



This is a repository copy of *Causes, patterns and severity of androgen excess in 487 consecutively recruited pre- and post-pubertal children..*

White Rose Research Online URL for this paper:
<https://eprints.whiterose.ac.uk/140386/>

Version: Accepted Version

Article:

Idkowiak, J., Elhassan, Y.S., Mannion, P. et al. (13 more authors) (2019) Causes, patterns and severity of androgen excess in 487 consecutively recruited pre- and post-pubertal children. *European Journal of Endocrinology*, 180 (3). pp. 213-221. ISSN 0804-4643

<https://doi.org/10.1530/EJE-18-0854>

Disclaimer: this is not the definitive version of record of this article. This manuscript has been accepted for publication in *European Journal of Endocrinology*, but the version presented here has not yet been copy-edited, formatted or proofed. Consequently, Bioscientifica accepts no responsibility for any errors or omissions it may contain. The definitive version is now freely available at <https://doi.org/10.1530/EJE-18-0854> [2018].

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



eprints@whiterose.ac.uk
<https://eprints.whiterose.ac.uk/>

1 **Causes, patterns and severity of androgen excess in 487 consecutively recruited pre- and**
2 **post-pubertal children**

3 Jan Idkowiak^{1,2,3}, Yasir S. Elhassan^{1,3}, Pascoe Mannion^{1,3}, Karen Smith⁴, Rachel Webster⁴, Vrinda
4 Saraff^{2,3}, Timothy G. Barrett^{2,3}, Nicholas J. Shaw^{1,2,3}, Nils Krone^{2,3,5}, Renuka P. Dias^{2,3}, Melanie
5 Kershaw^{2,3}, Jeremy M. Kirk^{1,2,3}, Wolfgang Högl^{1,2,3,6}, Ruth E. Krone^{2,3}, Michael W. O'Reilly^{1,3}, Wiebke
6 Arlt^{1,3}

7 ¹Institute of Metabolism and Systems Research, University of Birmingham, Birmingham, UK;
8 ²Department of Endocrinology and Diabetes, Birmingham Women's and Children's Hospital NHS
9 Foundation Trust, Birmingham, UK; ³Centre for Endocrinology, Diabetes and Metabolism, Birmingham
10 Health Partners, Birmingham, UK; ⁴Department of Clinical Biochemistry, University Hospitals
11 Birmingham NHS Foundation Trust, Birmingham, UK; ⁵Academic Unit of Child Health, Department of
12 Oncology & Metabolism, University of Sheffield, Sheffield, UK; ⁶Department of Pediatrics and
13 Adolescent Medicine, Johannes Kepler University Linz, Linz, Austria

14

15 **Short title:** Causes of childhood androgen excess

16 **Keywords:** Androgen excess, premature adrenarche, polycystic ovary syndrome, testosterone,
17 androstenedione, DHEAS, premature menarche, precocious puberty, adrenocortical carcinoma

18 **Word count (excluding abstract, figure legend and references): 3,245**

19 **Number of figures:** 3 (+1 supplemental)

Number of tables: 1 (+2 supplemental)

20 **Address all correspondence and requests for reprints to:**

21 Dr Jan Idkowiak

22 Institute of Metabolism and Systems Research (IMSR)

23 University of Birmingham, Birmingham B15 2TT, UK

24 Email: j.idkowiak@bham.ac.uk Phone: +441214148811 Fax: +441214158712

25 **Abstract**

26 **Objective:** Androgen excess in childhood is a common presentation and may signify sinister
27 underlying pathology. Data describing its patterns and severity are scarce, limiting the information
28 available for clinical decision processes. Here, we examined the differential diagnostic value of serum
29 dehydroepiandrosterone sulfate (DHEAS), androstenedione (A4), and testosterone (T) in childhood
30 androgen excess.

31 **Design:** Retrospective review of all children undergoing serum androgen measurement at a single
32 center over 5 years.

33 **Methods:** Serum A4 and T were measured by tandem mass spectrometry, DHEAS by immunoassay.
34 Patients with at least one increased androgen underwent phenotyping by clinical notes review.

35 **Results:** In 487 children with simultaneous DHEAS, A4, and T measurements, we identified 199 with
36 androgen excess (140 pre- and 59 post-pubertal). Premature adrenarche (PA) was the most common
37 pre-pubertal diagnosis (61%), characterized by DHEAS excess in 85%, while A4 and T were only
38 increased in 26% and 9%, respectively. PCOS was diagnosed in 40% of post-pubertal subjects,
39 presenting equally frequent with isolated excess of DHEAS (29%) or T (25%) or increases in both A4
40 and T (25%). CAH patients (6%) predominantly had A4 excess (86%); T and DHEAS were increased
41 in 50% and 33%, respectively. Concentrations increased above the two-fold upper limit of normal
42 were mostly observed in PA for serum DHEAS (>20fold in the single case of adrenocortical
43 carcinoma), and in CAH for serum androstenedione.

44 **Conclusions:** Patterns and severity of childhood androgen excess provides pointers to the underlying
45 diagnosis and can be used to guide further investigations.

47 **Introduction**

48 Androgen excess in childhood may present with a variety of symptoms and is thought to have
49 a broad spectrum of underlying pathologies (1). Premature pubic and axillary hair growth, change in
50 body odor and transient growth acceleration are typical presenting signs in pre-pubertal children (2);
51 menstrual disturbances with hirsutism are presenting features in post-pubertal girls (3). In the vast
52 majority of affected pre-pubertal children, premature adrenarche (PA) is the underlying diagnosis,
53 whereas adolescent polycystic ovary syndrome (PCOS) is the leading cause of androgen excess in
54 pubertal girls after menarche (1, 2, 4). Importantly, the diagnosis of PA and PCOS require exclusion
55 of other causes of androgen excess such as inborn steroidogenic enzyme defects, most commonly
56 congenital adrenal hyperplasia (CAH), precocious puberty or potentially malignant virilizing adrenal
57 tumors, with the latter being extremely rare in childhood (1, 5, 6).

58 To reach a conclusive diagnosis in a child presenting with androgen excess can be
59 challenging. Detailed history, including onset, acuity, severity and progression of symptoms and a
60 thorough clinical examination, followed by hormonal investigations, bone age assessment, and, where
61 appropriate, imaging studies, are part of the clinical work-up (1, 7). The extent of investigations
62 required usually depends on the severity and acuity of presenting symptoms, and clinicians tend to
63 tailor those investigations depending on the clinical presentation and the severity of biochemical
64 androgen excess (7). However, there is a paucity of data from larger cohorts delineating patterns and
65 severity of childhood androgen excess considered predictive for both common and rare underlying
66 pathologies.

67 Physiologically low circulating androgen levels in children and the widespread use of
68 radioimmunoassays, which are prone to cross-reactivity and low sensitivity, limit the diagnostic
69 accuracy of the measurement of the serum concentrations of the active androgen testosterone (T) and
70 the androgen precursors androstenedione (A4) and dehydroepiandrosterone sulfate (DHEAS), in
71 particular when measured in isolation (8, 9). Liquid chromatography-tandem mass spectrometry (LC-
72 MS/MS) analysis of serum steroids has emerged as a highly sensitive analytical tool, in particular
73 when measuring low-abundance steroids in children (10, 11). To date, there is a dearth of data on LC-
74 MS/MS based androgen measurements in childhood androgen excess conditions.

75 We have recently reported the utility of simultaneous measurement of serum DHEAS, A4 and
76 T in determining causes, patterns and severity of androgen excess in a large sample of adult women
77 recruited in a single center (12), generating useful guidance for clinicians to predict non-PCOS
78 pathology in adult women presenting with androgen excess. In this study, we aimed to develop the
79 evidence base for a rational approach to childhood androgen excess. To this end, we analyzed a large
80 cohort of consecutively recruited children from a single tertiary referral center to uncover the
81 signatures of distinct conditions underlying childhood androgen excess.

