Abstract

Polycystic ovary syndrome (PCOS) is a common but complex endocrine disorder and is a major cause of anovulation and consequent subfertility. It is also associated with a metabolic disturbance, characterized by hyperinsulinaemia and insulin resistance that carries an increased risk of type 2 diabetes in later life. Despite its prevalence little is known about its aetiology, but there is increasing evidence for an important genetic involvement. On the basis of experimental observations in the prenatally androgenized sheep and rhesus monkey, and supported by data from human studies, we propose that the clinical and biochemical features of PCOS can arise as a consequence of genetically determined hypersecretion of androgens by the ovary during, or very likely long before, puberty. The resulting hyperandrogenism results in ‘programming’ of the hypothalamic–pituitary unit to favour excess LH secretion, and encourages preferential abdominal adiposity that predisposes to insulin resistance. The severity of hyperinsulinaemia and insulin resistance (which has a profound influence on the phenotype of PCOS) is further influenced by both genetic factors (such as polymorphism in the insulin gene regulatory region) and environmental factors, notably obesity. This hypothesis therefore suggests a unifying, ‘linear’ model to explain the aetiology of the heterogeneous phenotype.

Introduction

Polycystic ovary syndrome (PCOS) is the most common, yet complex, endocrine disorder affecting women in their reproductive years. Its complexity stems from the syndrome’s typical heterogeneity (Table 1) and its unknown aetiology. There is increasing evidence to support a major genetic basis for PCOS, since the syndrome is strongly familial (Franks et al. 1997, Legro et al. 1998a). It is clear, however, that more than one gene (and probably several) contribute to the heterogeneous phenotype (Franks et al. 1997, Urbanek et al. 1999) and the clinical and biochemical presentation is undoubtedly influenced by additional environmental factors, such as diet and exercise (Huber-Buchholz et al. 1999). Given the complex interactions of such variables on the PCOS phenotype, a single developmental origin for the heterogeneous PCOS characteristics (Table 1) might seem unlikely. Nevertheless, results from recent experiments using animal models, together with supporting clinical evidence, lead us to propose that the development of PCOS is a linear process with an origin before adolescence (the contemporary clinical perception of age of onset of PCOS). Superimposed on this developmental process are interacting genetic and environmental factors that may alter phenotypic expression of PCOS during adult life, particularly the susceptibility to anovulation (White et al. 1995, Franks et al. 1997, Chang et al. 2000).

In utero androgen excess programmes for PCOS in non-human primates and sheep

Adult, female rhesus monkeys exposed, in utero, to levels of testosterone equivalent to those found in fetal males show many clinical and biochemical features of PCOS. They particularly exhibit hypersecretion of luteinizing hormone (LH), abnormal insulin secretion or action and, in obese (hyperinsulinaemic) individuals, hyperandrogenic anovulation (Abbott et al. 1998, Eisner et al. 2000). These observations have been verified in recent studies of sheep, in which exposure of the pregnant ewe to large doses of testosterone causes increased LH secretion and abnormal ovarian cycles in female offspring (Padmanabhan et al. 1998, Robinson et al. 1999). Interestingly, prenatally androgenized females in both species develop enlarged ovaries with multiple, medium-sized antral follicles.
Reproductive disorders
Polycystic ovaries
Hyperandrogenism (hirsutism, acne, androgenic alopecia)
Anovulation (amenorrhoea, oligomenorrhoea)
Hypersecretion of LH
Increased risk of early miscarriage

Metabolic disorders
Hyperinsulinaemia and insulin resistance
Impaired pancreatic β-cell insulin secretion and type 2 diabetes
Obesity (including preferential abdominal adiposity)
Hyperlipidaemia

Disorders of general health
Increased cardiovascular disease risk factors
Endometrial cancer

How, then, do these studies further our understanding of the aetiology of PCOS in women? They certainly suggest that abnormal LH and androgen secretion, menstrual cyclicity and insulin secretion and action represent exposure of the female fetus to very high levels of androgen. A similar phenomenon in PCOS seems unlikely since any maternal source of excess androgen production is unlikely to affect the human female fetus. Even pregnant women with extremely high circulating levels of testosterone (due, for example, to an ovarian thecoma) are unlikely to have a virilized female child (McLamrock & Adashi 1992). Together, high circulating concentrations of sex hormone-binding globulin and efficient placental metabolism of androgens provide an effective buffer against excess maternal androgen reaching the fetal circulation. In other words, it is difficult to imagine that hyperandrogenism is commonly passed across the placenta from a mother with PCOS to a previously unaffected daughter, unless other circumstances exist that compromise placental function, such as placental aromatase deficiency, stress or inadequate diet.

