REVIEW

Premature adrenarche: novel lessons from early onset androgen excess

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Abstract

Adrenarche reflects the maturation of the adrenal zona reticularis resulting in increased secretion of the adrenal androgen precursor DHEA and its sulphate ester DHEAS. Premature adrenarche (PA) is defined by increased levels of DHEA and DHEAS before the age of 8 years in girls and 9 years in boys and the concurrent presence of signs of androgen action including adult-type body odour, oily skin and hair and pubic hair growth. PA is distinct from precocious puberty, which manifests with the development of secondary sexual characteristics including testicular growth and breast development. Idiopathic PA (IPA) has long been considered an extreme of normal variation, but emerging evidence links IPA to an increased risk of developing the metabolic syndrome (MS) and thus ultimately cardiovascular morbidity. Areas of controversy include the question whether IPA in girls is associated with a higher rate of progression to the polycystic ovary syndrome (PCOS) and whether low birth weight increases the risk of developing IPA. The recent discoveries of two novel monogenic causes of early onset androgen excess, apparent cortisone reductase deficiency and apparent DHEA sulphotransferase deficiency, support the notion that PA may represent a forerunner condition for PCOS. Future research including carefully designed longitudinal studies is required to address the apparent link between early onset androgen excess and the development of insulin resistance and the MS.

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Introduction

Adrenarche refers to the developmental maturation of the adrenal gland, observed only in the human, chimpanzee and gorilla (1–4). At adrenarche, the innermost layer of the human adrenal cortex, the zona reticularis (ZR), starts to produce increasing amounts of the androgen precursor DHEA and its sulphate ester DHEAS (5). The term 'adrenarche' was coined by Fuller Albright and Nathan Talbot in the 1940s when they linked the developmental rise in adrenal androgens to the appearance of pubertal and axillary hair, which they called 'sexual hair' (6–8). Soon thereafter, Lawson Wilkins' group described a group of girls who developed pubic and axillary hair before the age of 8 years (9), a condition they termed 'premature pubarche' (PP). They considered PP a benign constitutional variant with no impact on later life if 'adrenal tumours' or 'adrenal hyperplasia' were excluded as underlying causes (9).

Adrenarche is a physiological mystery as it is not well understood how the development of the ZR is initiated or controlled (see (5) for review) nor why adrenal androgens are significant for human pre-pubertal development. Adrenal androgens contribute to changes in body composition and transient growth acceleration but without having a major impact on final height or subsequent developmental milestones like puberty. From the evolutionary perspective, it has been suggested that adrenarche is a key component of 'juvenility', a period that emerges during evolution in the late *Hominids* and prolongs the transition from childhood to adolescence and adult life; juvenility may serve the adaptation of body composition and metabolic status to environmental conditions (10, 11). Another interesting hypothesis refers to the neuromodulatory effects of DHEAS that may help to protect more metabolically active regions of the cerebral cortex to support brain maturation in the developing pre-pubertal child (12).

Premature adrenarche (PA), the precocious appearance of adrenarche, is a phenomenon increasingly receiving attention, as more evidence emerges for an intriguing link between early onset androgen excess and metabolic disease. This review aims to provide an overview of the current understanding of PA and its clinical implications. We specifically highlight novel insights into this multi-faceted condition provided by the recent discovery of two novel monogenic conditions that manifest with PA.

Adrenarche, pubarche and puberty

Circulating DHEAS is high in the immediate neonatal period, but quickly drops below the limit of detection during the first few months of life (13, 14), subsequent to the involution of the foetal zone of the adrenal cortex. The re-appearance and accelerating increase in circulating DHEAS, i.e. adrenarche, have previously been perceived as a relatively sudden surge, physiologically occurring between 6 and 8 years of age (15, 16). However, previous studies employing immunoassays for determination of serum DHEAS obviously only picked up increasing levels once they reached above the lower limit of detection. However, a recent study applied a highly sensitive method for the analysis of 24 h urinary androgen metabolite excretion, gas chromatography/ mass spectrometry (GC/MS); results clearly indicate that adrenarche is a continuous developmental process, starting with a detectable increase in the excretion of DHEA and related androgenic steroids at least as early as 3 years of age (17). In addition, there was no sex difference in androgen excretion within the pre-pubertal and early pubertal age groups, and consequently, these results may challenge the sex differences in the well-accepted age cut-offs for PA, i.e. 8 years in girls and 9 years in boys. However, these are derived from Marshall and Tanner's clinical observations that the appearance of pubic hair occurs about 1 year earlier in girls than in boys (18, 19).

In normal development, the first appearance of pubic hair, i.e. pubarche, from the age of 8 years onwards is the direct result of the physiological rise in adrenal androgen production during adrenarche. DHEA is converted to active androgens in the gonads and peripheral target tissues of androgen action including the skin, resulting in the development of pubic and also axillary hair. Women with adrenal insufficiency without physiological DHEA production suffer from lack of axillary and pubic hair, which reappears after initiation of DHEA replacement therapy (20). A recent study in adolescent girls with secondary adrenal insufficiency demonstrated onset and progression of pubic and axillary hair following DHEA replacement (21). Physiologically, increasing androgen production during adrenarche manifests with distinct changes in body odour and oily skin and hair, followed by the first appearance of pubic and axillary hair. In addition, the rise in adrenal androgens can result in transient growth acceleration and contributes to bone maturation (22–24).

Several studies have demonstrated that adrenarche and pubarche are a causally related sequence (25, 26) and dissociation of the two events is rarely observed. One of these exceptions is Turner syndrome in which an early onset of adrenarche with increased DHEA and DHEAS levels has been documented, but concurrently delayed pubarche in those girls who developed premature ovarian failure (27). Increased levels of DHEA and DHEAS despite low circulating levels of active androgens have also been described in premature ovarian failure of autoimmune origin (28, 29). The ovary not only synthesises DHEA but also takes up DHEA produced in the adrenals and converts it to active androgens (30). Possible disruption of this capacity in premature ovarian failure will result in increased levels of the androgen precursor DHEA but decreased active androgens, which would explain the apparent dissociation of adrenarche and pubarche in this condition.

Importantly, adrenarche generally appears to represent a developmental process independent of the maturation of the gonads (25, 26). Gonadarche, i.e. the onset of sex steroid production by the gonads, manifests with testicular enlargement and penile growth in boys and breast development and menarche in girls. Children with precocious puberty have been shown to have no corresponding advance in the timing of adrenarche; their basal and ACTH-stimulated adrenal androgens are lower than in children matched for pubertal stage and only slightly higher than in age-matched children (31, 32). Conversely, children with isolated hypogonadotrophic hypogonadism and subsequent lack of spontaneous puberty were found to have no corresponding delay in adrenarche (25, 26).

Although pubertal onset crucially relies on the emerging activity of the GNRH pulse generator in the hypothalamus and subsequent LH/FSH release from the anterior pituitary, no centrally derived factor regulating adrenarche has been identified yet. An N-terminal proopiomelanocortin fragment termed cortical androgen stimulating hormone (CASH) has been proposed as crucial to the regulation of adrenarche (33), but no convincing *in vitro* data for its action have been presented yet (34). A lack of adrenarche has been observed in patients with familial glucocorticoid deficiency due to disruption of ACTH signalling (35). However, in patients with combined pituitary hormone deficiency due to Pit1 (*POU1F1*) mutations, who are characterised by normal ACTH and cortisol secretion and spontaneous onset and progression of puberty, the absence or delay of adrenarche and pubarche has been documented (36). Thus, ACTH has a permissive effect on the initiation of adrenal androgen production, but its presence alone does not suffice. In addition, an ACTH receptor polymorphism has been found to be associated with the severity of PA also indicating a modulatory effect of the hypothalamic–pituitary–adrenal (HPA) axis in this condition (37). In the same cohort, Lappalainen *et al.* (38) could also show that mean CAG repeat length of the androgen receptor (*AR*) gene is shorter in PA girls and that a polymorphic allele of the transcription factor *TCF7L2*, involved in the Wnt signalling pathway, was more frequent in PA subjects (39). However, genome–wide association studies in appropriately powered cohorts of children with early androgen excess are currently lacking. Elucidating genetic variability in large-scale cohorts by applying next generation sequencing technologies will certainly be subject of future

studies aiming to identify novel regulators and predictors of PA.