82 PATIENTS AND METHODS

83 Subjects and Clinical Protocol

84 Institutional review board approval for retrospective data review was obtained from
85 Birmingham Women's and Children's Hospital (BWCH) NHS Foundation Trust (reference: CARMS-
86 00935). We included all children who had undergone measurements of serum T, A4 and DHEAS as
87 part of routine clinical care at BWCH between 1st January 2013 and 1st June 2017 (n=1,525),
88 identifying 487 who underwent simultaneous measurement of DHEAS, A4 and T. Samples were
89 collected at variable times during the day in the context of out-patient clinic appointments. Patients
90 with at least one serum androgen concentration increased above the Tanner stage-specific reference
91 range (n=199) underwent further clinical phenotyping by case note review, extracting information on
92 clinical presentation, medical history, height, weight, BMI, bone age, ethnicity, and the underlying
93 cause of androgen excess, as supported by clinical, biochemical and radiological findings in each case
94 with final review by a board-certified pediatric endocrinologist (V.S., T.G.B., N.J.S., N.K., R.P.D.,
95 M.K., J.K., W.H., R.E.K.). Reference data for standardized BMI (BMI SDS) were obtained from the
96 British 1990 dataset (13).

97 Serum androgen measurements

98 Biochemical androgen excess was defined as a serum concentration increased above a local,
99 age-specific reference range (for DHEAS) or above the Tanner-stage specific normative reference
100 range as reported in (14) for A4 and T. Serum A4 and T were analyzed by liquid chromatography-

101 tandem mass spectrometry on a Shimadzu Prominence XR UPLC coupled to a Sciex 6500 Triple
102 Quad mass spectrometer as described previously (12). Briefly, samples are analyzed by liquid-liquid
103 extraction following addition of deuterated internal standards and separated chromatographically
104 using an isocratic elution profile, ionized using positive atmospheric pressure chemical ionization
105 (APCI) and detected according to compound-specific transitions. Serum DHEAS was analyzed using
106 the Roche competitive electrochemiluminescence immunoassay on the Roche Cobas c702 analyzer
107 (12).

108 **Statistical analysis**

109 GraphPad Prism® was used for statistical analysis and generation of graphs. Data were
110 expressed as median and first and third quartile, unless otherwise stated. The Mann-Whitney U test
111 was used for comparison between two groups (pre- and post-pubertal). Spearman Rank correlation
112 was employed to assess correlation between two non-evenly distributed variables. Statistical
113 significance was set at $p < 0.05$.

114 **RESULTS**

115 **Description of the cohort and diagnostic spectrum**

116 A total of 1,525 children had at least one serum concentration of DHEAS, A4 or T measured
117 during the study period. In 487 children (31.9%), all three androgens had been measured
118 simultaneously and were taken forward as the analysis cohort (**Fig. 1**). When applying age-defined
119 cut-offs, 255 children (52.4%) had at least one increased serum androgen; however, when applying
120 Tanner stage-defined cut offs, thus taking into account pubertal development, only 199 children
121 (40.9%) had androgen excess (**Fig. 1**). Those 199 children were phenotypically further characterized
122 as described in the Methods section. There was a pre-dominance of girls (**Table 1**). The median BMI
123 SDS was increased in the overall cohort and higher in the pubertal than in the pre-pubertal group
124 (**Table 1**). The overall cohort was ethnically diverse, with the two largest group comprising Caucasian
125 children (44.2%) and children of South Asian ethnicity (38.7%) (**Table 1**).

126 The overall majority of pre-pubertal children had a diagnosis of PA (n=86; 61%), while at
127 pubertal age PCOS was the most common diagnosis (n=24; 40%) (**Fig. 1**). In both subgroups, rare
128 and very rare underlying causes of androgen excess were also identified, including congenital adrenal
129 hyperplasia (CAH; 7.0%), isolated premature menarche (IPM; 2.5%), central precocious puberty
130 (cPP; 2.5%) and one case each of adrenocortical carcinoma (ACC) and Cushing's disease (CD). In
131 about one third of cases, miscellaneous diagnoses and features were reported or no associated
132 diagnosis was made (**Fig. 1; Suppl. Table 1**).

133 The majority of the 86 children with PA were girls (79%). Girls with PA presented at a
134 median age of 7.2 years, boys at 8.2 years. 41 PA children (48%) were of Caucasian ethnicity, 31
135 children (26%) of South-Asian and 12 children (14%) of Afro-Caribbean descent; the general
136 population in the local area has been recorded as 58.0% Caucasian, 22.5% South Asian, and 9% Afro-
137 Carribean (15). There were no notable gender differences with regards to clinical presentation (**Suppl.**
138 **Table 2**), although acne was rare in boys. The median bone age advancement in the PA cohort was
139 1.88 years (IQR 1.16, 2.33). None of the subjects had notable co-morbidities or were on any regular
140 medication.

141 In subjects diagnosed with adolescent PCOS, the median age at presentation was 15.2 years
142 (IQR 13.1, 15.7). The majority was of South-Asian ethnicity (n=18; 75%); three were Caucasian
143 (12.5%) and two girls were African-Caribbean (8%). The diagnosis of PCOS was established on the
144 basis of the presence of an irregular menstrual cycle and biochemical features of androgen excess. In
145 addition, 63% (n=15) girls also had clinical signs of androgen excess (hirsutism and/or acne) and
146 seven subjects complained about weight gain (29%). The median BMI of the PCOS subjects was 27.1
147 kg/m² (2.24 SDS; IQR 0.91, 2.58). None of the PCOS subjects had significant co-morbidities, and
148 they were not on any anti-androgenic medication or metformin at presentation.

149 All 14 CAH patients had a genetically confirmed diagnosis of 21-hydroxylase (CYP21A2)
150 deficiency; 12 had the classic salt-wasting form and two subjects had non-classic CAH. All classic
151 CAH cases were on steroid replacement therapy; the non-classic cases were not on medication.

152 We identified five girls with isolated premature menarche (IPM) and five with central
153 precocious puberty (cPP). All IPM cases presented with isolated vaginal bleeding. All girls with cPP

154 presented with early breast development and additional signs of androgen excess (premature pubarche
155 n=4; early development of axillary hair n=3; acne n=2). As extremely rare cases, one boy presented
156 with adrenocortical carcinoma (ACC) and one boy with Cushing's disease (CD). The ACC case
157 presented at the age of 1.8 years with peripheral precocious puberty. The boy with CD presented at 13
158 years of age with weight gain, easy bruising, headaches and typical Cushingoid appearance and was
159 found to have an ACTH-producing pituitary micro-adenoma.

160 **Patterns of androgen excess according to the underlying diagnosis**

161 Isolated DHEAS excess was the most common biochemical presentation in children
162 presenting with PA (n=58; 67.4%) (**Fig. 2A**). 11 PA subjects (12.8%) had a combination of DHEAS
163 and A4 excess. Isolated A4 or T excess was rare in PA and only found in nine (10.5%) and four
164 (4.7%) subjects. A pattern with all three androgens elevated was only observed in three PA subjects
165 (3.5%). In adolescent PCOS, patients equally frequently presented with isolated DHEAS excess
166 (29%), isolated T excess (25%) or increased serum concentrations of both A4 and T (25%) (**Fig. 2B**).

167 Children with CAH predominantly presented with A4 excess (86%); T and DHEAS were
168 increased in 50% and 33%, respectively. (**Fig. 2C**). Isolated DHEAS was never observed in CAH
169 children, and only one pre-pubertal CAH patient presented with isolated T excess and increases in all
170 three androgens, respectively. In the ACC case, both DHEAS and A4 were increased, the CD case
171 had isolated A4 excess.

