 2014). Moreover, most of the existing studies are multicentre cross-sectional or case–control studies in which women at different stages of life and who have a varied prevalence of comorbidities associated with PCOS were analysed (Michelmore et al. 2001, Ibáñez et al. 2008, Legro et al. 2010, Chen et al. 2011, Hizli et al. 2012, Hwang et al. 2012, Jones et al. 2012, Shi et al. 2012, Louwers et al. 2013, Shaye et al. 2014).

The ethnic and geographic heterogeneity of PCOS demonstrates that this disorder is associated with environmental factors (Amsterdam ESHRE/ASRM-Sponsored 3rd PCOS Consensus Workshop Group 2012). The identification of geographical variations in the morbidity profiles of women with PCOS is therefore essential for establishing preventive measures to improve their health. In this context, birth cohorts seem to minimise these limitations because they include women of the same age range who are exposed to similar social, cultural and geographic factors. Moreover, birth cohort studies favour the simultaneous and prospective assessment of a variety of environmental, genetic and intra-uterine factors that may be associated with the development of PCOS and its clinical/metabolic changes at all stages of a woman’s life.

The aim of the present narrative review is to assess the multifactorial origins of PCOS and to explore how its origin involves the interaction of environmental, genetic and intra-uterine factors over a lifespan. With respect to genetic studies of PCOS, only GWAS published before November 2014 were included in the present review, because the external validity of the population case series of such studies is adequate. No study has yet assessed the environmental factors directly associated with PCOS, so articles on lifestyle modifications and theories based on experimental studies were considered. Articles were searched in the PubMed database relative to observational studies published in English from January 1990 to November 2014. The search keywords were (polycystic ovary syndrome AND (foetal programming OR genetic susceptibility)), (polycystic ovary syndrome AND foetal programming AND (androgen OR glucocorticoids)), (polycystic ovary syndrome AND (low birth weight OR birth weight OR small for gestational age)), (polycystic ovary syndrome AND association studies, genome-wide OR association study, genome-wide OR genome-wide association studies)) and (polycystic ovary syndrome AND (gene environment interaction OR environment OR lifestyle)). A total of 1114 articles were located. Of them, 16 observational studies were included in the present review; four of these were relevant to the genetic component of PCOS, and 12 were relevant to intra-uterine factors associated with PCOS.

Environmental factors associated with PCOS

Environmental factors associated with PCOS can be classified as prenatal (foetal developmental programming) or postnatal (diet, obesity, sedentary lifestyle, environmental toxins and prescription drugs) (Diamanti-Kandarakis et al. 2006). Evidence suggests that environmental stimuli can both mimic hormonal actions and activate pre-existing, predisposing factors that trigger the endocrine activity characteristic of PCOS (Escobar-Morreale et al. 2005, Norman et al. 2007). Dietary habits, exercise and cultural, social and economic factors might modify environmental exposure. For that reason, among others, the prevalence of the metabolic conditions associated with PCOS (obesity, metabolic syndrome and disorders of glucose metabolism) might vary as a function of the type of environmental exposure, especially in racially mixed populations that do not have a predominant genetic background. Thus, although environmental factors cannot be homogeneous in studies of the pathogenesis of PCOS in human subjects, the internal validity of such studies can be increased by including women of the same ethnicity who are from the same geographic area.

It has been suggested that PCOS presents a non-genetic inheritance pattern in populations with a poor lifestyle (high-saturated-fat diet, sedentary lifestyle, alcoholism and smoking). In such populations, changes in the foetal–placental unit, the onset of IUGR and the frequency of SGA newborns may occur. Hyperinsulinaemia and visceral obesity are more likely to develop during childhood and to culminate in a higher prevalence of IR, systemic arterial hypertension (SAH) and hyperandrogenism (Ibáñez et al. 2001) in reproductive-age women. During pregnancy, women who were born SGA also present a higher risk for placental disorders and the delivery of SGA newborns, which suggests a non-genetic inheritance pattern of PCOS. If they maintained a proper lifestyle throughout their childhood and their reproductive period, these women would not experience placental changes; thus, the process described earlier would be interrupted, and their children would be born AGA (Fig. 2) (Escobar-Morreale et al. 2005). Studies of familial aggregation in
Genetic factors associated with PCOS

Familial aggregation studies of PCOS suggest that it is an inherited disorder. Genetic inheritance of the condition has been demonstrated in studies of twins in which women with monozygotic twin sisters affected by PCOS were shown to have twice the risk of developing the disorder by the time they reached reproductive age (Vink et al. 2006). Studies of first-degree relatives of women with PCOS demonstrated an increased incidence of abnormal glucose metabolism and metabolic syndrome in men, which suggests a genetic background effect (Yildiz et al. 2003). Despite these considerations, the absence of a male PCOS phenotype, differences in the methodologies used in the studies, which were case-controlled and did not consider the multifactorial aspects of the aetiology of PCOS, fertility problems in women with PCOS and the irreproducibility of the results obtained in non-familial studies limit the internal and external validity of current assessments of the genetic components of PCOS.

