

Rebecca Clarke-Harris,^{1,2} Terence J. Wilkin,³ Joanne Hosking,⁴ Jonathan Pinkney,⁴ Alison N. Jeffery,⁴ Brad S. Metcalf,³ Keith M. Godfrey,^{2,5} Linda D. Voss,⁴ Karen A. Lillycrop,⁶ and Graham C. Burdge¹



PGC1 α Promoter Methylation in Blood at 5–7 Years Predicts Adiposity From 9 to 14 Years (EarlyBird 50)

Diabetes 2014;63:2528–2537 | DOI: 10.2337/db13-0671

The early environment, acting via epigenetic processes, is associated with differential risk of cardiometabolic disease (CMD), which can be predicted by epigenetic marks in proxy tissues. However, such measurements at time points disparate from the health outcome or the environmental exposure may be confounded by intervening stochastic and environmental variation. To address this, we analyzed DNA methylation in the peroxisome proliferator-activated receptor γ coactivator 1 α promoter in blood from 40 children (20 boys) collected annually between 5 and 14 years of age by pyrosequencing. Body composition was measured annually by dual X-ray absorptiometry, physical activity by accelerometry, and pubertal timing by age at peak high velocity. The effect of methylation on transcription factor binding was investigated by electrophoretic mobility shift assays. Seven cytosine guanine dinucleotide (CpG) loci were identified that showed no significant temporal change or association with leukocyte populations. Modeling using generalized estimating equations showed that methylation of four loci predicted adiposity up to 14 years independent of sex, age, pubertal timing, and activity. Methylation of one predictive locus modified binding of the proadipogenic pre-B-cell leukemia homeobox-1/homeobox 9 complex. These findings suggest that temporally stable CpG loci measured in childhood may have utility in predicting CMD risk.

Genetic variations explain only part of the variability in risk of cardiometabolic disease (CMD) (1). Epidemiological studies suggest that the early life environment also makes an important contribution (1), and both experimental and observational studies have implicated variation in the epigenetic regulation of specific genes as a key mechanism (2). An epigenetic explanation is supported by altered patterns of DNA methylation in individuals exposed to nutritional constraint in utero and by predictive associations between epigenetic marks in samples collected early in life and subsequent assessment of risk factors for CMD (3–9). For example, exposure to famine in utero is associated with altered methylation status of specific cytosine guanine dinucleotide (CpG) loci in blood in imprinted (6) and nonimprinted (7) genes related to the CMD phenotype in elderly individuals. Furthermore, methylation of the retinoid-x-receptor- α in umbilical cord predicted >25% of the variation in age- and sex-adjusted fat mass in children at 6 and 9 years old (3). Such findings imply that epigenetic changes associated with the CMD phenotype are induced by environmental exposures early in life and persist beyond the period of challenge.

However, crucial evidence from studies in childhood and from longitudinal studies is lacking (10) and may yet be challenged by recent reports of marked variation in DNA methylation of specific CpG loci during childhood

¹Academic Unit of Human Development and Health, Faculty of Medicine, University of Southampton, Southampton, U.K.

²National Institute for Health Research Southampton Biomedical Research Centre, University of Southampton, and University Hospital Southampton National Health Service Foundation Trust, Southampton, U.K.

³University of Exeter Medical School, Exeter, U.K.

⁴Plymouth University Peninsula Schools of Medicine and Dentistry, Plymouth, U.K.

⁵Medical Research Council Lifecourse Epidemiology Unit, University of Southampton, Southampton, U.K.

⁶Faculty of Natural and Environmental Sciences, University of Southampton, Southampton, U.K.

Corresponding author: Karen A. Lillycrop, k.a.lillycrop@soton.ac.uk.

Received 3 May 2013 and accepted 6 March 2014.

© 2014 by the American Diabetes Association. See <http://creativecommons.org/licenses/by-nc-nd/3.0/> for details.

(11) and of its response to acute exercise (12) and environmental pollutants (13). Such influences could confound the contribution of early epigenetic variation to future risk of CMD in relation to that of later environmental exposures. Mechanism is a key component of hypothesis testing, but none of the studies reporting association between promoter methylation and CMD risk have so far demonstrated that differential methylation alters gene function (3–9). This limits the plausibility that differentially methylated loci in proxy tissues reflect altered epigenetic regulation of genes in the tissue of interest.