172 **Severity of Androgen Excess**

173 In children with PA, serum DHEAS was mostly increased one to two-fold above the upper
174 limit of normal (ULN) and did not exceed 8-fold ULN (**Fig. 3A; Suppl. Table 3**). PA girls had higher
175 DHEAS than boys (p=0.036) (**Suppl. Table 3; Suppl. Fig. 1**). The single ACC case presented with
176 serum DHEAS increased to 28-fold ULN. The majority of children with CAH had normal DHEAS
177 levels (**Fig. 3A; Suppl. Table 3**).

178 A4 excess above two-fold ULN was typically observed in classic CAH patients (**Fig. 3B;**
179 **Suppl. Table 3**). Mild to moderate A4 excess (one- to two-fold ULN) was observed in adolescent

180 PCOS (42%), in some children with PA (24%) and in the ACC case. The boy with CD had severe A4
181 excess. In PA, A4 was higher in boys than girls ($p = 0.0008$) (**Suppl. Fig. 1**).

182 Both mild to moderate (one- to two-fold ULN) and severe (>two-fold ULN) excess of serum
183 T was found in a number of subjects with PA, PCOS and CAH (**Fig. 3C; Suppl. Table 3**). T excess
184 was found in a minority of children with PA (10%), but 2 boys had severe T excess; overall, serum T
185 did not differ between boys and girls with PA (**Suppl. Fig. 1**). In PCOS, T excess was found in 63%
186 of cases, but was severe in one only (**Fig. 3 C**). In classic CAH, six subjects (50%) had T excess,
187 which was severe (5-fold elevation) in one adolescent girl.

188 **DISCUSSION**

189 Here we have simultaneously measured the serum concentrations of the androgen precursors
190 DHEAS and A4 as well as the active androgen T in 487 consecutively recruited children and
191 adolescents in a single tertiary paediatric referral center, covering a population of 5.5 million. The size
192 of our cohort, comprising 199 children with biochemically confirmed androgen excess, enabled us to
193 provide separate analyses of androgen excess pattern and severity in the pre- and post-pubertal age
194 subgroups. Our study cohort included children presenting with clinical features of androgen excess,
195 but also patients with suspicion of complex adrenal and gonadal pathologies, increasing the diverse
196 and complex spectrum of underlying conditions. This enriched our study population for rare and very
197 rare diagnoses. The study population was ethnically very diverse; in comparison to the local
198 background population, there was some over-representation of South Asian and African-Caribbean
199 ethnicities in PA children and particular over-representation of South-Asian ethnicity in the PCOS
200 group. This may partially reflect the higher incidence of PCOS in South Asian subjects (16) as well as
201 the proximity of our center to areas with higher ethnic diversity within the overall catchment area.

202 Previous studies have assessed serum androgens in pre-selected samples of children with
203 distinct androgen excess conditions, mainly PA and adolescent PCOS. PA has been studied over the
204 past 30 years in several case-control studies, in well described cohorts consisting of 10-100 study
205 subjects of various ethnical-geographical backgrounds, but mainly focusing on metabolic
206 consequences in PA (see (1, 2, 17, 18) for comprehensive reviews), however, generally without

207 providing full details on androgen metabolism including severity levels. Two studies reported
208 immunoassay-based androgen concentrations in subjects with PA (19, 20): Virdis et al (1993)
209 reported elevated DHEAS levels in the majority of subjects up to 9-fold above the upper limit of age-
210 matched controls, but normal A4 and T excess only in most subjects studied (19). Voutilainen (1983)
211 did not report DHEAS levels, but found that unconjugated DHEA and A4 were up to 5-fold elevated
212 in 18 PA subjects studied (20).

213 Adrenal androgen excess with elevated serum DHEAS above the age specific-reference range
214 and a marginal increase in downstream androgens is recognized as a key feature of PA (2, 21); others
215 suggested increased serum DHEAS appropriate for Tanner pubertal stage but increased when
216 referring to age-specific reference ranges (22, 23). Of note, the pattern and severity of androgen
217 excess in PA has not been analyzed in detail previously, neither how these differentiate PA from other
218 conditions presenting with androgen excess such as CAH or other even rarer causes.

219 In our cohort, increased serum DHEAS was detected in the majority of children with PA
220 while A4 and T were increased only in a minority of subjects, despite clinical evidence of increased
221 androgen action. DHEAS is an inactive metabolite with no affinity to the androgen receptor,
222 suggesting that downstream conversion of de-sulfated DHEA to potent androgens could occur within
223 the target tissues of androgen action. Our group and others have recently highlighted 11-oxygenated
224 androgens as a major source of androgen excess in conditions like PCOS and CAH (24, 25, 26, 27).
225 The adrenal P450 cytochrome 11 β -hydroxylase (CYP11B1) enzyme efficiently converts A4 to 11-
226 hydroxy-androstenedione, which can be further converted to 11-ketotestosterone (11KT), which has
227 been shown to bind and activate the androgen receptor with similar potency to T (24, 28, 29). In fact,
228 11KT has very recently been shown to feature prominently in children with PA (30), supporting the
229 theory that androgenic effects in PA may be mediated via increased 11-oxygenated androgens.
230 However, measurement of 11-oxygenated androgens does not yet form part of routine androgen
231 assessment in childhood androgen excess and, thus, was not measured in our cohort.

232 Radioimmunoassays (RIAs) were employed in the past in studies assessing androgen
233 metabolism in children, in particular the initial reports from the 1970s (31, 32), which are frequently
234 referenced. RIAs are prone to cross-reactivity and less sensitive to lower circulating concentrations

235 usually found in children. Our study has employed more sensitive and specific tandem mass
236 spectrometry (LC-MS/MS) for the measurement of A4 and T. Clinical biochemistry laboratories are
237 now using mass spectrometry-based steroid panels with increasing frequency, which confronts the
238 clinician often with more results than requested in the first place. Our findings can provide guidance
239 for risk stratification in the assessment of childhood androgen excess.

240 Only recently, LC-MS/MS-based longitudinal measurements of androgens were reported in
241 40 obese girls with adolescent PCOS (33). Interestingly, that study reported elevated A4 and T levels,
242 but normal DHEAS compared to BMI-matched controls. This is in contrast to this study, but also our
243 previous report on pre-menopausal PCOS women (12), where elevated serum DHEAS was the most
244 common finding. We used standard reference values obtained from a lean cohort (14), which is
245 probably most appropriate for daily clinical practice when referring to reference data.

246 In order to biochemically characterize common childhood androgen excess conditions, the
247 patterns and severity of androgen levels may help the clinician to discriminate non-PA and non-PCOS
248 pathology. Children with CAH presented pre-dominantly with A4 and T excess. Certainly, 17OHP
249 elevation would be the key biochemical discriminator to detect of the most common form of CAH,
250 21-hydroxylase deficiency, and should be included in the diagnostic work-up of childhood androgen
251 excess (1, 7). A basal serum 17OHP threshold of 2 ng/ml (6 nmol/L) has been shown to distinguish
252 PA from non-classic CAH with high sensitivity and specificity (34). All the patients with classic CAH
253 in our cohort were on hydrocortisone replacement therapy and hence severity and pattern of androgen
254 excess will be distinct from androgen excess in newly diagnosed CAH patients. However, the serum
255 androgen signatures observed in our CAH study sample form a very characteristic profile, which is
256 helpful for the clinician in interpreting serum androgen profiles to differentiate CAH from other
257 disorders associated with androgen excess.