Although gene variants of hundreds of coding genes associated with the clinical and laboratory features of PCOS (genes related to hyperandrogenism, IR, SHBG, gonadotrophins, metabolic and inflammatory markers and obesity, among others) have been demonstrated in specific populations (Escobar-Morreale et al. 2005), these results present low external validity. A group of researchers from China conducted the first large GWAS on the human genome in Chinese women with PCOS and demonstrated a higher frequency of genetic polymorphism at 2p16.3 (rs13405728), 2p21 (rs13429458) and 9q33.3 (rs2479106) in women with PCOS. These single-nucleotide polymorphisms (SNPs) were related to the following genes: LHCGR (the LH/hCG receptor gene, which is associated with increased luteinising hormone (LH), enlarged ovaries, oligomenorrhea, resistance to LH or human chorionic gonadotrophin (HCG) and infertility), DENND1A (a gene that codes for a modifier of guanine that is associated with multiple organ dysfunction, including dysfunction of the ovary, hypothalamus, pituitary and adrenal glands and tissue-specific responses to insulin, type 2 DM and obesity) and THADA (a thyroid adenoma gene associated with disorders of glucose metabolism, polycystic ovarian morphology, hypersecretion of LH, hyperandrogenism and dyslipidaemia) in the PCOS group (Chen et al. 2011). However, the cases included in this initial evaluation were insufficient to establish genetic susceptibility to PCOS, which requires the evaluation of other polymorphisms in a larger sample. Subsequently, in 2254 cases of PCOS vs 3001 controls (women without PCOS), eight new loci were identified by the Chinese group. These included C9orf3, which is associated with hyperandrogenism and is located at 9q22.32 (rs3802457), YAP1, a gene associated with cell proliferation and apoptosis at 11q22.1 (rs1894116), RAB3B and

**Figure 2** Environmental factors in the pathogenesis of polycystic ovary syndrome. Adapted from Escobar-Morreale et al. (2005). IUGR, intrauterine growth restriction; IR, insulin resistance; SAH, systemic arterial hypertension; SGA, small for gestational age; AGA, appropriate for gestational age.

which different members of the same family are considered could establish the potential influence of the genetic component in the cascade of events described earlier.

The relevance of environmental factors to the development of PCOS is evidenced by the effect of lifestyle changes on obesity, which is a highly prevalent comorbidity among women with PCOS. Such measures might alter the phenotypic expression of PCOS. Reduction in body weight is the first line of treatment in obese women with PCOS. A loss of 2–5% of body weight reduces hyperinsulinaemia, increases sex hormone-binding globulin (SHBG) levels, reduces free androgen levels, restores the ovulatory cycle and improves clinical hyperandrogenism and metabolic disorders, such as dyslipidaemia (Thessaloniki ESHRE/ASRM-Sponsored PCOS Consensus Workshop Group 2008, Moran et al. 2011). Contrarily, diets that are high in saturated fat and sedentary lifestyles are associated with the development of PCOS and its metabolic consequences, mainly obesity (Amsterdam ESHRE/ASRM-Sponsored 3rd PCOS Consensus Workshop Group 2012).
SUOX, two genes associated with type 1 DM at 12q13.2 (rs705702), HMGA2, a gene associated with infertility at 12q14.3 (rs22720), TOX3, a gene associated with DNA modification at 16q12.1 (rs4784165), INSR, a gene associated with IR at 19p13.3 (rs205980), SUMO1P1 and ZNF217, two genes associated with telomere dysfunction at 20q13.2 (rs6022786) and LHCGR at 2p16.3 (rs2268361). These new findings have demonstrated other genetic variants related to glucose metabolism disorders, sex hormone functions, insulin/calcium signalling and endocytosis. The discovery of these new loci confirms the genetic predisposition to PCOS in Chinese women (Shi et al. 2012).

Although the findings obtained in Chinese populations have been confirmed in women with PCOS in the USA with respect to variants in the DENND1A (Goodarzi et al. 2012, Welt et al. 2012), THADA (Goodarzi et al. 2012), LHCGR and FSHR (Mutharasan et al. 2013) genes as well as in European populations (12 genetic variants in the LHCGR, THADA, DENND1A, FSHR, c9orf3, YAPI, RAB5B/SUOX and SUMO1P1 loci) (Louwers et al. 2013). A GWAS study conducted by a Korean group failed to confirm these results and found that only the glycogen synthase 2 (GYS2) gene could be linked to PCOS and its metabolic complications (Hwang et al. 2012). Another GWAS study conducted in the USA that analysed genes that code for proteins associated with metabolic and cardiovascular abnormalities also did not demonstrate a hereditary component of PCOS (Jones et al. 2012). These discrepancies may occur because genetic background varies according to ethnicity. Furthermore, some multicentre case–control studies included women at stages of life that ranged from adolescence to menopause who had heterogeneous social/cultural lifestyles and different clinical and metabolic manifestations of PCOS (certain patients were too young to present comorbidities). In addition, these studies did not consider other aspects of the pathogenesis of PCOS, such as birth weight and environmental factors. Table 1 presents data from GWAS studies of women with PCOS.