Finally, there is some evidence that adrenarche and gonadarche are interdependent in the physiological situation. A prospective cohort study in 109 healthy children showed that adrenal androgens do influence pubertal timing and importantly indicate that adrenarche triggers the pattern of subsequent pubertal development: higher pre-pubertal urinary androgen excretion correlated with an earlier onset of breast development and penile growth respectively, and a shorter duration of pubertal growth spurt (40). Furthermore, adrenal androgens are positively correlated with diaphyseal bone strength during adrenarche and in late puberty (22, 41). These data suggest that adrenal androgens may either directly or after peripheral conversion (e.g. to oestrogens) modulate the GNRH pulse generator, thereby fine-tuning pubertal development. Nutritional status has been suggested as linked to adrenal androgen production (40) and obese children have significantly increased serum DHEAS levels (42), with evidence of advanced bone maturation and less but significantly decreased final height (43). As consistently shown in a number of different study populations, final height is not significantly affected in children with PA (23, 44–47) but they have earlier transient pre-pubertal growth acceleration, i.e. they are taller than their peers upon entering puberty. Also, compared with controls matched for chronological age, bone age in PA is significantly advanced (23, 45, 48), whereas height-adjusted bone mineral density is similar to age-matched controls, with evidence for a higher body fat mass in PA (49).

PA: definitions and differential diagnosis

It is important to note that PA is not equivalent to PP. Indeed, there is some inconsistency in the literature where PP is often used synonymously for PA. First, some of these studies only scored the onset of pubic hair growth but lack biochemical confirmation of increased adrenal androgen production. Second, equating the two terms would limit the attention to the development of pubic hair only, but ignore other signs of increased androgen action including adult-type body odour and oily hair and skin (23, 46, 47, 50, 51). Conversely, some investigators have defined PA very strictly as the biochemical detection of a premature increase in circulating adrenal androgens irrespective of the clinical presentation (52). The additional use of the term 'exaggerated adrenarche' has created further confusion, as it has been used to describe adrenal androgen levels above the pubertal range in children of pre-pubertal age (53, 54) but also as a definition for the presence of exaggerated clinical features of androgen action associated with physiological, normal-timed adrenarche (55).

A recently proposed definition of PA is the concurrent presence of adrenal androgen levels increased above the age- and sex-specific reference range and clinical signs of an increase in androgen action, such as adult-type body odour, oily hair and skin and/or PP, occurring before the age of 8 years in girls and 9 years in boys (56). We consider this a very useful definition for clinical purposes (Table 1). The definition of the exact age limits should take influences of ethnicity into account. In Caucasian populations, two studies found pubic hair Tanner stage 2 or above before the age of 8 years in girls in 0.6 and 0.8% of US American and Lithuanian girls respectively (57, 58). By contrast, a fivefold higher incidence of PP was reported in girls of Afro-American descent (59). All these studies focussed on the premature appearance of pubic hair only and did not report on the incidence of other signs of increased androgen action such as adult-type body odour or oily skin. Thus the overall incidence of PA may well be higher. Generally, the reported prevalence of PA is about tenfold higher in girls than in boys (60), which may at least in part be explained by a sex-specific detection and reporting bias.

Constitutional or idiopathic PA (IPA) is most often observed, and is a diagnosis of exclusion. Distinct conditions manifesting PA include milder and non-classic variants of congenital adrenal hyperplasia (CAH) that have been diagnosed in 0–40% of children with PP (51, 61–65), depending on the pre-selection bias applied to the studied cohorts. Baseline blood sampling for measurement of DHEAS, androstenedione, 17α-hydroxyprogesterone (17OHP), testosterone, and sex hormone binding globulin (SHBG) will be generally sufficient to confirm increased adrenal androgens and to differentiate between IPA, CAH, and virilising tumours (55, 61). Other causes potentially underlying a presentation with PA are summarised in Table 1.

If in addition to the clinical signs and symptoms associated with PA, progressive signs of pubertal development are also present, such as breast development or menarche in girls and penile or testicular growth in boys, a diagnosis of precocious puberty or precocious pseudo-puberty has to be considered (Table 1). The clinical picture of these two distinct conditions is relatively similar. However, they can be distinguished by analysing the gonadotrophin response to GNRH stimulation. Centrally driven true precocious puberty results from premature activation of the hypothalamic GNRH pulse generator, resulting in upregulated gonadotrophins that increase further after exogenous GNRH stimulation. Constitutional or idiopathic precocious puberty is the most frequent underlying cause, in particular, in girls aged 6 years or older while more than half of affected boys have an identifiable cause of precocious puberty. A lesion of the central nervous system affecting the hypothalamic–pituitary region has to be excluded and is a frequent cause of the condition in particular in children presenting at age 6 years or

Table 1 Definition and differential diagnosis of disorders associated with early androgen excess.

Definition	Causes	Laboratory investigations

Premature adrenarche
Increased adrenal androgen secretion above the age- and sex-specific normal reference range before the age of 8 years in girls and 9 years in boys (=premature biochemical adrenarche)
AND
Clinical signs of androgen action before the age of 8 years in girls and 9 years in boys including
  Adult-type body odour
  Oily hair and skin, acne
  Pubic hair (premature pubarche), axillary hair
AND
No signs of pubertal development (i.e. no development of secondary sexual characteristics including breast development in girls or penile growth in boys)
	Most frequent
	  Idiopathic (constitutional) premature adrenarche
	Rare
	  ACTH-driven stimulation of adrenal androgen production due to
	    Congenital adrenal hyperplasia
	      21-Hydroxylase deficiency
	      11β-Hydroxylase deficiency (152, 153)
	      3β-Hydroxysteroid dehydrogenase deficiency (152, 153)
	    Cushing's disease
	    Glucocorticoid resistance (due to inactivating glucocorticoid receptor (*GR*) mutations) (154, 155)
	  Apparent cortisone reductase deficiency (due to inactivating hexose-6-phosphate dehydrogenase (*H6PD*) mutations) (135)
	  Apparent DHEA sulfotransferase deficiency (due to inactivating PAPS synthase type 2 (*PAPSS2*) mutations) (136)
	  Autonomous endogenous or exogenous androgen excess
	    Virilising tumours originating from adrenals or gonads
	    Exogenous testosterone treatment (156)
		Elevated adrenal androgen levels (DHEA, DHEAS and androstenedione)
		Gonadotrophins are in the normal pre-pubertal range