258 Previous work has provided limited information on circulating androgens in girls with central
259 precocious puberty (cPP) or isolated premature menarche (IPM). Pubic or axillary hair development
260 are rarely part of the spectrum in IPM (35), but have been reported in more than 60% of children with
261 cPP (36). All girls with cPP (but none of the girls with IPM) in our cohort had additional (early)
262 pubarche, which prompted the assessment of serum androgens. In our study, all five girls with IPM

263 had mild DHEAS excess, which could reflect concomitant (or pre-existing) exaggerated adrenarche.
264 Indeed it has been shown that higher adrenal androgens are linked to an earlier onset of puberty with a
265 shorter peak height velocity (37). The underlying etiology of IPM is not well understood, and it is
266 considered to be a benign, self-limiting condition (35). However, one might speculate that
267 aromatization of excess androgens could expose the endometrium to higher levels of estrogens,
268 enhancing the build-up of the endometrial lining, ultimately resulting in menarche.

269 Adrenocortical carcinoma (ACC) is an extremely rare entity in children, apart from certain
270 geographical areas like Brazil where ACC is more prevalent due to a distinct founder mutation
271 (p.R337H) of the *TP53* gene (38). The general rarity of ACC is also reflected in our study population
272 with a single case diagnosed in 487 children over a 5-year study period. Interestingly, our patient also
273 carried the Brazilian TP53 founder mutation, although the family was of South Asian origin. Based on
274 a recent larger case series of children with ACC from the US (41 cases identified over a period of 60
275 years), androgen excess is the most frequently presenting steroid abnormality in childhood ACC (39).
276 Details on serum androgen concentrations at presentation, however, are not widely reported in
277 childhood ACC, presumably due to the rarity of the disease, complicated by historic nature of cases
278 and varying assay methodologies. Based on our study and what is known from the literature, the
279 findings certainly indicate that severe DHEAS excess beyond 8-fold ULN should prompt urgent
280 further investigations to exclude ACC-related androgen excess.

281 In conclusion, we have undertaken a detailed analysis of pattern and severity of androgen
282 excess in a large cohort of children of pre- and post-pubertal age. Our findings provide unique insights
283 into the variety and frequency of childhood androgen excess conditions and the utility of combined
284 measurements of serum DHEAS, A4 and T. DHEAS excess is rare in CAH, which typically features
285 A4 excess. In contrast, DHEAS excess is characteristic for PA and frequently found in adolescent
286 PCOS; serum DHEAS increased above 8-fold ULN should prompt the clinician to perform further
287 investigations to exclude sinister underlying pathology.

288

289 **Disclosure summary:** The authors have nothing to declare.

290 **Study approval:** Full study approval has been obtained according to local Institutional Review Board
291 procedures.

292 **Financial and Fellowship support:** This work was funded by the Wellcome Trust (Investigator
293 Award 209492/Z/17/Z, to W.A.). J.I. is a National Institute of Health Research (NIHR) UK Clinical
294 Lecturer and W.A. receives support from the NIHR Biomedical Research Centre Birmingham. The
295 views expressed in this publication are those of the author(s) and not necessarily those of the National
296 Health Service, the National Institute for Health Research, or the Department of Health.

297

299 **REFERENCES**

300

- 301 1. Idkowiak J, Lavery GG, Dhir V, Barrett TG, Stewart PM, Krone N, Arlt W. Premature
302 adrenarche: novel lessons from early onset androgen excess. *European journal of*
303 *endocrinology / European Federation of Endocrine Societies* 2011 **165** 189–207.
- 304 2. Utriainen P, Laakso S, Liimatta J, Jääskeläinen J, Voutilainen R. Premature Adrenarche - A
305 Common Condition with Variable Presentation. *Hormone research in paediatrics* 2015 **83(4)**
306 221-231.
- 307 3. Williams RM, Ong KK, Dunger DB. Polycystic ovarian syndrome during puberty and
308 adolescence. *Molecular and cellular endocrinology* 2013 **373(1-2)** 61-67.
- 309 4. Rosenfield RL. The Diagnosis of Polycystic Ovary Syndrome in Adolescents. *PEDIATRICS*
310 2015 **136** 1154–1165.
- 311 5. Gupta N, Rivera M, Novotny P, Rodriguez V, Bancos I, Lteif A. Adrenocortical Carcinoma in
312 Children: A Clinicopathological Analysis of 41 Patients at the Mayo Clinic from 1950 to 2017.
313 *Hormone research in paediatrics* 2018 **90(1)** 8-18.
- 314 6. El-Maouche D, Arlt W, Merke DP. Congenital adrenal hyperplasia. *Lancet* 2017 **390** 2194–
315 2210.
- 316 7. Williams RM, Ward CE, Hughes IA. Premature adrenarche. *Archives of disease in childhood*
317 2012 **97** 250–254.
- 318 8. Taieb J, Mathian B, Millot F, Patricot MC, Mathieu E, Queyrel N, Lacroix I, Somma-Delpero
319 C, Boudou P. Testosterone measured by 10 immunoassays and by isotope-dilution gas
320 chromatography-mass spectrometry in sera from 116 men, women, and children. *Clinical*
321 *chemistry* 2003 **49** 1381–1395.
- 322 9. Rosner W, Auchus RJ, Azziz R, Sluss PM, Raff H. Position statement: Utility, limitations, and
323 pitfalls in measuring testosterone: an Endocrine Society position statement. *Journal of Clinical*
324 *Endocrinology & Metabolism* 2007 **92** 405–413.
- 325 10. Kulle AE, Riepe FG, Melchior D, Hiort O, Holterhus PM. A novel ultrahigh pressure liquid
326 chromatography tandem mass spectrometry method for the simultaneous determination of
327 androstenedione, testosterone, and dihydrotestosterone in pediatric blood samples: age- and
328 sex-specific reference data. *The Journal of clinical endocrinology and metabolism* 2010 **95**
329 2399–2409.
- 330 11. Fanelli F, Gambineri A, Mezzullo M, Vicennati V, Pelusi C, Pasquali R, Pagotto U. Revisiting
331 hyper- and hypo-androgenism by tandem mass spectrometry. *Rev Endocr Metab Disord* 2013
332 **14** 185–205.
- 333 12. Elhassan YS, Idkowiak J, Smith K, Asia M, Gleeson H, Webster R, Arlt W, O'Reilly MW.
334 Causes, Patterns, and Severity of Androgen Excess in 1205 Consecutively Recruited Women.
335 *The Journal of clinical endocrinology and metabolism* 2018 **103** 1214–1223.
- 336 13. Pan H, access TCBLGAMEAIT, 2012. LMSgrowth, a Microsoft Excel add-in to access
337 growth references based on the LMS method.
- 338 14. Kushnir MM, Blamires T, Rockwood AL, Roberts WL, Yue B, Erdogan E, Bunker AM,
339 Meikle AW. Liquid chromatography-tandem mass spectrometry assay for androstenedione,