Table 1 Genome-wide association study in women with polycystic ovary syndromea.

<table>
<thead>
<tr>
<th>Author</th>
<th>Population</th>
<th>Genes</th>
<th>Loci</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chen et al. (2011)</td>
<td>PCOS: 744 vs control: 895</td>
<td>DENND1A (9q33.3)</td>
<td>rs2479106</td>
</tr>
<tr>
<td>(China)</td>
<td>Replication 1</td>
<td>LHCGR (2p16.3)</td>
<td>rs13405728</td>
</tr>
<tr>
<td>(GWAS1)</td>
<td>PCOS: 2840 vs control: 5012</td>
<td>THADA (2p21)</td>
<td>rs13429458</td>
</tr>
<tr>
<td></td>
<td>Replication 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(South China)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PCOS: 498 vs control: 780</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shi et al. (2012)</td>
<td>GWAS2</td>
<td>C9orf3 (9q22.32)</td>
<td>rs3802457</td>
</tr>
<tr>
<td>(China)</td>
<td>PCOS: 1510 vs control: 2106</td>
<td>HMGA2 (12q14.3)</td>
<td>rs2272046</td>
</tr>
<tr>
<td>(GWAS2)</td>
<td>Meta-analysis</td>
<td>INSR (19p13.3)</td>
<td>rs205980</td>
</tr>
<tr>
<td></td>
<td>(GWAS1 and 2)</td>
<td>LHCGR (2p16.3)</td>
<td>rs2268361</td>
</tr>
<tr>
<td></td>
<td>PCOS: 2254 vs control: 3001</td>
<td>RAB5B and SUOX (12q13.2)</td>
<td>rs705702</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SUMO1P1 and ZNF217 (20q13.2)</td>
<td>rs6022786</td>
</tr>
<tr>
<td></td>
<td></td>
<td>YAPI (11q22.1)</td>
<td>rs4784165</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>rs1894116</td>
</tr>
<tr>
<td>Jones et al. (2012)</td>
<td>PCOS: 443 vs control: 193</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>(USA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hwang et al. (2012)</td>
<td>PCOS: 774 vs control: 967</td>
<td>GYS2</td>
<td>rs6487237, rs7485509,</td>
</tr>
<tr>
<td>(Korea)</td>
<td></td>
<td></td>
<td>rs10841843</td>
</tr>
<tr>
<td>Louwers et al. (2013)</td>
<td>PCOS: 703 vs control: 2164</td>
<td>C9orf3</td>
<td>rs4385527</td>
</tr>
<tr>
<td>(The Netherlands/Dutch study)</td>
<td></td>
<td>DENND1A</td>
<td>rs10986105</td>
</tr>
<tr>
<td></td>
<td>Meta-analysis</td>
<td>THADA</td>
<td>rs12468395, rs12478601</td>
</tr>
<tr>
<td></td>
<td>(USA, China and The Netherlands)</td>
<td>YAPI</td>
<td>rs1894116</td>
</tr>
<tr>
<td></td>
<td>PCOS: 2254 vs control: 3001</td>
<td>Meta-analysis</td>
<td>rs2349415, rs4385527</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C9orf3</td>
<td>rs10818854, rs10986105</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DENND1A</td>
<td>rs2268361</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FSHR</td>
<td>rs13405728</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LHCGR</td>
<td>rs1894116</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RAB5B and SUOX</td>
<td>rs705702, rs6022786</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SUMO1P1</td>
<td>rs12468394, rs12478601</td>
</tr>
<tr>
<td></td>
<td></td>
<td>THADA</td>
<td>rs3802457</td>
</tr>
</tbody>
</table>

GWAS, genome-wide association study; LHCGR, luteinising hormone/human chorionic gonadotrophin receptor gene; THADA, thyroid adenoma-associated gene; DENND1A, gene modifier of guanine; C9orf3, chromosome 9 open reading frame 3; YAPI, yes-associated protein 1; RAB5B, oncogene family; SUOX, sulphite oxidase gene; HMGA2, high-mobility group AT-hook2; TOX3, TOX high-mobility group box family member 3; INSR, insulin receptor gene; ZNF217, zinc finger protein 217; GYS2, glycogen synthase 2 (liver); FSHR, follicle-stimulating hormone receptor gene.