It is more likely that a hyperandrogenic fetal ovary (Barbieri et al. 1986, Beck-Peccoz et al. 1991), hyperandrogenic adrenal cortex (Barnes et al. 1994), or both, are sources of excess prenatalthird androgen production. Barnes et al. (1994) noted that patients with adrenal hyperandrogenism, due to 21-hydroxylase deficiency, also showed evidence of polycystic ovaries and excess ovarian androgen production. Adrenal androgens may be used as a substrate for ovarian androgen production. Both the fetal and adult ovary are able to convert steroid precursors, including adrenal dehydroepiandrosterone sulphate, to potent androgens (and thence to oestrogens) (Payne & Jaffe 1974, Bonser et al. 2000).

Androgens produced during differentiation are potent gene transcription factors and induce other critical transcription factors (such as c-fos) that interact with their own receptors in many fetal tissues, permanently enhancing gene expression (including increased serine phosphorylation of the cAMP response element) (Auger et al. 2001). It is therefore feasible that fetal androgen excess in human females simultaneously reprogrammes multiple organ systems that will later manifest the heterogeneous phenotype of PCOS (Table 1). Virilization of female genitalia, as a potential phenotypic consequence of fetal androgen excess, does not occur in women with PCOS. Such virilization, however, does not reliably accompany fetal androgen excess in either humans (Barnes et al. 1994) or rhesus monkeys (Herman et al. 2000), illustrating the subtle but permanent, effects androgen reprogramming can exert on female physiology.

Evidence for a primary ovarian disorder affecting androgen production in PCOS

Irrespective of the mode of clinical presentation or degree of menstrual cycle dysfunction, excess production of androgen is the most consistent biochemical feature of both women with PCOS (Franks 1991, Legro et al. 1998b) and prenatally androgenized female rhesus monkeys (Abbott et al. 1998). Even women or female monkeys with typical ovarian morphology and normal menstrual cyclicity have biochemical evidence of hyperandrogenism. Although the adrenal may contribute to excess testosterone circulating in women with PCOS (Aziz et al. 1998) and in prenatally androgenized female rhesus monkeys, the major source of excess androgens is the ovary (Ehrmann et al. 1995, Gilling-Smith et al. 1997, Eisner et al. 2002).

Both in vivo and in vitro studies of theca cell function show an intrinsic abnormality of ovarian steroidogenesis. The ovarian androgen response is exaggerated in women with PCOS following stimulation by exogenous human chorionic gonadotrophin (hCG) (Gilling-Smith et al. 1997) or by endogenous gonadotrophin (after treatment with exogenous gonadotrophin–releasing–hormone (GnRH) analogue) (Ehrmann et al. 1995, White et al. 1995). A pronounced ovarian androgen response is also evoked by exogenous hCG in adult female rhesus monkeys, androgenized prenatally (Eisner et al. 2002). In women with PCOS, increased thecal steroid production in response to hCG remains evident after long-term LH suppression by a GnRH analogue (Gilling-Smith et al. 1997).

Cultured human theca cells from polycystic ovaries produce 20 times more androstenedione than similar cells from normal ovaries (Gilling-Smith et al. 1994). Recently, these observations have been confirmed in long-term cultures of human theca cells, in which increased mRNA expression for many steroidogenic enzymes was evident (Wickenheisser et al. 2000). These findings reflect the increase in progesterone and 17–hydroxyprogesterone accumulation (as well as androstenedione) observed in primary theca cell cultures (Gilling-Smith et al. 1994) and suggest a global enhancement of steroidogenesis.

Table 1 Important disorders of reproduction, metabolism and general health that are manifest in women with polycystic ovaries: their combination and degree of expression are highly variable between individuals, including first-degree relatives

<table>
<thead>
<tr>
<th>Reproductive disorders</th>
<th>Metabolic disorders</th>
<th>Disorders of general health</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polycystic ovaries</td>
<td>Hyperinsulinaemia and insulin resistance</td>
<td>Increased cardiovascular disease risk factors</td>
</tr>
<tr>
<td>Hyperandrogenism</td>
<td>Impaired pancreatic β-cell insulin secretion and type 2 diabetes</td>
<td>Endometrial cancer</td>
</tr>
<tr>
<td>Anovulation</td>
<td>Obesity (including preferential abdominal adiposity)</td>
<td></td>
</tr>
<tr>
<td>Hypersecretion of LH</td>
<td>Hyperandrogenic adrenal cortex</td>
<td></td>
</tr>
<tr>
<td>Increased risk of early miscarriage</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
These findings in cultured human theca cells prompted consideration of genes encoding steroidogenic enzymes as candidate loci in the aetiology of PCOS. One polymorphism – a pentanucleotide repeat – was identified in the promoter region of \(CYP11a\). Evidence has been found for association and linkage of variants at the \(CYP11a\) locus with hyperandrogenism in women with PCOS (Gharani et al. 1997). While it is unlikely to be the exclusive cause of PCOS, variation at this locus may contribute to excess androgen production, supporting the view that there is a genetically determined abnormality of ovarian function. It is possible that abnormal theca cell function is the consequence of abnormal ovarian follicular development. As yet, there is little evidence for a genetic basis for impaired follicular development in PCOS since the recent findings implicating the follistatin gene in the aetiology of the syndrome (Urbanek et al. 1999) remain unconfirmed (Urbanek et al. 2000b). Nevertheless, such studies reinforce the possibility that abnormal ovarian folliculogenesis may indeed be the key ovarian abnormality.