Precocious pseudo-puberty
Development of secondary sexual characteristics (penile growth, breast development and menarche) before the age of 8 years in girls or 9 years in boys
AND
Low gonadotrophins before and after GNRH stimulation
GNRH independent; usually non-harmonic chronology of sexual characteristics, e.g. lack of bilateral testicular enlargement in boys (exceptions: gonadal tumours and familial testotoxicosis)
Also termed peripheral precocious puberty
	Rare
	  ACTH-driven stimulation of adrenal androgen production due to
	    Congenital adrenal hyperplasia
	      21-Hydroxylase deficiency
	      11β-Hydroxylase deficiency
	  Autonomous endogenous or exogenous androgen excess
	    Virilising tumours originating from adrenals or gonads
	    Exogenous sex steroid treatment
	  LH- or HCG-driven stimulation of adrenal androgen production due to
	    β-HCG-secreting tumours
	    Familial testotoxicosis (due to activating LH receptor (*LH/CGR*) mutations)
	  McCune–Albright syndrome (due to activating Gsα protein (*GNAS1*) mutations)
		Pubertal range serum testosterone in boys (and 17β-oestradiol in girls)
		Gonadotrophins remain low after GNRH stimulation

Precocious puberty
Development of secondary sexual characteristics (testicular/penile growth, breast development and menarche) before the age of 8 years in girls or 9 years in boys
AND
Increase of gonadotrophins after GNRH stimulation
GNRH dependent; usually harmonic chronology of sexual characteristics, e.g. bilaterally enlarged testicular volume in boys
Also termed central precocious puberty
	Most frequent
	  Idiopathic (constitutional) precocious puberty
	Rare
	  Central nervous system lesions, e.g. glioma, astrocytoma, hypothalamic hamartoma and arachnoid cysts
	  Post-infectious (e.g. meningitis and encephalitis)
	  Post-traumatic
	  Hypothyroidism
	  Activating mutations in the genes encoding kisspeptin 1 (*KISS1*) (157) and its receptor KISS1R (*GPR54*) (158)
		Pubertal range testosterone in boys and 17β-oestradiol in girls
		Gonadotrophins increase after GNRH stimulation

younger. Precocious pseudo-puberty is defined by the occurrence of sexual characteristics driven by GNRH-independent peripheral sex steroid production, most frequently without concurrent signs of gonadal maturation, i.e. no testicular enlargement in boys (Table 1). Accordingly, in precocious pseudo-puberty, the gonadotrophins are low and remain low after GNRH stimulation. The condition is rare and most of the identified cases in boys are due to simple virilising and non-classic CAH variants. In CAH, transition from precocious pseudo-puberty to secondary central precocious puberty has been observed and is thought to be due to the induction of the GNRH pulse generator by persistently increased sex steroids (66). Pubertal progression in central precocious puberty is efficiently halted by GNRH analogues blocking GNRH action (67, 68).

Metabolic implications of PA

Traditionally, IPA has been considered to be an extreme variation of the normal (9, 23, 45). However, a number of studies in children with early onset androgen excess provide increasing evidence for the notion that IPA in girls may precede the development of polycystic ovary syndrome (PCOS). PCOS manifesting during adolescence or early adulthood carries a significantly increased risk for developing the metabolic syndrome (MS) (52, 69–71) and represents the leading cause of female infertility (72–74). IPA and adolescent PCOS are linked by two similarities, early onset androgen excess and an increased prevalence of insulin resistance. The following section reviews the available evidence associating IPA with insulin resistance, MS and PCOS.

Metabolic risk factors in PA

The first evidence for a link between premature androgen excess and MS emerged in 1995 from a study in American–Hispanic girls who presented with PP and evidence of insulin resistance (75) (Table 2). Later on, Ibanez *et al.* (76) published a number of case–control studies in lean Spanish (Catalonian) girls with a history of PP that showed evidence of insulin resistance based on both fasting insulin levels and the insulin response to a standard oral glucose tolerance test (OGTT) (76–80). Interestingly, these observations could not be confirmed in boys from the same population (81) but similar findings were obtained in pre-pubertal boys with PA from North America (82). In PP girls from North America, an inverse correlation between insulin sensitivity and ACTH-stimulated Δ5-androgen precursors (17-hydroxypregnenolone, DHEA) has been found; however, the study population was not body mass index (BMI) matched (83). Overall, impaired insulin sensitivity is a consistent finding in the majority of studies (Table 2).

Ibanez *et al.* (78) could show that Catalonian PP girls develop significant dyslipidaemia, a finding indicative of an increased cardiovascular risk profile and consistently found in PCOS (84). Moreover, Catalonian PP girls had increased waist circumference, waist-to-hip-ratio and total fat mass in comparison to their BMI-matched peers (85). Dyslipidaemia and elevated blood pressure were also found in smaller cohorts of Turkish (86) and Brazilian (87) PP girls. However, the validity of these latter studies was also hampered by a lack of BMI-matched controls and insulin resistance was only observed in obese PP girls. In a recent case–control study from Turkey, PP girls had elevated lipoprotein(a) levels, another risk factor for cardiovascular morbidity (88). By contrast, in Finnish girls with IPA, evidence of insulin resistance was identified using the OGTT, but no alterations in lipid metabolism or blood pressure were found (56). Similarly, in recent studies from Greece, Andalusia and Scotland girls with IPA had normal lipid profiles (55, 89, 90).

Accumulation of visceral fat has been related to an increased risk of cardiovascular disease evolving through distinct metabolic and inflammatory perturbations (91) and adipose tissue is increasingly recognised as an active endocrine organ secreting adipokines that act as immunoendocrine signals linking obesity to the development of atherosclerosis. A pro-inflammatory shift in the adipokine profile including increased secretion of interleukin 6 (IL6), plasminogen activator inhibitor 1 (PAI1) and leptin has been shown to positively correlate with measures of insulin resistance (92, 93) and is a feature frequently found in the context of PCOS (94). Several studies in IPA girls from different ethnic backgrounds studied in comparison to BMI-matched controls have shown a pro-inflammatory shift of their adipokine profile comprising higher levels of TNFα, IL8, C-reactive protein (CRP), PAI1 and a decrease in tissue plasminogen activator (t-PA) (79, 89, 95).

To date, only a single study has assessed the presence of the diagnostic consensus criteria for the childhood MS in IPA girls, demonstrating an increased frequency of childhood MS in comparison to BMI-matched controls, both according to modified United States (US) National Cholesterol Education Program (NCEP) Adult Treatment Panel (ATP) III (ATPIII) criteria (24 vs 10%) and modified World Health Organization (WHO) criteria (16 vs 5%) (56).

PA and the PCOS

Ibanez *et al.* (72) published a number of studies investigating 35 adolescent Catalonian girls with a history of PP and found that 16 (45%) went on to develop PCOS with hirsutism, menstrual disturbances and elevated androgen levels (Table 3). Ovarian stimulation with the GNRH analogue leuprolide acetate in this cohort resulted in exaggerated levels of 17OHP and androstenedione and correlated with baseline

Table 2 Summary of clinical studies investigating the presence of features of MS in children with PP or PA. All studies were cross sectional.