aAll of the studies mentioned were case–control studies. This table includes only the genome-wide association studies on women with PCOS.
Genetic studies of PCOS also include the analysis of structural/anatomical changes in chromosomes (changes in non-coding sequences) based on the assessment of telomere length. The telomere is a structure located at the end of the chromosome that is involved in chromatin organisation, the control of cell proliferation, the preservation of genome integrity and the stability and prevention of chromosome fusion (Allsopp et al. 1992). Physiologically, telomere length decreases with ageing. However, this process can be accelerated by cardiovascular disease, SAH, hypercholesterolaemia and type 2 DM, conditions that are associated with an inflammatory and oxidative environment (Fuster & Andres 2006). Because women with PCOS are at greater risk for these clinical and metabolic conditions, and because PCOS is associated with inflammation and oxidative stress (Cussons et al. 2006), telomere shortening may be another mechanism associated with the pathogenesis of PCOS and its comorbidities. In this context, a Chinese group showed that women with PCOS have shorter telomeres than do subjects without PCOS in a single-assessment, cross-sectional study of women of various ages (PCOS: n=698 vs control: n=611) (Li et al. 2014). These data were not confirmed by other investigators who assessed Brazilian women with PCOS (PCOS: n=150 vs control: n=124) (Pedroso et al. 2014). The discrepancy might occur because the two studies compared women at different stages of life (reproductive age and menopause) and the assessments of women at reproductive age might have occurred too early to detect differences in telomere length between women with PCOS and those without PCOS. Birth cohort studies may be more suitable for elucidating the dynamic of telomere shortening because this methodology can assess the same population at different stages of life (lifespan assessment).

Role of developmental programming in the pathogenesis of PCOS

Developmental programming refers to changes in gene expression that result from the presence of increased levels of steroid hormones in the foetal circulation at critical stages of foetal development and that result in permanent structural and functional modifications of the body organs. This phenomenon might be caused either by the presence of excess glucocorticoids (resulting from foetal hypoxia and IUGR) (Wells 2011, Longo et al. 2013) or by the elevation of maternal androgen levels during pregnancy (Padmanabhan & Veiga-Lopez 2011, Escobar-Morreale et al. 2014). In addition to anatomic and functional changes in organs and organ systems, developmental programming might also be associated with the programming of endocrine pathways and thus also with clinical, metabolic and reproductive changes during postnatal life.

Changes in gene expression are necessary for the physiological development of the foetus. However, under unfavourable intra-uterine conditions, excessive steroid levels might induce alterations in gene expression that can result in epigenetic modifications (hereditary changes in the genome that do not involve any alteration in the DNA nucleotide sequence and are transmitted during cell division). DNA methylation, in which the chemical structure of cytosine is modified through the addition of a methyl group (CH3), is one such epigenetic alteration (Li & Huang 2008). Xu et al. (2011) have shown that exposure of foetal female monkeys to testosterone excess changes the epigenome of their visceral fat cells. Therefore, epigenetic alterations might represent the molecular basis of developmental programming related to the reproductive and metabolic phenotypes exhibited by women with PCOS over the course of their lives (Wang et al. 2014).

Developmental programming by glucocorticoid excess

The proper growth of the foetus results from a balance between anabolic and catabolic processes that occur during the functional maturation and differentiation of foetal organs and tissues. If foetal hypoxia develops during this period because of dietary restrictions and/or maternal or placental disease, the catabolic process will predominate, which results in IUGR and ultimately an SGA newborn. To assure survival and reduce energy expenditure (‘thrift phenotype’) (Barker 1995), foetal blood flow is redirected to essential organs (heart, brain and adrenal glands) in a phenomenon called centralisation. Consequently, there is an increased production of glucocorticoids because of the hyperactivity of the hypothalamic–pituitary–adrenal (HPA) axis, which results in epigenetic modifications (Wells 2011, Longo et al. 2013).

Clinical assessments of the effects of developmental programming that result from glucocorticoid excess on the development of disease at later stages of life are hindered by the multifactorial aetiology of most reproductive, metabolic and cardiovascular diseases. However, studies with experimental animals have found that foetuses with IUGR caused by placental insufficiency or maternal malnutrition were born SGA and that these animals showed a predisposition to developing pathologies in postnatal life after compensatory growth during the first 2 years of life (Bloomfield et al. 2003, Reynolds 2012). Clinical data show that compensatory growth might also be associated with the development of comorbidities in humans, such as precocious puberty (Ibáñez et al. 1998), SAH (Elting et al. 2001), cardiovascular disease (Bonamy et al. 2008), type 2 DM, glucose intolerance (Willemsen et al. 2008), dyslipidaemia, obesity (Martinez-Aguayo et al. 2007),
metabolic syndrome (Jaquet et al. 2005) and PCOS (Pandolfi et al. 2008, Melo et al. 2010, Hizli et al. 2012). Thus, children born SGA would exhibit a clinical marker of developmental programming by glucocorticoids associated with the development of PCOS and its associated comorbidities, although SGA may also be constitutional (variation of normal).