To address these issues, we investigated the temporal stability of CpG loci in the promoter region of peroxisome proliferator-activated receptor γ coactivator (PGC) 1 α in the blood of children obtained annually from 5–14 years. PGC1 α is central to energy homeostasis through regulation of mitochondrial function, pancreatic β -cell function, and adipogenesis (14) and is, therefore, of potential relevance to obesity and CMD risk. We also investigated whether differential methylation of individual CpG loci was related to adiposity and whether differential methylation of any CpGs that were associated with body composition might alter transcription factor binding at that locus.

RESEARCH DESIGN AND METHODS

Subjects and Study Design

We conducted the study in accordance with the ethics guidelines of the Declaration of Helsinki II; ethics approval was granted by the Plymouth Local Research Ethics Committee (1999), and parents gave written consent and children verbal assent. The EarlyBird Diabetes Study incorporates a 1995/1996 birth cohort recruited in 2000/2001 when the children were 5 years old (307 children, 170 boys) (15). Here, we report findings for 40 subjects (20 boys) selected randomly, stratified by insulin resistance at 14 years. (Subject characteristics at 5 and 14 years are summarized in Table 1.) Insulin resistance was determined each year from fasting

glucose (Cobas Integra 700 analyzer; Roche Diagnostics) and insulin (DPC IMMULITE) (cross-reactivity with proinsulin <1%) using the homeostasis model assessment program (16), which has been validated in children (17). BMI was derived from direct measurement of height (Leicester Height Measure; Child Growth Foundation, London, U.K.) and weight (Tanita Solar 1632 electronic scales), performed in blind duplicate and averaged. BMI SD scores were calculated from the British 1990 standards (18). Whole-body dual-energy X-ray absorptiometry scans for body composition were performed annually from age 9 years using a Prodigy Advance fan beam densitometer and analyzed using enCORE 2004 software, version 8.10.027 (GE Healthcare). Physical activity was measured annually from 5 years by accelerometry (ActiGraph [formerly MTI/CSA]) (19,20). Children were asked to wear the accelerometers for 7 consecutive days at each annual time point, and only recordings that captured at least 4 days were used. Pubertal stage was adjusted for by age at peak height velocity (APHV), determined as the tangential velocity at the middle time point of three consecutive rolling height measurements taken 6 months apart. Peripheral blood was collected annually into EDTA tubes after an overnight fast and stored at -80°C .

Analysis of Methylation of Specific CpG Loci by Pyrosequencing

Genomic DNA was prepared from 400 μL whole blood using the QIAamp DNA Blood Mini kit (Qiagen), according to the manufacturer's instructions. Analysis of methylation of individual CpG loci within the PGC1 α promoter was carried out by pyrosequencing (21). Briefly, genomic DNA (1 μg) was treated with sodium metabisulphite using the EZ DNA Methylation kit (Cambridge Bioscience). Modified DNA was amplified with hot start Taq DNA Polymerase (Qiagen) using the PCR primers in Table 2. PCR products (10 μL) were immobilized on streptavidin-sepharose beads (GE Healthcare), washed, denatured, and released into annealing buffer containing the sequencing

Table 1—Subject characteristics at 5 and 14 years

	Boys		Girls	
	5 years	14 years	5 years	14 years
Age (years)	5.0 \pm 0.4	14.0 \pm 0.4	5.0 \pm 0.3	13.9 \pm 0.3
Adiposity (% fat)		22.1 \pm 10.2		31.0 \pm 8.2
BMI SDS	0.17 \pm 0.85	0.68 \pm 1.04	0.40 \pm 0.59	0.75 \pm 0.97
Moderate-vigorous physical activity (min/day)	51.2 \pm 24.9	58.0 \pm 36.1	51.7 \pm 15.6	43.0 \pm 20.0
Insulin resistance (HOMA-IR)	0.49 \pm 0.52	1.21 \pm 1.10	0.75 \pm 0.66	0.98 \pm 1.57
APHV		13.3 \pm 0.58		11.9 \pm 0.97

Data are means \pm SD except for insulin resistance (median \pm interquartile range). Significant sex differences by one-way ANOVA were detected for APHV ($P < 0.001$) and adiposity ($P = 0.03$ at 5 years, $P = 0.004$ at 14 years). HOMA-IR, homeostasis model assessment of insulin resistance; SDS, SD scores standardized for age and sex.