- 340 dehydroepiandrosterone, and testosterone with pediatric and adult reference intervals. *Clinical*
341 *chemistry* 2010 **56** 1138–1147.
- 342 15. Office for National Statistics, 2011 Census: Digitised Boundary Data (England and Wales).
343 UK Data Service Census Support. Downloaded from: <https://borders.ukdataservice.ac.uk/>
- 344 16. Bozdag G, Mumusoglu S, Zengin D, Karabulut E, Yildiz BO. The prevalence and phenotypic
345 features of polycystic ovary syndrome: a systematic review and meta-analysis. *Human*
346 *reproduction (Oxford, England)* 2016 **31** 2841–2855.
- 347 17. Ibáñez L, Dimartino-Nardi J, Potau N, Saenger P. Premature adrenarche--normal variant or
348 forerunner of adult disease? *Endocrine reviews* 2000 **21** 671–696.
- 349 18. Rosenfield RL. Hyperandrogenism in peripubertal girls. *Pediatric clinics of North America*
350 1990 **37** 1333–1358.
- 351 19. Virdis R, Zampolli M, Ibanez L, Ghizzoni L, Street ME, Vicens-Calvet E. Il pubarca
352 prematuro. *Riv Ital Pediatr* 1993 **19** 569–579.
- 353 20. Voutilainen R, Perheentupa J, Apter D. Benign premature adrenarche: clinical features and
354 serum steroid levels. *Acta paediatrica Scandinavica* 1983 **72** 707–711.
- 355 21. Rosenfield RL. Clinical review: Identifying children at risk for polycystic ovary syndrome.
356 *The Journal of clinical endocrinology and metabolism* 2007 **92** 787–796.
- 357 22. Utriainen P, Voutilainen R, Jääskeläinen J. Continuum of phenotypes and sympathoadrenal
358 function in premature adrenarche. *European journal of endocrinology* 2009 **160** 657–665.
- 359 23. Voutilainen R, Jääskeläinen J. Premature adrenarche: Etiology, clinical findings, and
360 consequences. *The Journal of steroid biochemistry and molecular biology* 2014 **145** 226–236.
- 361 24. Pretorius E, Africander DJ, Vlok M, Perkins MS, Quanson J, Storbeck KH. 11-
362 Ketotestosterone and 11-Ketodihydrotestosterone in Castration Resistant Prostate Cancer:
363 Potent Androgens Which Can No Longer Be Ignored. *PloS one* 2016 **11** e0159867.
- 364 25. Pretorius E, Arlt W, Storbeck KH. A new dawn for androgens: Novel lessons from 11-
365 oxygenated C19 steroids. *Molecular and cellular endocrinology* 2017 **441** 76–85.
- 366 26. Turcu AF, Nanba AT, Chomic R, Upadhyay SK, Giordano TJ, Shields JJ, Merke DP, Rainey
367 WE, Auchus RJ. Adrenal-derived 11-oxygenated 19-carbon steroids are the dominant
368 androgens in classic 21-hydroxylase deficiency. *European journal of endocrinology /*
369 *European Federation of Endocrine Societies* 2016 **174** 601–609.
- 370 27. O'Reilly MW, Kempegowda P, Jenkinson C, Taylor AE, Quanson JL, Storbeck KH, Arlt W.
371 11-oxygenated C19 steroids are the predominant androgens in polycystic ovary syndrome. *The*
372 *Journal of clinical endocrinology and metabolism* 2016 **102** 840–848.
- 373 28. Rege J, Nakamura Y, Satoh F, Morimoto R, Kennedy MR, Layman LC, Honma S, Sasano H,
374 Rainey WE. Liquid chromatography-tandem mass spectrometry analysis of human adrenal
375 vein 19-carbon steroids before and after ACTH stimulation. *The Journal of clinical*
376 *endocrinology and metabolism* 2013 **98** 1182–1188.
- 377 29. Storbeck KH, Bloem LM, Africander D, Schloms L, Swart P, Swart AC. 11β-
378 Hydroxydihydrotestosterone and 11-ketodihydrotestosterone, novel C19 steroids with

- 379 androgenic activity: a putative role in castration resistant prostate cancer? *Molecular and*
380 *cellular endocrinology* 2013 **377** 135–146.
- 381 30. Rege J, Turcu A, Kasa-Vubu JZ, Lerario AM, Auchus GC, Auchus RJ, Smith JM, White PC,
382 Rainey WE. 11-ketotestosterone is the dominant circulating bioactive androgen during normal
383 and premature adrenarche. *The Journal of clinical endocrinology and metabolism* 2018 **98**
384 1182-1188.
- 385 31. Korth-Schutz S, Levine LS, New MI. Evidence for the adrenal source of androgens in
386 precocious adrenarche. *Acta endocrinologica* 1976 **82** 342–352.
- 387 32. de Peretti E, Forest MG. Pattern of plasma dehydroepiandrosterone sulfate levels in humans
388 from birth to adulthood: evidence for testicular production. *Journal of Clinical Endocrinology*
389 *& Metabolism* 1978 **47** 572–577.
- 390 33. Reinehr T, Kulle A, Rothermel J, Knop-Schmenn C, Lass N, Bosse C, Holterhus PM.
391 Longitudinal analyses of the steroid metabolome in obese PCOS girls with weight loss.
392 *Endocrine connections* 2017 **6** 213–224.
- 393 34. Armengaud JB, Charkaluk ML, Trivin C, Tardy V, Bréart G, Brauner R, Chalumeau M.
394 Precocious pubarche: distinguishing late-onset congenital adrenal hyperplasia from premature
395 adrenarche. *The Journal of clinical endocrinology and metabolism* 2009 **94** 2835–2840.
- 396 35. Nella AA, Kaplowitz PB, Ramnitz MS, Nandagopal R. Benign vaginal bleeding in 24
397 prepubertal patients: clinical, biochemical and imaging features. *Journal of pediatric*
398 *endocrinology & metabolism* 2014 **27** 821–825.
- 399 36. Giabicani E, Allali S, Durand A, Sommet J, Couto-Silva AC, Brauner R. Presentation of 493
400 consecutive girls with idiopathic central precocious puberty: a single-center study. *PloS one*
401 2013 **8** e70931.
- 402 37. Remer T, Shi L, Buyken AE, Maser-Gluth C, Hartmann MF, Wudy SA. Prepubertal
403 Adrenarchal Androgens and Animal Protein Intake Independently and Differentially Influence
404 Pubertal Timing. *The Journal of clinical endocrinology and metabolism* 2010 **6** 3002-3009.
- 405 38. Achatz MI, Zambetti GP. The Inherited p53 Mutation in the Brazilian Population. *Cold Spring*
406 *Harbor perspectives in medicine* 2016 **6** a026195.
- 407 39. Grundy R, Walker DA. Androgen secreting adrenocortical carcinomas. *Archives of disease in*
408 *childhood* 2000 **82** 183–183.

409

410

411 **FIGURE LEGENDS**

412

413 **Fig. 1:** Flowchart of the distribution of diagnoses according to pre-pubertal vs. post-pubertal status in
414 487 children who underwent simultaneous measurement of serum DHEAS, A4 and T.

415 PA, premature adrenarche; CAH, congenital adrenal hyperplasia; IPM, isolated premature menarche;
416 ACC, adrenocortical carcinoma; CD, Cushing's disease; PCOS, polycystic ovary syndrome; cPP,
417 central precocious puberty.

418

419 **Fig. 2:** Distribution of serum androgen excess patterns in (A) children with premature adrenarche, (B)
420 girls with polycystic ovary syndrome and (C) children with congenital adrenal hyperplasia. White
421 bars represent pre-pubertal subjects, black bars post-pubertal subjects.

422

423 **Fig. 3:** Severity of androgen excess according to diagnosis and serum androgen measured. Median
424 values for each diagnosis are denoted by a solid black or white line. Androgen excess levels are
425 represented as 'fold increase above upper limit of normal (ULN)'; levels above '1' therefore indicate
426 androgen excess, indicated by the black interrupted line. An arbitrary defined cut-off for severe
427 androgen excess from 2-fold ULN is indicated by a black dotted line.