**Developmental programming by androgen excess**

In addition to elevated glucocorticoid levels, hyperactivity of the HPA axis secondary to IUGR might also favour the occurrence of hyperandrogenism resulting from overactivity of the adrenal gland. Excessive levels of adrenal androgens may alter gene expression in such a way as to favour the development of the reproductive and metabolic phenotypes of PCOS in animals (Reynolds 2012). Among other factors, this mechanism might account for the higher risk of PCOS and associated clinical/metabolic conditions exhibited by the offspring of mothers with PCOS (Padmanabhan & Veiga-Lopez 2011). Adrenal androgen excess in the maternal circulation occurs in the absence of IUGR (a characteristic that has been shown in animal models) (Zhou et al. 2005), and hyperandrogenism might be consequence of obesity, DM, IR (Escobar-Morreale et al. 2014), PCOS and/or any other condition associated with androgen excess (Sir-Petermann et al. 2009).

Obesity (Chandrasekaran et al. 2014), DM, IR and excessive weight gain during pregnancy (Xiang et al. 2015) are predictors of large-for-gestational-age (LGA) offspring. Because these conditions may also be associated with hyperandrogenism (Macut et al. 2014), LGA babies might exhibit a higher risk for PCOS via developmental programming by androgen excess, but this hypothesis remains to be confirmed through clinical studies. Mumm et al. (2013) found that the risk of PCOS was not higher among LGA female babies of mothers with type 2 DM. However, those authors used data they had located through a search of medical records using International Classification of Diseases (ICD) codes that was performed before the publication of any consensus on the diagnostic criteria for PCOS.

Based on the results of experiments conducted in animals, it has been established that the stage of pregnancy during which exposure to androgen excess occurs is crucial for determining the reproductive and metabolic phenotypes associated with PCOS. PCOS-like reproductive disorders were found to predominate in animals that had been treated with androgens during both the first and second halves of pregnancy, whereas problems related to glucose metabolism and visceral obesity predominated in animals that had been treated with androgens during the first half of pregnancy (Abbott et al. 2005; Table 2).

<table>
<thead>
<tr>
<th>Reproductive</th>
<th>Metabolic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anovulation</td>
<td>Insulin resistance</td>
</tr>
<tr>
<td>Ovarian hyperandrogenism</td>
<td>Glucose intolerance</td>
</tr>
<tr>
<td>Polycystic ovaries</td>
<td>Type 2 diabetes mellitus</td>
</tr>
<tr>
<td>LH hypersecretion</td>
<td>Visceral obesity</td>
</tr>
<tr>
<td>Infertility</td>
<td>Dyslipidaemia</td>
</tr>
</tbody>
</table>

LH, luteinising hormone.

*PCOS-like reproductive disorders occur in the offspring of animals treated with androgens in both the first and second halves of pregnancy, whereas PCOS-related metabolic disorders appear in the offspring of animals treated with androgens at the beginning of pregnancy.

**Developmental programming related to PCOS manifestations: aspects relevant to childhood and adolescence**

Approximately 90% of SGA children present rapid growth and weight gain during the first 2 years of life (compensatory growth). At the end of this period, the growth curves and development of these children are similar to the patterns observed in children born AGA (Albertsson-Wikland et al. 1998). Compensatory growth is associated with hyperinsulinaemia, central obesity and adipose tissue dysfunction in childhood, factors that can alter the distribution of body fat and accelerate the onset of adrenarche and puberty, especially pubarche (Ibáñez et al. 1998).

During the peripubertal period, increased levels of leptin caused by dysfunctions in adipose tissue are associated with the hypersecretion of LH and the development of ovarian hyperandrogenism. Consequently, anovulatory cycles are more frequently observed in women who were born SGA (Ibáñez et al. 2002), which suggests that these women have a higher risk of developing PCOS. In addition, insulin acts on the ovarian theca through insulin-like growth factor 1 (IGF1), which results in increased levels of ovarian androgens. This process occurs because hyperinsulinaemia decreases the hepatic synthesis of IGF binding protein 1 (IGFBP1), which thus increases the free fraction of IGF1 (Poretsky et al. 1999). A reduction in the hepatic synthesis of SHBG, with a resulting increase in the levels of the free fraction of circulating androgens in SGA women, is another process that may be associated with hyperinsulinaemia (Ibáñez et al. 1998, 2002). Foetuses of animals exposed to androgen excess at the beginning of pregnancy may also exhibit an increased risk of hyperinsulinaemia and visceral obesity in infancy (Escobar-Morreale et al. 2014). Although developmental programming by androgen excess might be associated with IUGR in rodents (Sathishkumar et al. 2011) and sheep (Beckett et al. 2014) and with low birth weight (LBW), these characteristics are not frequently found in that process in non-human primate models for PCOS (Abbott et al. 2010).
Development programming related to PCOS manifestations: aspects relevant to reproductive age

The hyperinsulinaemia and hyperandrogenism observed during and after the immature stage of development of the HPA in SGA women, which is associated with a higher frequency of anovulatory cycles (Ibáñez et al. 2002), characterises SGA women as a group that is at risk for developing PCOS at reproductive age (Fig. 3). During the third decade of life, this risk can be twice as high in women born SGA as it is in women born AGA (Melo et al. 2010). However, PCOS does not occur in all women born SGA (Laitinen et al. 2003, Mumm et al. 2013), and...
women born AGA or daughters of women without PCOS can also develop this disorder, which suggests a multifactorial aetiology of PCOS (Melo et al. 2010).