Reference	Subjects	Controls	Population	Evidence of IR?	Measures and outcomes
Oppenheimer *et al.* (75)	Pre-pubertal PP girls with (n=5) and without (n=7) acanthosis nigricans	None	American–Hispanic	Yes	Increased insulin resistance (HOMA-IR) in PP girls with acanthosis nigricans
Ibanez *et al.* (76)	Adolescent girls with a history of PP (n=24)	n=21 matched for age, sex and BMI	Spanish (Catalan)	Yes	Higher serum insulin levels during OGTT in all PP girls, insulin sensitivity inversely correlated with the increase in 17OHP and androstenedione following GNRH analogue
Ibanez *et al.* (77)	PP girls (n=98; divided in five subgroups from pre- to post-pubertal)	n=86 matched for Tanner stage and bone age	Spanish (Catalan)	Yes	All PP subgroups showed an increased fasting insulin resistance index, increased mean blood glucose and mean serum insulin, increased early insulin response to glucose (OGTT), elevated free androgen index, decreased SHBG and IGFBP1 levels
Ibanez *et al.* (78)	PP girls (n=81; divided into five subgroups from pre- to post-pubertal)	n=55 matched for Tanner stage and bone age	Spanish (Catalan)	Yes	In all PP subgroups higher mean serum insulin after OGTT, increased triglycerides (TG), VLD-TG, VLD-cholesterol, LDL/HDL-ratio and decreased SHBG
Potau *et al.* (81)	Boys with a history of PP (n=29)	n=29 matched for age and sex	Spanish (Catalan)	No	No difference in serum insulin and plasma glucose during OGTT
Vuguin *et al.* (83)	Pre-pubertal PP girls (n=35); n=25 with history of T2DM and acanthosis nigricans	None	American–Black/ Hispanic	Yes	PP girls with decreased insulin sensitivity and higher BMI had higher ACTH-stimulated androgens and higher IGF1 levels compared with PP girls with normal insulin sensitivity
Silfen *et al.* (103)	Pre-pubertal obese PP girls (n=17)	n=9 matched for age, sex and BMI	American–Hispanic	No	IGF1 levels in PP girls were elevated and positively correlated to androgen levels. No differences in fasting insulin and insulin response after OGTT
Denburg *et al.* (82)	Pre-pubertal PP boys (n=11)	n=8 matched for age and sex	American	Yes	PP boys had higher IGF1 levels, higher fasting insulin and a higher AUC insulin during the OGTT
Meas *et al.* (116)	Post-menarcheal PP girls (n=27)	n=25 matched for age and sex age	French	No	No significant difference in fasting serum insulin, insulin and glucose levels (AUC) during OGTT and fasting lipids
Ibanez *et al.* (79)	Pre-pubertal PP girls (n=33)	n=13 matched for age, sex, and Tanner stage	Spanish (Catalan)	Yes	Higher levels of plasminogen activator inhibitor 1 (PAI1-act) in PP girls. In small follow-up sub-cohort (n=10; 3 years), PAI1-act positively correlates with insulin and androgen levels
Ibanez *et al.* (85)	Pre- to post-pubertal PP girls (n=67)	n=65 matched for sex, pubertal stage and BMI	Spanish (Catalan)	NM	Increased waist circumference, waist-to-hip ratio and total fat mass in PP girls

Table 2 *Continued*

Reference	Subjects	Controls	Population	Evidence of IR?	Measures and outcomes
Potau et al. and Ibanez et al. (80, 85)	Pre- to post-pubertal PP girls (n=51)	n=68 matched for sex, pubertal stage and BMI	Spanish (Catalan)	Yes	Increased fasting insulin, decreased fasting insulin sensitivity (HOMA-IR) and higher insulin levels during OGTT in PP girls are most closely related to cardiovascular risk factors (total/LDL cholesterol, TG, abdominal fat (DXA)). Fasting insulin levels were correlated with higher central fat mass (DXA) in PP girls
Teixeira et al. (87)	PP girls (obese and non-obese) (n=25)	n=14 matched for age and sex	Brazilian	Yes	Higher fasting serum insulin, glucose, leptin and cholesterol levels only in obese PP girls
Güven et al. (86)	Pre-pubertal PP girls (n=24)	n=13 matched for age, sex and BMI	Turkish	NM	Unfavourable lipid profile and higher blood pressure in PP girls
Utriainen et al. (56)	Pre-pubertal PA girls (PP+PA (n=32), PA only (n=31))	n=80 matched for age, sex and BMI	Finnish	Yes	Increased mean insulin during OGTT in all PA girls; increased fasting insulin, decreased SHBG and diagnostic criteria for childhood MS only in PA-PP group. No difference in lipid profile, glucose after OGTT and blood pressure
Andiran & Yordam (88)	Pre- to post-pubertal PP girls (n=25)	n=20 matched for age and sex	Turkish	No	No significant differences between fasting insulin and fasting insulin/glucose ratio between PP and controls. Lp(a) levels were higher in pubertal PP girls
Mathew et al. (95)	Pre-pubertal PP children (n=10)	n=10 matched for age, sex and BMI	American	NM	Android fat distribution (DXA), higher TC/HDL-ratio and higher inflammation markers (TNFα, IL8) in PP group
Livadas et al. (89)	Adolescent girls with history of PP (n=45)	n=19 matched for age, sex and BMI	Greek	Yes	Increased insulin resistance (HOMA-IR), higher baseline glucose and insulin levels, inflammation markers (CRP, PAI1) and androgen levels, decreased SHBG in PP girls. No differences in lipid profile
Paterson et al. (55)	Pre-pubertal PP girls (n=42) and boys (n=8)	None	Scottish	Yes	Higher fasting insulin levels in PP boys compared with age- and sex-related reference ranges
Larque et al. (90)	Pre-pubertal PP girls (n=22)	n=20 matched for age and sex only	Spanish (Andalusia)	Yes	No difference in lipid metabolism, increased mean insulin levels in the OGTT and decreased postprandial adiponectin levels in PP girls

IR, insulin resistance; OGTT, oral glucose tolerance test; VDL, very low density; IGF1, insulin-like growth factor 1; IGFBP1, insulin-like growth factor binding protein 1; SHBG, sex hormone binding globulin; DXA, dual-energy X-ray absorptiometry; HOMA-IR, homeostasis model assessment-insulin resistance; PAI1, plasminogen activator inhibitor type 1; NM, not measured.

DHEAS and androstenedione levels at the time of presentation with PP (72, 96). The pattern of ovarian hyper-responsiveness was more pronounced during mid and late puberty (96) and associated with a degree of hyperinsulinism (76). Importantly, the same study sample also showed adrenal hyper-responsiveness following ACTH stimulation in pre- and post-puberty (97). By contrast, both ACTH and GNRH stimulation in a smaller sample of American PP adolescents revealed exclusively adrenal hyper-responsiveness (98). Based on the chronological pattern of adrenal hyper-responsiveness at presentation with PP followed by ovarian hyper-responsiveness after menarche, Ibáñez *et al.* (69) suggested that the underlying mechanism may be abnormal regulation or increased expression of the crucial androgen synthesising enzyme CYP17A1 in adrenals and ovaries resulting in androgen excess during adrenarche and puberty. Recently, two studies on pre-pubertal PP girls measured anti-Müllerian hormone (AMH), a marker of ovarian function that is increased in PCOS (99). In a cross-sectional study in Scottish PP girls (mean age 5.5–8.8 years), AMH levels were increased above the sex- and age-specific reference ranges (55), whereas a case–control study found normal AMH levels in Finnish PA girls (100).

Hyperinsulinism has been suggested as the common origin of both IPA and PCOS (69, 71). From a mechanistic point of view, this hypothesis seems to be plausible as insulin and insulin-like growth factors (IGF1 and IGF2) are able to stimulate steroidogenesis in human foetal and adult adrenal cells *in vitro* (101, 102). Low levels of IGF binding protein 1 (IGFBP1) would increase the amount of active unbound IGF1, and several studies in children with PP have described disturbances in the IGF system (77, 83, 103, 104). However, a recent meta-analysis examining the available evidence for a decrease in IGFBP1 in PCOS patients concluded that IGFBP1 levels inversely correlate with BMI and thus are primarily associated with obesity rather than androgen excess (105).