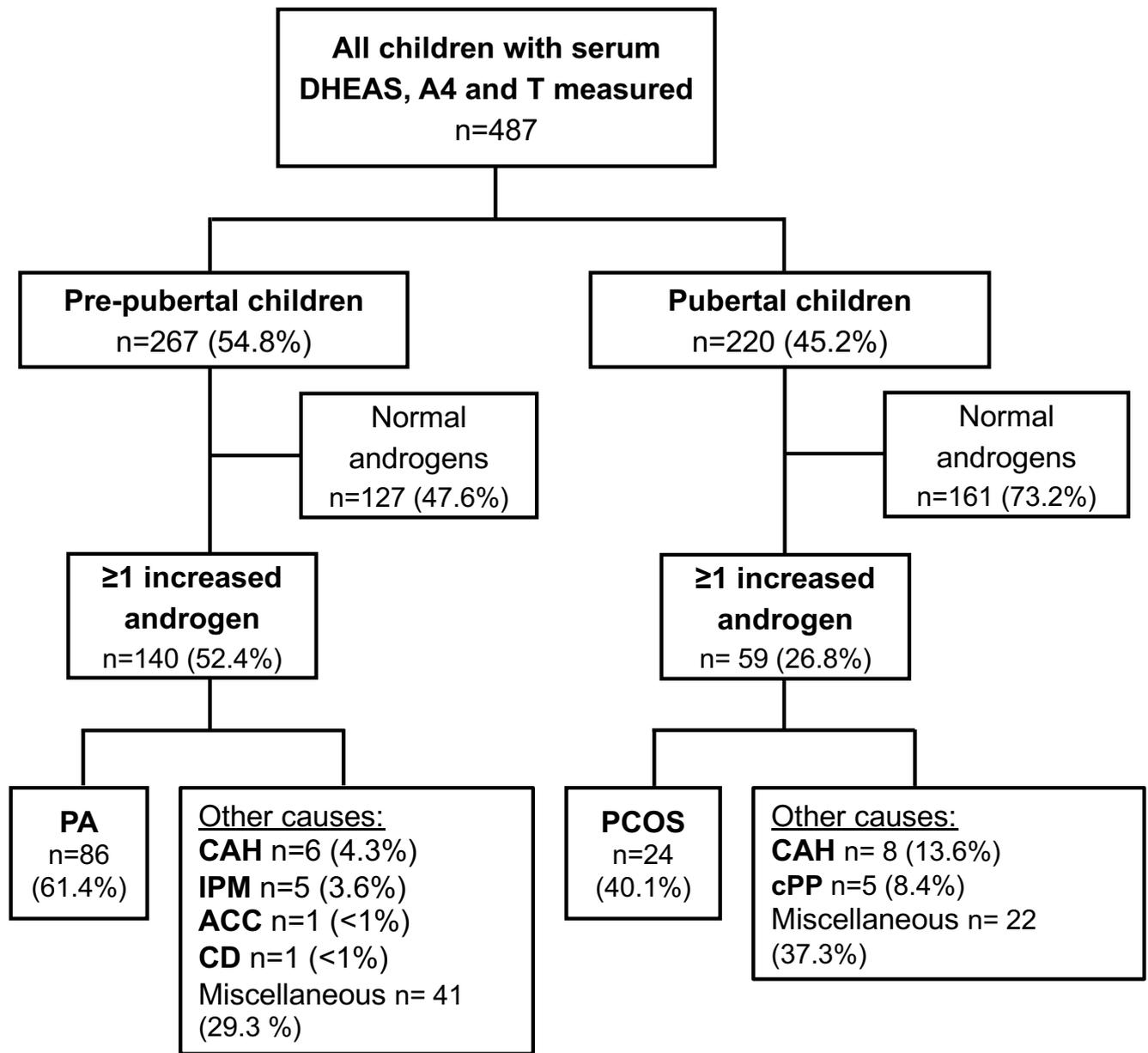
428 PA, premature adrenarche; PCOS, polycystic ovary syndrome; DoP, disorders of puberty (closed
429 circles: central precocious puberty; open circles: isolated premature menarche); CAH, congenital
430 adrenal hyperplasia (closed circles: classic CAH; open circles: non-classic CAH); ACC,
431 adrenocortical carcinoma; CD, Cushing's disease.