Because women born SGA and the daughters of hyperandrogenic women show higher frequencies of hyperinsulinaemia, visceral obesity, adipose tissue dysfunction and IR during childhood, these characteristics could be considered early clinical markers of the development of SAH, dyslipidaemia, metabolic syndrome and type 2 DM related to PCOS. Typically, these metabolic comorbidities are more prevalent after the age of 40 in the general population without PCOS. However, PCOS women, especially obese women with family histories of type 2 DM, histories of gestational diabetes, acanthosis nigricans or irregular menstrual cycles and hyperandrogenism, begin to present these comorbidities beginning in the fourth decade of life (Elting et al. 2001, Moran et al. 2010).

In addition to the multiple aetiological aspects of PCOS, ethnicity and geographical region are relevant factors in the study of birth weight and the development of PCOS. Although SGA women in Brazil (Melo et al. 2010) and those with LBW in Italy (Pandolfi et al. 2008) and Turkey (Hizli et al. 2012) present a higher risk for developing PCOS, these findings were not confirmed in individuals from the USA (Legro et al. 2010), UK (Cresswell et al. 1997, Michelmore et al. 2001, Shaye et al. 2014), The Netherlands (Sadrzadeh et al. 2003), Finland (Laitinen et al. 2003), Spain (Ibañez et al. 2008) or Denmark (Mumm et al. 2013). One study conducted in Australia analysed birth weight as a continuous variable and found that each 100 g increase in birth weight increased the risk of hyperandrogenism. The authors of that study also found that the subjects’ thinness was related to PCOS symptoms and to IR (Davies et al. 2012; Table 3). These apparent regional differences may result from the limitations of these studies, which include the use of varying definitions of PCOS (Cresswell et al. 1997, Laitinen et al. 2003, Sadrzadeh et al. 2003, Ibañez et al. 2008, Hizli et al. 2012, Mumm et al. 2013), the inclusion of women using hormonal contraceptives (Ibañez et al. 2007, Davies et al. 2012, Mumm et al. 2013), the small numbers of participants (Ibañez et al. 2001, Pandolfi et al. 2008), the use of self-reported birth data (Laitinen et al. 2003, Sadrzadeh et al. 2003, Legro et al. 2010, Hizli et al. 2012), the inclusion of women with immature HPG axes (Ibañez et al. 2001) and the absence of compensatory growth assessments (Cresswell et al. 1997, Michelmore et al. 2001, Laitinen et al. 2003, Sadrzadeh et al. 2003, Ibañez et al. 2008, Pandolfi et al. 2008, Legro et al. 2010, Melo et al. 2010, Hizli et al. 2012, Mumm et al. 2013, Shaye et al. 2014). The use of birth weight classifications as an exposure factor across studies was perhaps the most important limitation, because not all of the studies adjusted the subjects’ birth weight for GA. For that reason, some of the studies included preterm newborn infants. This feature might indicate the presence of selection bias (Cresswell et al. 1997, Michelmore et al. 2001, Sadrzadeh et al. 2003, Ibañez et al. 2008, Legro et al. 2010, Hizli et al. 2012, Mumm et al. 2013, Shaye et al. 2014), especially considering that the functional maturation of organs and tissues of a preterm newborn is completed during postnatal life (Ben 2008).

There are two main birth weight classifications: i) the classification of birth weight based on GA (AGA: birth weight between P10 and P90 for GA; SGA: birth weight below P10 for GA; LGA: birth weight above P90 for GA), which is the most frequently used classification to confirm IUGR using postnatal data (birth weight, GA and newborn sex), can be used to determine the effects of foetal growth deficits regardless of prematurity (Battaglia & Lubchenco 1967) and is crucial for reducing bias (prematurity, for example) in the interpretation of results; and ii) the classification of birth weight independent of GA (macrosomic: birth weight ≥4000 g; appropriate: 3000–3999 g; inadequate: 2500–2999 g; LBW: 1500–2499 g; very LBW <1500 g; extremely LBW: <1000 g) (FIGO 1977). This information is an important health indicator that reflects the living conditions, nutrition and access to healthcare services in a population, which is extremely important when prenatal data are not available (Paneth 1995). However, birth weight data alone cannot determine preterm individuals; thus, this classification is inappropriate for studying the relationship between birth weight and the prevalence of disease at different stages of life. For example, a newborn weighing 2300 g can be either a preterm AGA newborn or a full-term SGA newborn.