Abnormal LH secretion is secondary to ovarian dysfunction

In anovulatory PCOS women, the predominant reason for high serum LH concentrations (representing increased LH pulse amplitude and – in some studies – pulse frequency) is abnormal negative feedback that would otherwise be provided by cyclical changes in gonadal steroids. If, for example, LH levels are monitored regularly over a period of several weeks, tonically high serum LH concentrations may fall into the normal range if a spontaneous ovulatory cycle occurs (Franks 1989, Taylor et al. 1997). Nevertheless, LH secretion remains higher than normal (although significantly lower than in anovulatory subjects) in women with polycystic ovaries and regular cycles, but who have symptoms and signs of hyperandrogenism (Franks 1989, 1991). This also is a feature of prenatally androgenized rhesus monkeys and ewes, suggesting that in utero exposure to androgen may permanently diminish hormonal negative feedback on the hypothalamic–pituitary axis, thereby stimulating androgen hypersecretion. Indirect evidence for such in utero programming in humans is provided by elevated serum LH levels in women with hyperandrogenaemia from classical 21-hydroxylase deficiency, an adrenal cause of hyperandrogenism (Ehrmann et al. 1995). The mechanism for this LH hypersecretion is not entirely clear, but recent data suggest that it involves impaired negative feedback on LH secretion mediated by either oestradiol or progesterone in women with PCOS (Eagleson et al.)

Figure 1 Diagrammatic representation of our hypothesis for the developmental origin of PCOS. During gestation, placental hCG, fetal pituitary LH and genes regulating folliculogenesis and steroidogenesis individually, or in concert, result in fetal ovarian hyperandrogenaemia leading to prenatal (and potentially prepubertal) exposure of the developing female to excess androgen. Post-pubertally, the early exposure to androgen excess (i) diminishes steroid hormone negative feedback on pituitary LH producing abnormal LH secretion and (ii) predisposes to preferential accumulation of abdominal (central) adiposity that exaggerates insulin resistance (the latter are enhanced by genes regulating adipocyte differentiation, and insulin secretion and action). The resultant hyperinsulinaemia synergistically interacts with LH hypersecretion to augment ovarian steroidogenesis and to induce premature arrest of follicle development and anovulation.

1 genes regulating
- folliculogenesis
- steroidogenesis (\(CYP11a\))

2 genes regulating
- insulin secretion (\(INS-VNTR\))
- insulin action
- adipocyte differentiation
induce premature arrest of follicle development (Willis et al. 1998).

Prenatal androgen excess provides the developmental origin for PCOS

We therefore conclude that although PCOS is a complex, heterogeneous disorder, most – if not all – of the clinical and biochemical features can be explained on the basis of a developmental disorder of ovarian androgen production (Fig. 1). This fetal (and/or prepubertal; Ibanez et al. 1999) androgen excess ‘programmes’ the hypothalamic–pituitary control of LH, enhances visceral fat distribution (thus predisposing to insulin resistance and anovulation) and causes the clinical manifestations of hyperandrogenism in adulthood. Other secondary genetic and environmental (particularly dietary) factors may interact with this underlying linear process to modify the final phenotype and produce the heterogeneous nature of the syndrome that affects so many women (Fig. 1). Such a defined, developmental aetiology for PCOS holds great promise for targeted clinical interventions that not only eliminate expression of the adult phenotype, but also improve the constellation of metabolic derangements associated with this disorder.

References


Bonser J, Walker J, Purohit A, Reed MJ, Potter BV, Willis DS, Frank S & Mason HD 2000 Human granulosa cells are the site of sulphatase activity and are able to utilize dehydroepiandrosterone sulphate as a precursor for oestradiol production. Journal of Endocrinology 167 465–471.


Received 25 February 2002

Accepted 25 April 2002