Low birth weight and early onset androgen excess

About 20 years ago, Barker *et al.* (106–108) introduced the hypothesis that malnutrition in prenatal life leads to metabolic programming of the foetal organs with subsequent development of insulin resistance and MS, if nutrients are available in abundance later in life. This hypothesis, also known as 'thrifty phenotype hypothesis' (109), was based on epidemiological associations between poor infant and foetal growth and the subsequent development of the MS and cardiovascular mortality in adult life. These findings are paralleled by a number of cross-sectional case–control studies in Catalonian girls that consistently found premature androgen excess, hyperinsulinaemia, dyslipidaemia and ovarian hyper-responsiveness

associated with low birth weight (110–112) (Table 4). In a longitudinal follow-up study in Catalonian babies born small for gestational age (SGA, i.e. birth weight <10th percentile), hyperinsulinaemic visceral adiposity without weight gain, low adiponectin and higher IGF1 levels started to develop at around 2–4 years of age (113–115). These metabolic changes were observed after sufficient weight gain of the SGA babies, usually occurring before 2 years of age. In addition, DHEAS was higher and SHBG was lower in SGA children between 6 and 8 years (115).

French, Finnish and Scottish girls presenting with PP did not have significantly lower birth weight than controls (55, 56, 116) (Table 4). Moreover, data from Finnish and British birth cohort studies indicate no correlation between the occurrence of PCOS and low birth weight (117, 118). In contrast, an association between low birth weight and PP in girls has been found in three different study samples from France, Italy and Australia (119–121). In a large birth cohort study from the UK investigating 770 boys and girls at 8 years of age, low birth weight was associated with higher adrenal androgen levels (122). Interestingly, children with a more rapid postnatal catch-up weight gain had higher adrenal androgen levels (122). In a cross-sectional study in 190 healthy children from the UK, urinary steroid excretion was measured at the age of 9 years (123). Androgen excretion was higher in children with low birth weight, showing up to 40% increase in excretion by a 1 kg decrease in birth weight. However, cortisol metabolite excretion was also higher in children with low birth weight, possibly indicating an altered function of the hypothalamo–pituitary–adrenal axis (123).

These observations suggest that the origins of premature androgen excess and associated disorders such as childhood MS and PCOS may in some cases already be defined by the pre-natal environment. However, most of this evidence derives from investigations in the Catalonian population and other studies performed in children from diverse ethnical backgrounds are contradictory. Thus more research and in particular well-controlled longitudinal studies are required for a proper assessment of metabolic risk. However, low birth weight followed by excessive catch-up weight gain may initiate a pattern of events leading to the clustering of metabolic complications, with the successive manifestation of PA, PCOS and the MS (Fig. 1).

Adrenal steroidogenesis during adrenarche

A basic understanding of adrenal steroidogenesis in the developmental context is important to approach disorders presenting with precocious androgen excess. The adrenal cortex comprises three distinct zones, the outer zona glomerulosa responsible for mineralocorticoid production, the middle zona fasciculata

Table 3 Summary of clinical studies investigating features of PCOS in children with PP or PA. All studies were cross-sectional.

Reference	Subjects	Controls	Population	PCOS risk*	Outcome
Ibanez *et al.* (72)	35 adolescent PP girls	12, age- and sex-matched	Spanish (Catalan)	Yes	16 of 35 PP girls had hirsutism, oligome-norrhoea, elevated baseline androste-nedione and/or testosterone levels; higher 17OHP and androstenedione response to GNRH analogue in oligo-menorrhoeic PP girls compared with PP girls with regular menstruation
Ibáñez *et al.* (96)	76 adolescent PP girls	49, sex- and age-matched	Spanish (Catalan)	Yes	Higher increases in 17Preg and DHEA throughout puberty and in 17OHP and androstenedione at Tanner stage B4 in PP girls after GNRH analogue
Ibanez *et al.* (73)	36 adolescent PP girls	49, age- and sex-matched	Spanish (Catalan)	Yes	Higher frequency of anovulatory cycles only in PP girls in late post-menarche (more than 3 years after menarche)
Ibanez *et al.* (97)	47 PP girls at pre- and post-puberty	None	Spanish (Catalan)	Yes	Increased baseline DHEAS and andros-tenedione; increased 17OHP response to ACTH at time of diagnosis, increased DHEA and androstenedione response to ACTH during adolescence
Mathew *et al.* (98)	13 pre-pubertal PP girls	8, age- and sex-matched	American–Black and American–White	Yes	Increased 17Preg, DHEA and androste-nedione response to ACTH in PP girls; by contrast, 17OHP, androstenedione and oestradiol response to GNRH analogue in PP girls similar to controls
Paterson *et al.* (55)	42 pre-pubertal PP girls	None	Scottish	Yes	Increased AMH levels in PP girls
Utriainen *et al.* (100)	52 pre-pubertal PA girls	48, age-matched	Finnish	No	No abnormalities in AMH concentrations in PP girls

*Evidence of increased PCOS risk. 17Preg, 17-hydroxypregnenolone; 17OHP, 17α-hydroxyprogesterone; AMH, anti-Müllerian hormone.

synthesising glucocorticoids and the inner ZR that produces the crucial androgen precursor DHEA (124–129). Importantly, recent studies based on cell morphometry and analysis of steroidogenic enzyme expression support the results of earlier, histology-based studies from the 1970s suggesting that maturation of the adrenal ZR starts at least 4–5 years before the physiological manifestation of pubarche (17, 124, 129).

Adrenal steroidogenesis is facilitated by the import of cholesterol esters into adrenocortical cells via scavenger receptor B1 and their cleavage by hormone-sensitive lipase to yield free cholesterol, which is subsequently imported into the mitochondrion by action of the STAR protein. For *de novo* synthesis of DHEA from cholesterol, only two steroidogenic cytochrome P450 (CYP) enzymes are required, CYP11A1 (or P450scc) and CYP17A1 (Fig. 2). CYP11A1 is located in the mitochondrion and cleaves the cholesterol side chain, yielding pregnenolone. CYP11A1 is equally expressed in all three zones of the adrenal cortex throughout childhood (127).

The microsomal enzyme CYP17A1 is the qualitative regulator of adrenal steroid synthesis and exerts two distinct catalytic activities. Its 17α-hydroxylase activity catalyses the production of the glucocorticoid precursors 17OHP and 17α-hydroxypregnenolone (17Preg; Fig. 2). The 17,20 lyase activity of CYP17A1 catalyses their subsequent conversion to the adrenal androgen precursors androstenedione and DHEA respectively

(Fig. 2). Of note, 17,20 lyase has an about 100-fold increased substrate preference for 17Preg over 17OHP (130). Consequently, in the physiological situation, almost all androgen synthesis proceeds through DHEA, which, therefore, is considered the principal human androgen precursor. An early study employing human adrenal microsomes from individuals of different ages found lower CYP17A1 activities in individuals aged 2 months to 9 years than in adults (131) and subsequently has been cited as evidence for a characteristic increase in 17,20 lyase activity at the time of adrenarche. However, current *in vivo* evidence points towards a much earlier onset of adrenal androgen secretion at around age 3 years (17).

Recent immunohistochemistry data are consistent with this latter suggestion, demonstrating a significant increase in CYP17A1 expression in ZR from 5 years of age onwards. This is paralleled by reticularis-specific increase in P450 oxidoreductase (POR) that transfers electrons from NADPH to microsomal CYP enzymes including CYP17A1 (127). In addition, reticularis-specific expression of cytochrome b5 is observed (127), which is thought to enhance the allosteric interaction of the CYP17A1 and POR proteins, thereby specifically enhancing 17,20 lyase activity (130).