**Development programming related to PCOS manifestations: aspects relevant to menopause**

Subclinical cardiovascular disease is common in reproductive-age women with PCOS (increased carotid intima-media thickness, reduced arterial elasticity and calcification of the coronary artery and aorta), regardless of the presence of obesity, IR or SAH (Talbott et al. 2004, Luque-Ramirez et al. 2007). The characteristics associated with early exposure to cardiovascular risk factors in inflammatory and oxidative environments during the reproductive years suggest an increased risk of cardiovascular events for patients in menopause and for elderly patients with PCOS (Cussons et al. 2006). However, the multifactorial aetiology of cardiovascular disease and the lack of well-designed prospective studies in which these women were assessed at different stages of life make conclusions regarding this possible association difficult. Although currently available evidence suggests that women with PCOS have twice the risk for cardiovascular events than that of the population without PCOS, this finding has some limitations: i) the lack of a
<table>
<thead>
<tr>
<th>Author</th>
<th>Study design</th>
<th>Population</th>
<th>Diagnosis of PCOS</th>
<th>Birth weight classification in relation gestational age</th>
<th>Association of SGA or LBW and PCOS (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cresswell et al. (1997) (UK)</td>
<td>Birth cohort</td>
<td>Polycystic ovaries: 49&lt;br&gt;Normal ovaries: 186 (born term and preterm)</td>
<td>Not mentioned</td>
<td>No (birth weight records in medical reports)</td>
<td>No (RR not evaluated)</td>
</tr>
<tr>
<td>Michelmore et al. (2001) (UK)</td>
<td>Cross-sectional</td>
<td>Polycystic ovaries: 74&lt;br&gt;Normal ovaries: 150 (born term and preterm)</td>
<td>Hyperandrogenism, menstrual irregularity and polycystic ovaries (prior to the Rotterdam consensus)</td>
<td>No (birth weight self-reported)</td>
<td>No (higher birth was related to polycystic ovaries)</td>
</tr>
<tr>
<td>Sadrzadeh et al. (2003) (The Netherlands)</td>
<td>Retrospective cohort (IVF centres)</td>
<td>PCOS: 265 (LBW: 27, ABW: 173, Unknown: 65)&lt;br&gt;Control: 957&lt;br&gt;Oocyte donation: 98&lt;br&gt;Low responders: 351</td>
<td>Not mentioned</td>
<td>No (birth weight self-reported)</td>
<td>No (LBW) 0.88 (0.53–1.48)</td>
</tr>
<tr>
<td>Laitinen et al. (2003) (Finland)</td>
<td>Birth cohort</td>
<td>SGA: 144&lt;br&gt;AGA: 1863&lt;br&gt;LBW: 71&lt;br&gt;No LBW: 1936 (born term and preterm)</td>
<td>Only self-reported symptoms of hirsutism and/or menstrual disturbances</td>
<td>Yes (two classifications) (birth weight records in medical reports)</td>
<td>No (SGA) 1.0 (0.76–1.33)&lt;br&gt;No (LBW) 0.80 (0.51–1.26)</td>
</tr>
<tr>
<td>Ibáñez et al. (2008) (Spain)</td>
<td>Cross-sectional</td>
<td>Polycystic ovaries: 33&lt;br&gt;No polycystic ovaries: 53</td>
<td>Not mentioned</td>
<td>No (birth weight records in medical reports)</td>
<td>Yes Prevalence PCOS (SGA and AGA)&lt;br&gt;LBW group: 40%&lt;br&gt;Control group: 5.7% (RR not evaluated)</td>
</tr>
<tr>
<td>Pandolfi et al. (2008) (Italy)</td>
<td>Birth cohort</td>
<td>LBW: 35&lt;br&gt;(SGA: 19 born term or preterm plus AGA: 16 born preterm)&lt;br&gt;Control: 35 born term AGA</td>
<td>NIH</td>
<td>Yes (two classifications) (birth weight records in medical reports)</td>
<td>Yes Prevalence PCOS (SGA and AGA)&lt;br&gt;LBW group: 40%&lt;br&gt;Control group: 5.7% (RR not evaluated)</td>
</tr>
<tr>
<td>Legro et al. (2010) (USA)</td>
<td>Case-control</td>
<td>PCOS: 467&lt;br&gt;Control: 86&lt;br&gt;LBW: 46&lt;br&gt;NBW: 390&lt;br&gt;HBW: 31 (born term and preterm)</td>
<td>NIH</td>
<td>No (birth weight self-reported)</td>
<td>No (LBW) 0.88 (0.53–1.48)</td>
</tr>
<tr>
<td>Melo et al. (2010) (Brazil)</td>
<td>Birth cohort</td>
<td>SGA: 43&lt;br&gt;AGA: 122 (born term)</td>
<td>Rotterdam and NIH consensus</td>
<td>Yes (birth weight records in medical reports)</td>
<td>Yes (Rotterdam consensus) 2.44 (1.39–4.28)&lt;br&gt;Yes (NIH consensus) 1.66 (0.9–3.05)</td>
</tr>
<tr>
<td>Davies et al. (2012) (Australia)</td>
<td>Birth cohort</td>
<td>948 singleton births (users or non-users of hormonal contraceptives)</td>
<td>Only self-reported symptoms (270 women had a blood sample collected and 112 had a transvaginal ultrasound)</td>
<td>No (birth weight records in medical reports)&lt;br&gt;Weight was available as a continuous variable</td>
<td>Although each 100 g increase in birth weight increased the risk of hyperandrogenism, thinness was related to PCOS symptoms and insulin resistance</td>
</tr>
<tr>
<td>Mumm et al. (2013) (Denmark)</td>
<td>Birth cohort</td>
<td>Birth weight (g):&lt;br&gt;*&lt;2500: 29 535&lt;br&gt;*2000–2999: 90 176&lt;br&gt;*3000–3499: 200 370&lt;br&gt;*3500–3999: 151 527&lt;br&gt;*4000–4499: 44 953&lt;br&gt;*4500–4999: 7196 (born term and preterm)</td>
<td>Not mentioned (included cases of hirsutism and PCOS based on ICD)</td>
<td>Yes (birth weight records in medical reports)</td>
<td>No RR: 1.57 (1.21–2.01) (high birth weight ≥4500 g related to PCOS)</td>
</tr>
</tbody>
</table>
standardised diagnosis of PCOS; and ii) the lack of case stratification as fatal and non-fatal (De Groot et al. 2011). When such stratification was performed, an increased risk of non-fatal stroke was observed in menopausal PCOS women (OR, 1.94; 95% CI, 1.19–3.17) (Anderson et al. 2014), but no increased risk for acute myocardial infarction and/or mortality caused by cardiovascular events in women aged 61–79 years was observed during a 21-year follow-up (Schmidt et al. 2011). However, these studies did not provide proper external validity to allow these findings to be extrapolated to menopausal/elderly PCOS women of other ethnic groups who might have been exposed to different environmental factors.