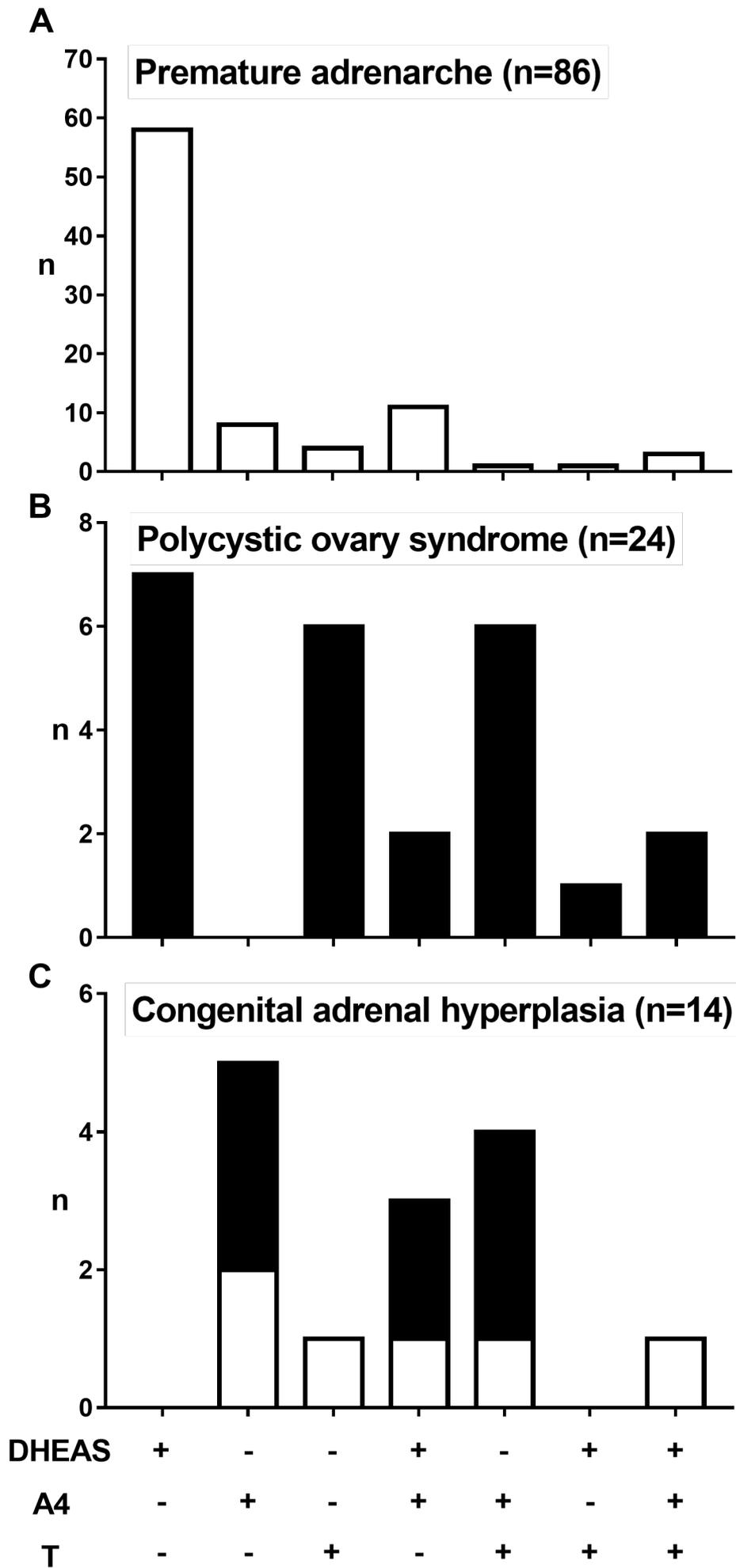
432

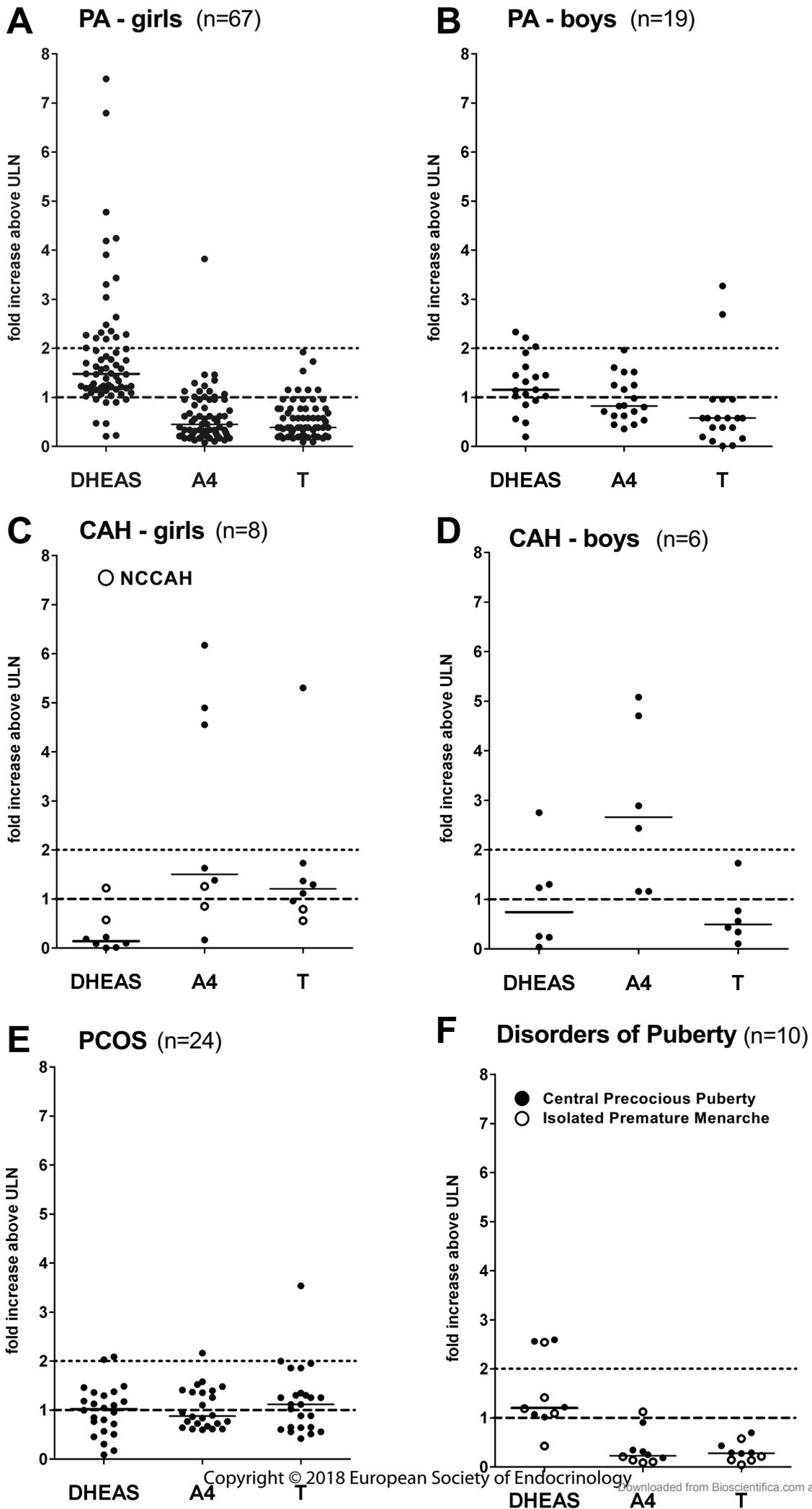
Table 1: Baseline demographics of 199 children with biochemical androgen excess as defined by serum concentrations above the reference range for at least one of three measured androgens (DHEAS, androstenedione, and testosterone).

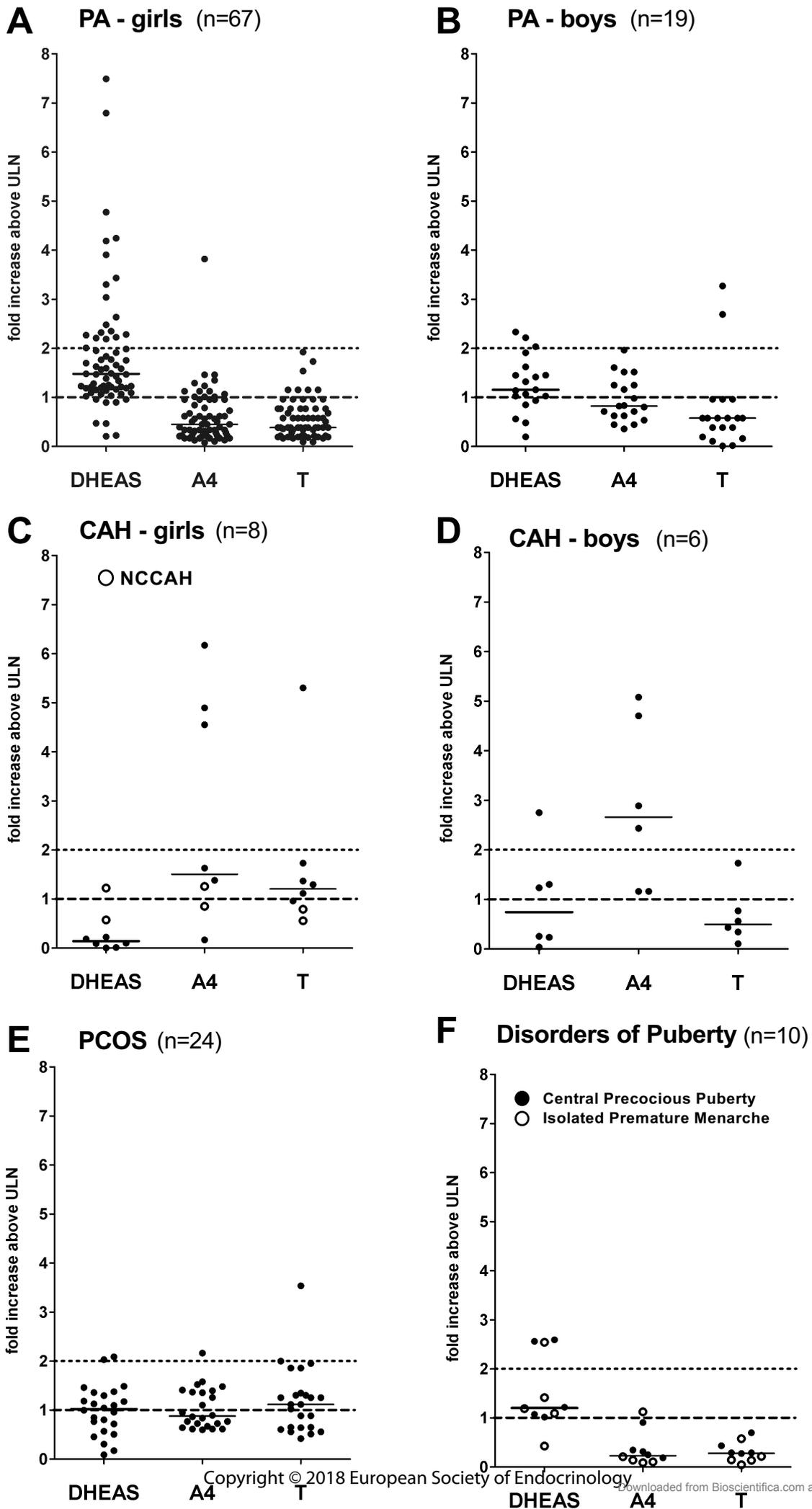
| | Total | Pre-pubertal | Pubertal |
|---|----------------------|----------------------|----------------------|
| Patients with ≥ 1 of 3 androgens increased | 199 | 140 (70.3%) | 59 (29.7%) |
| Age (years) Median (Q1, Q3) | 8.3 (6.8; 13.3) | 7.4 (4.6, 8.5) | 14.9 (13.4, 15.6) |
| Gender | | | |
| Girls | 141 (70.8%) | 89 (63.6%) | 52 (88.1%) |
| Boys | 58 (29.2%) | 51 (36.4%) | 7 (11.9%) |
| BMI (kg/m²) Median (Q1, Q3) | 19.5 (16.4; 25.1) | 17.9 (15.9; 22.0) | 26.8 (19.8; 31.0) |
| BMI SDS Median (Q1, Q3) | 1.35 (0.2; 2.6) | 1.26 (-0.1; 2.5) | 1.88 (0.6; 2.7) |
| Ethnicity* | | | |
| Caucasian | 91 (44.2%) | 64 (44.2%) | 27 (44.2%) |
| South Asian | 76 (38.7%) | 50 (36.9%) | 26 (44.1%) |
| Afro-Caribbean | 16 (8.0%) | 13 (9.4%) | 3 (4.9%) |
| Mixed background | 3 (1.5%) | 2 (1.5%) | 1 (1.6%) |
| Other | 1 (0.5%) | 0 | 1 (1.6%) |
| Unknown | 13 (6.5%) | 11 (7.2%) | 3 (4.9%) |