While CYP11A1 and CYP17A1 are essential and theoretically sufficient to create the biochemical environment observed in adrenarche, other steroidogenic enzymes also affect androgen synthesis.

Table 4 Summary of clinical studies investigating the relationship between low birth weight (LBW) and disorders of androgen excess.

Reference	Subjects	Controls	Population	LBW[*]	Outcome
Cresswell et al. (117)	235 women at 40–42 years	None	UK	No	49 women (21%) had polycystic ovaries on ultrasound, a higher frequency of hirsutism and acne and higher LH and androgens; overweight mothers and a high birth weight slightly increased the risk of development of PCOS in later life
Clark et al. (123)	190 healthy children (89 boys and 101 girls) investigated at 9 years	None	UK	Yes	Higher urinary androgen excretion in children with low birth weight
Ibanez et al. (110)	102 pre- to post-pubertal PP girls	83, matched for pubertal stage and bone age	Spanish (Catalan)	Yes	Lowest birth weight in PP girls with most severe phenotype (PP+increased 17OHP+androstenedione response to GNRH analogue+insulin resistance)
Ibanez et al. (111)	83 pre- to post-pubertal girls with PP	104, matched age and BMI	Spanish (Catalan)	Yes	PP girls with dyslipidaemia and low IGFBP1 levels had lower birth weight
Ibanez et al. (112)	23 healthy girls born SGA, investigated at 14 years	40 healthy girls born AGA, investigated at 14 years	Spanish (Catalan)	Yes	Higher DHEAS, androstenedione and baseline insulin levels in SGA group
Ghirri et al. (119)	31 SGA girls (12 pre-pubertal, 19 post-menarche)	31, age-matched	Italian	Yes	DHEAS levels higher in SGA group. No difference in final height and sexual maturation/menarche age
Meas et al. (116)	27 post-menarcheal PP girls	25, age- and sex- matched	French	No	No correlation between PP and birth weight
Laitinen et al. (118)	2007 adult women	None	Finnish	No	Data from longitudinal, population-based cohort. No correlation between birth weight and presence of PCOS
Charkaluk et al. (120)	216 pre-pubertal PP children (189 girls)	None	French	Yes	18.5% of PP girls had birth weight <10th percentile (expected rate: 10%)
Ong et al. (122)	770 children at 8 years from birth cohort	None	UK	Yes	Data from birth cohort study. Inverse correlation between birth weight and adrenal androgen levels. Children with rapid postnatal catch-up growth had higher DHEAS levels
Neville & Walker (121)	89 children with PP (79 girls)	None	Australia	Yes	Retrospective analysis. 35% were SGA, 24% premature birth
Ibanez et al. (113)	29 children born SGA	22 children born AGA; no difference in weight, height and BMI	Spanish (Catalan)	Yes	Follow-up at 2, 3 and 4 years. After catch-up, weight gain between birth and 2-year SGA children develop central adiposity (DXA) and insulin resistance (HOMA-IR) between 2 and 4 years
Ibanez et al. (114)	32 children born SGA	32 children born AGA, matched for sex, height and weight	Spanish (Catalan)	Yes	Follow-up at 6 years. SGA children have more visceral fat (DXA), are hyperinsulinaemic and had lower adiponectin levels than AGA controls
Ibanez et al. (115)	32 children born SGA	32 children born AGA, matched for sex, height and weight	Spanish (Catalan)	Yes	Follow-up at 8 years. Visceral obesity (DXA), hyperinsulinaemia and hypo-adiponectinemia stabilises in SGA children; more-over, DHEAS levels were higher and SHBG levels were lower
Utriainen et al. (104)	54 pre-pubertal PA girls	52, age-matched	Finnish	No	Retrospective analysis. No correlation between LBW and PA. PA girls were taller at diagnosis and had enhanced early childhood growth
Paterson et al. (55)	52 pre-pubertal PP (42 girls, 8 boys)	No	Scottish	No	No evidence of reduced foetal growth in PP children

[*]Association with LBW. SGA, small for gestational age; AGA, appropriate for gestational age; DXA, dual-energy X-ray absorptiometry; HOMA-IR, homeostasis model assessment-insulin resistance.
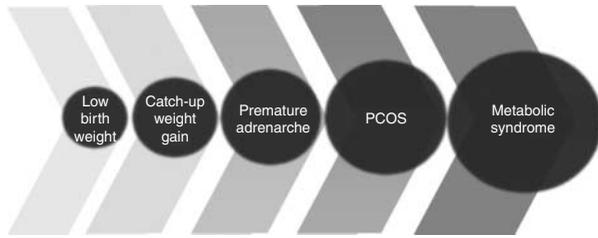
Figure 1 Graphic representation of a potentially causally related pattern of subsequent events linking low birth weight to premature adrenarche, polycystic ovary syndrome and the development of the metabolic syndrome later in life. This order of events is not consistently supported by all studies in the field as discussed in the text.

3β-Hydroxysteroid dehydrogenase type 2 (HSD3B2; also termed $\Delta4/\Delta5$ isomerase) converts the $\Delta5$ steroids pregnenolone and 17Preg to the $\Delta4$ steroids progesterone and 17OHP, thus crucially facilitating mineralocorticoid and glucocorticoid synthesis (Fig. 2). As it competes with CYP17A1 for substrate, decreased HSD3B2 activity will result in increased DHEA synthesis. Indeed, the expression level of HSD3B2 is lowest in ZR cells (132, 133), even in the adrenals of 3-year-old children well before clinical signs of adrenarche occur (134). The significance of relatively low HSD3B2 expression in the adrenal ZR that would consequently shift steroidogenesis towards DHEA is endorsed by earlier studies based on human adrenal primary cultures (126).

Recent work has highlighted the significance of two further enzyme systems in the regulation of adrenal androgen synthesis, with associated inactivating mutations identified as novel monogenic causes of PA: apparent cortisone reductase deficiency (ACRD) (135) and apparent DHEA sulfotransferase deficiency (136).

ACRD (hexose-6-phosphate deficiency)

The enzyme 11β-hydroxysteroid dehydrogenase type 1 (11β-HSD1) is important for amplifying glucocorticoid signals in target tissues such as liver, adipose and muscle by interconverting cortisol and its metabolically inactive metabolite cortisone (137). In principle, 11β-HSD1 is a bidirectional enzyme, interconverting cortisone and cortisol via its oxo-reductase and dehydrogenase activities; however, 11β-HSD1 oxo-reductase activity predominates *in vivo*, leading to the activation of cortisone to cortisol within the lumen of the endoplasmic reticulum (ER; Fig. 2). Recent *in vitro* and *in vivo* studies have identified a further layer of regulation of this crucial glucocorticoid-activating enzyme system. Within the ER, 11β-HSD1 oxo-reductase activity is dependent upon the maintenance of a high $NADPH/NADP^+$ ratio and NADPH is supplied by a second ER lumen enzyme, hexose-6-phosphate dehydrogenase (H6PDH). Indeed, 11β-HSD1 oxo-reductase activity is absent in *H6PDH* KO mice (138–140). However, as the

11β-HSD1 enzyme is not directly affected, the altered ER redox environment subsequent to loss of H6PDH function permits an increase in 11β-HSD1 dehydrogenase activity, resulting in increased inactivation of cortisol to cortisone. In *H6PDH* KO mice, this leads to insensitivity to feedback suppression of the HPA axis and resultant ACTH-mediated adrenal hyperplasia and elevated circulating glucocorticoid levels (138–140).