Although the aetiology of cardiovascular disorders is multifactorial, visceral obesity and hyperinsulinaemia play an important role in the development of cardiovascular events in women with PCOS. Visceral obesity and increased insulin levels may promote adipose tissue dysfunction and the subsequent elevation of inflammatory and metabolic markers that have an atherogenic effect in women of reproductive age (Melo et al. 2014). This adipose tissue dysfunction is associated with an increased prevalence of SAH, dyslipidaemia, metabolic syndrome, IR, type 2 DM and maintenance of hyperandrogenism, and it promotes endothelial dysfunction in inflammatory, oxidative and procoagulant environments, so it thus favours the occurrence of arterial thrombosis during menopause (Fig. 4; Cussons et al. 2006). However, regional studies are needed to determine the profile of morbidity and mortality of specific populations and to establish effective preventive interventions for PCOS and the metabolic and cardiovascular changes with which it is associated.

![Figure 4 Pathogenesis of PCOS: evolutionary and multifactorial assessment from the reproductive age to menopause/senescence. Modified from Cussons et al. (2006). SAH, systemic arterial hypertension; IR, insulin resistance.](www.reproduction-online.org)
Conclusion

PCOS has a multifactorial aetiology with ethnic and regional aspects. Although being born SGA or being the child of a hyperandrogenic mother might be considered clinical markers for developmental programming by steroids, individuals who are not exposed to excess steroids and the offspring of non-hyperandrogenic mothers can also develop PCOS. This indicates that postnatal environmental factors and genetic predisposing factors also lie at the origin of this disorder. Follow-up studies that assess the same population at different stages of life will facilitate a better understanding of the interactions between environmental, genetic and intrauterine factors in the development of PCOS and its comorbidities over a lifespan.

Declaration of interest

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

Funding

This review did not receive any specific grant from any funding agency in the public, commercial or not-for-profit sector.

References


Goodarzi MO, Jones MR, Li X, Chua AK, Garcia OA, Chen YD, Krauss RM, Rotter JI, Ankener W, Legro RS et al. 2012 Replication of association of R22 A S Melo and others

www.reproduction-online.org


Downloaded from Bioscientifica.com at 08/02/2019 10:29:54PM via free access
DENND1A and THADA variants with polycystic ovary syndrome in European cohorts. *Journal of Medical Genetics* 49 90–95. (doi:10.1136/jmgenet-2011-100427)


Moran LJ, Hutchison SK, Norman RJ & Teede HJ 2011 Lifestyle changes in women with polycystic ovary syndrome. *Cochrane Database of Systematic Reviews* 7 CD007506. (doi:10.1002/14651858.CD007506.pub3)


Received 24 September 2014
First decision 3 November 2014
Revised manuscript received 17 March 2015
Accepted 2 April 2015