* Ethnicity distribution pattern in the Birmingham area is: Caucasian 58.0%, Asian 26.6% (South Asians 22.5%, other Asians 4.08%), Afro-Caribbean 9.0%, Mixed 4.4% and other 2.0%. Source: United Kingdom Census 2011, Office for National Statistics (15).









Suppl. Table 1: Miscellaneous diagnoses and features (as specified in Fig. 1) identified in 63 patients with at least one serum androgen concentration increased above the Tanner stage-specific reference range, but no conclusive diagnosis explaining androgen excess.

| | Pre-pubertal N=41 | | Post-pubertal N=22 | |
|---|---------------------------------|--|--|---------------------------------|
| | Girls | Boys | Girls | Boys |
| Diagnoses/ features likely to be associated with or due to androgen excess N=13 | N=4 | N=3 | N=6 | N=0 |
| | Clitoromegaly, resolving (n=2) | Bilateral adrenal hemorrhages | Clitoromegaly (resolved) | |
| | Hypertrichosis, resolving | Germ cell tumor | Isolated acne (n=2) | |
| | Isolated thelarche | Anti-Müllerian-Hormone resistance | Oligomenorrhea (resolved) Excessive sweating Mood swings | |
| Diagnoses/ features not likely to be associated with or due to androgen excess N=50 | N=13 | N=21 | N=13 | N=3 |
| | No diagnosis (n=5) | No diagnosis (n=9) | Simple Obesity (n=9) | Delay of growth and puberty |
| | Complex cloacal anomaly | Micropenis (n=2) | Road traffic accident | Buried penis, impalpable testes |
| | Electrolyte abnormalities | Klinefelter syndrome | Bardet Biedl Syndrome | Wiedemann Beckwith Syndrome |
| | Primary ovarian failure | Septo-optic dysplasia (n=2) | Atopic skin | |
| | Alström syndrome (n=2) | Pubertal arrest/ primary gonadal failure | Silver Russell Syndrome | |
| | CHARGE syndrome | CHARGE syndrome | | |
| | Obesity | Hypospadias (n=2) | | |
| | Aldosterone synthase deficiency | Alström syndrome Prader Willi syndrome Supra-sellar cyst | | |

Suppl. Table 2: Clinical signs and symptoms in 86 children presenting with premature adrenarche

| | Total N=86 (100%) | Girls N=67 (79%) | Boys N=18 (21%) |
|--|-----------------------------|----------------------------|---------------------------|
| Premature Pubarche | 60 (71%) | 50 (75%) | 10 (56%) |
| Body odor | 48 (56%) | 38 (57%) | 10 (56%) |
| Premature development of axillary hair | 25 (29%) | 21 (31%) | 4 (22%) |
| Tall stature/ growth acceleration | 21 (25%) | 17 (31%) | 4 (22%) |
| Acne | 14 (17%) | 13 (19%) | 1 (6%) |
| Mood swings | 14 (17%) | 11 (16%) | 3 (17%) |
| Breast development/ gynecomastia | 12 (14%) | 11 (16%) | 1 (6%) |

Suppl. Table 3: Severity of androgen excess in children 136 according to underlying diagnosis. Serum androgen data are presented as fold increased above the upper limit of normal (ULN) and as absolute serum concentrations, both expressed as median value and inter quartile ranges (IQR), if appropriate.

| | Premature Adrenache girls n=67 | Premature Adrenarche boys n=19 | Polycystic ovary syndrome n=24 | Congenital adrenal hyperplasia girls n=8 | Congenital adrenal hyperplasia boys n=6 | Isolated premature menarche n=5 | Central Precocious puberty n=5 | Adreno-cortical carcinoma n=1 | Cushing's disease n=1 |
|---------------------------------------|--|--|--|--|---|---|--|---|---------------------------------|
| Serum DHEAS | | | | | | | | | |
| Fold increase above ULN (median, IQR) | 1.5 (1.2; 2.2) | 1.1 (1.0; 1.5) | 1.0 (0.7, 1.3) | 0.1 (0.1; 0.3) | 0.7 (0.2; 1.3) | 1.2 (1.0; 1.4) | 1.2 (1.1; 2.7) | 29.8 | 0.4 |
| µmol/L (median, IQR) | 2.8 (2.2; 3.7) | 3.6 (2.7; 5.3) | 9.1 (6.0; 11.7) | 0.7 (0.4; 2.8) | 2.2 (0.9; 3.3) | 2.6 (2.4; 3.3) | 5.9 (2.5; 6.0) | 15.8 | 2.3 |
| Serum androstenedione | | | | | | | | | |
| Fold increase above ULN (median, IQR) | 0.4 (0.3; 1.0) | 0.8 (0.6, 1.3) | 0.9 (0.7; 1.4) | 1.5 (1.2; 4.6) | 2.7 (1.5; 4.2) | 0.1 (0.1; 0.2) | 0.3 (0.3; 0.4) | 1.5 | 3.8 |
| nmol/L (median, IQR) | 1.0 (0.6; 1.7) | 1.2 (0.8; 1.7) | 6.3 (5.1; 9.9) | 7.8 (5.3; 25.7) | 9.1 (2.8; 13.4) | 1.0 (0.7; 1.1) | 1.5 (1.2; 2.7) | 4.5 | 6.4 |
| Serum testosterone | | | | | | | | | |
| Fold increase above ULN (median, IQR) | 0.4 (0.2; 0.8) | 0.6 (0.3; 0.8) | 1.1 (0.7, 1.3) | 1.2 (0.9; 1.5) | 0.5 (0.4; 0.7) | 0.1 (0.1; 0.2) | 0.3 (0.3; 0.4) | 0.1 | 0.6 |
| nmol/L (median, IQR) | 0.3 (0.2; 0.4) | 0.3 (0.2; 0.5) | 2.4 (1.4; 2.9) | 1.8 (1.1; 2.0) | 6.7 (1.5; 12.2) | 0.3 (0.2; 0.3) | 0.6 (0.4; 0.6) | 0.9 | 0.1 |