In humans, ACRD is characterised by decreased urinary excretion of cortisol metabolites and ACTH-driven adrenal androgen excess manifesting as PA and PCOS (141–143). To date, approximately eight cases have been reported in the literature that have a biochemical and clinical presentation consistent with ACRD. In four of these cases, a complete clinical, biochemical and genetic work-up has been published (135); three adult women presented with a PCOS phenotype and one 6-year-old boy presented with PA (143, 144). In all cases, hyperandrogenaemia was confirmed with markedly elevated serum levels of DHEAS, androstenedione and testosterone.

Genetic analyses determined a normal sequence of the *HSD11B1* gene (encoding 11β-HSD1) in all affected individuals, but revealed inactivating mutations in the *H6PD* gene encoding H6PDH, including homozygous and compound heterozygous nonsense, missense and splicing mutations, which were all shown to disrupt enzymatic activity (135). Thus in ACRD, loss of H6PDH activity yields reduced 11β-HSD1 oxo-reductase activity and a concurrent gain in 11β-HSD1 dehydrogenase activity, resulting in enhanced peripheral clearance of cortisol, thereby reducing the negative feedback suppression of the HPA axis, which in turn increases the ACTH drive and an ACTH-mediated increase in adrenal androgen secretion.

Diagnostically, the use of GC/MS to generate steroid profiles from 24 h urine collections has proved invaluable (135). In most cases, serum cortisol levels were within the normal range, as might be expected due to the compensatory increase in HPA axis activity. However, the urinary levels of cortisone metabolites were grossly elevated in all affected individuals, resulting in characteristically decreased ratios of cortisol over cortisone metabolites (5α tetrahydrocortisol (THF) + THF/tetrahydrocortisone and cortols/cortolones, see Fig. 2). Thus urinary steroid profiling by GC/MS provides a clear-cut diagnostic marker for H6PDH deficiency (135, 145) and reliably helps to distinguish ACRD from other causes of premature androgen excess.

Apparent DHEA sulphotransferase deficiency (PAPS synthase type 2 deficiency)

DHEA serves as the principal human androgen precursor via conversion to the active androgens testosterone and 5α-dihydrotestosterone that bind and activate the AR. Alternatively, DHEA can undergo

sulphate conjugation yielding DHEAS, a reaction catalysed by the enzyme DHEA sulphotransferase (SULT2A1; Fig. 2). In human adrenals, SULT2A1 is exclusively expressed in the ZR and its immunoreactivity increases from early childhood to adolescence (127). DHEAS represents the most abundant steroid in the human circulation, and it was previously thought that DHEA and its sulphate ester DHEAS would undergo continuous interconversion by action of SULT2A1, converting DHEA to DHEAS, and steroid sulphatase (STS), yielding DHEA after cleavage of the sulphate group from DHEAS. Accordingly, DHEAS was found to serve as a circulating storage pool for the generation of DHEA in peripheral target tissues of sex steroid action. However, while exogenous administration of DHEA in humans yields ample generation of both active sex steroids and DHEAS (20), we have previously shown that the administration of DHEAS does not result in appreciable levels of DHEA or active sex steroids (146, 147). This suggests that DHEA sulphation is a permanent inactivating step and that the reverse reaction, cleavage of DHEAS to DHEA by STS, does not have a major impact on circulating steroid concentrations. This is true with the exception of human foetal development and pregnancy, during which ample cleavage of DHEAS has been demonstrated, driven by abundant placental STS activity. Consequently, we hypothesised that disruption of SULT2A1 activity will result in decreased inactivation of DHEA to DHEAS, thereby fuelling the alternative conversion, i.e. the activation of DHEA to androgens, which will result in androgen excess.
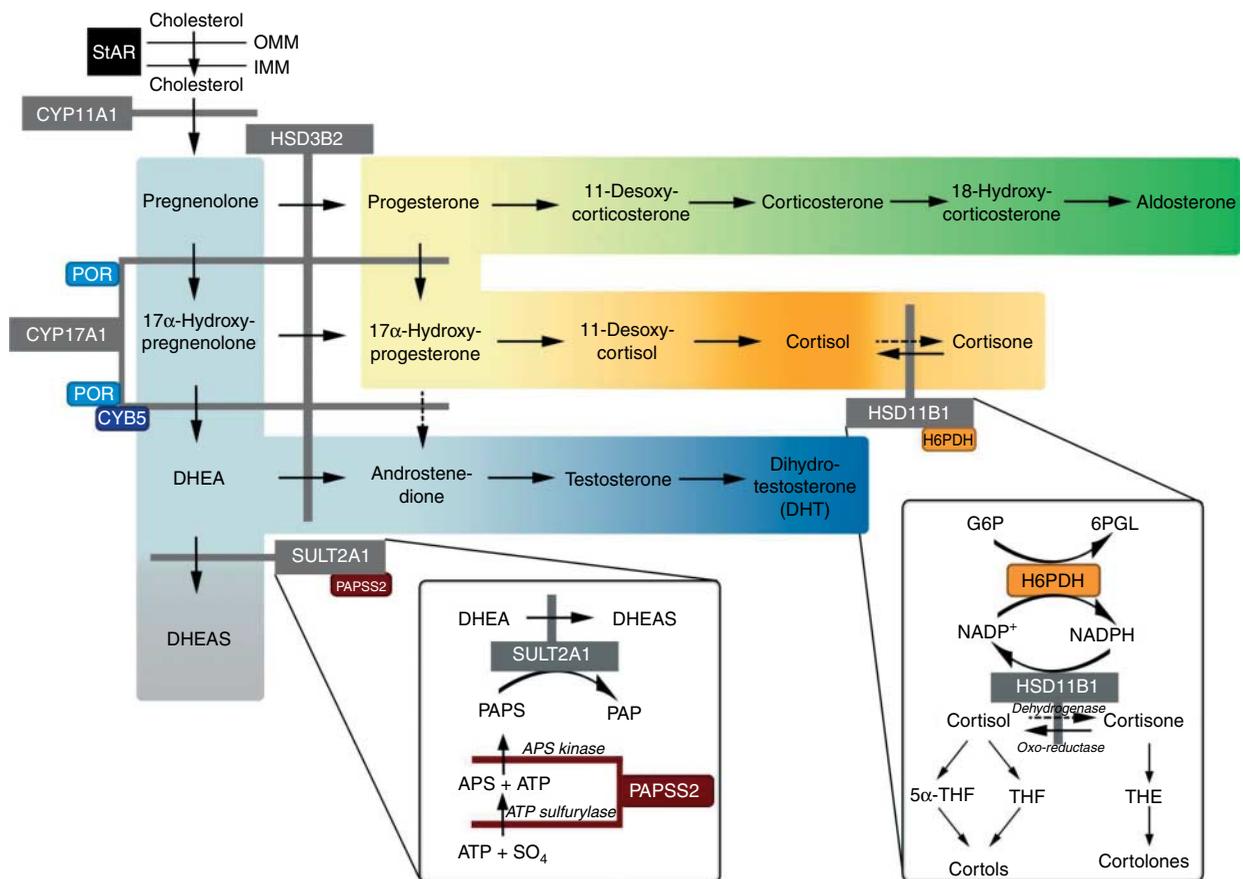

Figure 2 Schematic representation of human adrenal steroidogenesis and androgen synthesis with additional details on the co-factor regulation of DHEA sulphotransferase (SULT2A1) and 11β-hydroxysteroid dehydrogenase (HSD11B1) activities. Disruption of PAPS synthase 2 activity results in apparent DHEA sulphotransferase deficiency, whereas disruption of hexose-6-phosphate dehydrogenase (H6PDH) activity results in apparent cortisone reductase deficiency, two recently described conditions manifesting with early onset androgen excess including premature adrenarche and polycystic ovary syndrome. StAR (transports cholesterol from the outer mitochondrial membrane (OMM) to the inner mitochondrial membrane (IMM)); CYP11A1, cholesterol side chain cleavage enzyme; CYP17A1, 17α-hydroxylase/17,20 lyase; CYB5, cytochrome b5; POR, P450 oxidoreductase; HSD3B2, 3β-hydroxysteroid dehydrogenase type 2; HSD11B1, 11β-hydroxysteroid dehydrogenase; H6PDH, hexose-6-phosphate dehydrogenase; G6P, glucose-6-phosphate; 6PGL, 6-phosphogluconate; PAP, 3′-phosphoadenosine-5′-phosphate; PAPS, 3′-phosphoadenosine-5′-phosphosulphate; PAPSS2, PAPS synthase 2; SULT2A1, DHEA sulfotransferase; THF, tetrahydrocortisol; THE, tetrahydrocortisone. Androgens are shown in blue, glucocorticoids in orange and mineralocorticoids in green.
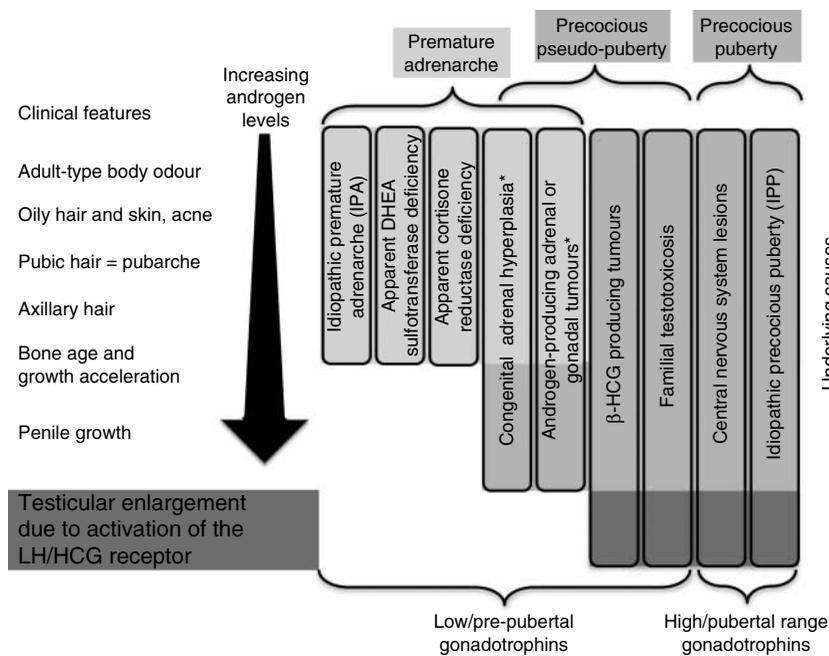
Figure 3 Schematic representation of the causes underlying premature adrenarche, precocious pseudo-puberty and true precocious puberty respectively, as well as associated clinical features and androgen and gonadotrophin levels. *These conditions can present either with premature adrenarche or with precocious pseudo-puberty, depending on the degree of androgen excess.

We recently reported a case about a girl who presented with PA manifesting with pubic hair development at the age of 6 years (136). She subsequently developed acne and hirsutism at 11 years of age and secondary amenorrhoea at 13 years of age, i.e. a phenotype progressing from PA to a presentation resembling PCOS. Lab investigations revealed increased serum androstenedione and mildly elevated testosterone, as frequently seen in early onset androgen excess, with her body weight progressing from overweight to the obese range. However, of note, her serum DHEAS levels were undetectable throughout, whereas serum DHEA was at the upper limit of normal, suggestive of impaired DHEA sulfation as the driver of androgen excess. Surprisingly, genetic analysis did not reveal any mutations in the *SULT2A1* gene, which prompted us to explore further mechanisms potentially impacting on DHEA sulphation. For catalytic activity, SULT2A1 crucially depends on provision of the universal sulphate donor 3′-phosphoadenosine-5′-phosphosulphate (PAPS), which is generated by the two human isozymes PAPS synthase type 1 (PAPSS1) and type 2 (PAPSS2). PAPSS1 is ubiquitously expressed, whereas PAPSS2 is predominantly expressed in liver and adrenals (148), the major sites of DHEA sulphation. Sequencing of the *PAPSS2* gene in our patient revealed compound heterozygous mutations: a nonsense mutation, R329X, resulting in early truncation of the PAPSS2 ATP sulphurylase subdomain and a missense mutation, T48R, located in an area of the PAPSS2 APS kinase domain that is crucial for protein function. *In vitro* assays demonstrated complete disruption of DHEA sulphation by the R329X nonsense mutation while T48R maintained 5% residual activity (136). Interestingly, the mother of the patient, who carried R329X on one allele, developed symptoms of PCOS including obesity, oligomenorrhoea and hirsutism at the age of 30 years, suggestive of a possible impact of milder genetic variation in *PAPSS2* on presentation with androgen excess.

Of note, our patient also showed very mild signs of bone dysplasia that was not clinically apparent but revealed by X-ray. A previously reported consanguineous Pakistani kindred carrying a homozygous PAPSS2 nonsense mutation void of any catalytic function presented with severe spondyloepimetaphyseal dysplasia (149). An androgen phenotype in that kindred was not reported, but the researchers were only allowed to examine male family members and learned that affected female individuals suffered from infertility.

These findings indicate that PAPSS2 deficiency has to be considered a multi-system disorder, which, in principle, is not surprising, as sulfation is a major metabolic reaction occurring in multiple tissue types and organs such as liver, bone and cartilage and is also involved in endocrine pathways such as neuropeptide, thyroid and catecholamine signalling (150). Importantly, PAPSS2 deficiency reveals DHEA sulphation as a major regulator of human androgen synthesis, with impaired sulfation of DHEA to DHEAS resulting in increased conversion of DHEA to active androgens and subsequent androgen excess, which manifests with PA and PCOS. Of note, the biochemical phenotype in our patient, low DHEAS and increased androstenedione, would have previously been labelled as 'ovarian hyperandrogenism' while androgen excess in our patient clearly stems from an adrenal cause. Previous studies have found low or undetectable DHEAS in 5–10% children with PP (55, 151), suggestive of a potentially significant role of dysregulation of this pathway in the pathogenesis of PA.

Conclusions and future directions

We feel that given the available evidence of PA can no longer routinely be considered a benign extreme of normal variation. Early onset androgen excess, whether presenting with PA or adolescent PCOS, appears to represent a significant risk factor for the development of MS. In an age of increasing numbers of childhood obesity and considering the intriguing links between the insulin–IGF1 system and androgen regulation, we may be set to observe an increasing number of patients with early onset androgen excess. The recent elucidation of several conditions manifesting with early androgen excess including PA and PCOS has provided with novel mechanistic insights into the underlying pathophysiology and it is likely that the coming years will show the elucidation of further distinct causes underlying PA, which first and foremost requires careful phenotyping and use of nomenclature (Fig. 3) to identify potentially novel entities. Systematic longitudinal studies in children with PA are warranted to address the apparent link between early onset androgen excess, insulin resistance and metabolic risk and will also elucidate the frequency of novel monogenic causes of childhood androgen excess, i.e. (apparent) cortisone reductase and DHEA sulphation deficiencies.

Declaration of interest

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

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