Table 2—PCR and pyrosequencing primers and electrophoretic mobility shift assay probes

	Forward primers (5' to 3')	Reverse primers (3' to 5')	Sequencing primers
CpG loci covered*			
CpG -783 to -841	AAAGTATTTTAAGGAGTAGTTAGGGAGGAAA	CCCCATCCCTTCAACTCCCTTCTTA	
CpG -617 to -652	TGTGGTTTGTTTTTTTTATATGGAGTAAAG	TAAACAACCTCCACCCCAAAAT	
CpG -515 to -521	GAATTTTGGGTGGGAGT	ATCTCCAAATAAACTCAAACTCAAIT	
CpG -783 to -841			ACTCCCAAAAAACAATATTAAATAA (3' to 5')
CpG -617 to -652			GGAGTAAAGAAAATTTAGTAAT (5' to 3')
CpG -515 to -521			AAAAAAAAAAAAAAAAAAAAAAAAAGT (5' to 3')
Electrophoretic mobility shift assay			
Unmethylated probe	GAGCAGAGCAGCAGCGACTGTATTACTA ACACT	AGTGTAGTAAATACAGTCGCTGCTGC TCTGCTC	
Methylated probe	GAGCAGAGCAGCAG ^{me} CGACTGTATTACT AACACT	AGTGTAGTAAATACAGT ^{me} CGCTGCTG CTCTGCTC	
Nonspecific competitor PBX1/Hoxb9 consensus sequence	CCCCAGCCTCCCGGGGTCACCC ATGATTTACGAC	GGGTGACCCCGGGGAGGCTGGGG GTCGTAATCAT	

*Position relative to transcription start site (bases).

primers (Table 2). Pyrosequencing was carried out using PyroMark Gold Q96 Reagents on a PyroMark Q96 MD pyrosequencer (Qiagen), and the percentage methylation was calculated using PyroMark CpG software 1.0.11 (Qiagen). Within-assay precision (coefficient of variation) was CpG -841, 0.3%; CpG -816, 1.6%; CpG -783, 1.9%; CpG -652, 2.6%; CpG -617, 2.7%; CpG -521, 1.8%; and CpG -515, 1.8%. Between-assay precision was CpG -841, 2.0%; CpG -816, 2.4%; CpG -783, 3.4%; CpG -652, 4.4%; CpG -617, 2.8%; CpG -521, 2.7%; and CpG -515, 3.7%.

Analysis of Transcription Factor Binding by Electromobility Shift Assay

Electrophoretic mobility shift assays were performed as described (22) using a LightShift Chemiluminescent EMSA kit (Thermo Scientific). Oligonucleotide probes are detailed in Table 2. Biotin-labeled double-stranded oligonucleotide probes (10 fmol) corresponding to a region of the PGC1 α promoter from -797 to -764 relative to the transcription start site containing either an unmethylated or methylated cytosine base at -783 were incubated with 5 μ g nuclear extracts derived from the SW-872 liposarcoma cells. For testing of specificity of binding, a 50-, 100-, or 500-fold excess of either the unlabeled probe, a nonspecific competitor, a homeobox (HOXB)9/pre-B-cell leukemia homeobox (PBX)-1 consensus sequence, or 1 μ g anti-HOXB9 monoclonal antibody (AbCam) or anti-PBX-1 polyclonal antibody (Abcam) was incubated with the nuclear extract prior to addition of 10 fmol biotin-labeled probe and a further 20-min incubation on ice. Complexes were resolved on a prerun 5% nondenaturing polyacrylamide gel in 0.5 \times Tris-borate-EDTA for 50 min at 100 V and 4°C, followed by semidry transfer (200 mA for 1h) to a positive nylon membrane and ultraviolet cross-linking. After incubation in blocking buffer, the membrane was incubated with streptavidin-horseradish peroxidase conjugate and visualized with a chemiluminescent substrate according to the manufacturer's instructions (Thermo Scientific).

Transfection and Luciferase Reporter Gene Assays

SW-872 cells were transfected using with FuGENE HD (SwitchGear Genomics) according to the manufacturer's instructions. Transfections were carried out with 5×10^3 cells in a 96-well plate and transfected with 100 ng pGL3PGC1 α promoter (-909 to 92 bp) and 1.25 ng pCMV *Renilla* (Promega), together with 0, 250, 500, 750, and 1,000 ng expression vector containing the full-length cDNA of PBX-1 (IRQLp5017E064D; Source BioScience LifeSciences) for 48 h. The amount of transfected DNA for all transfections was equalized by the addition of empty expression vector. Transfections were carried out in triplicate. Luciferase and *Renilla* activity were determined using the dual luciferase assay (Promega) according to the manufacturer's instructions. Data were normalized by dividing luciferase activity by *Renilla* activity.

Statistical Analysis and Modeling

Statistical analyses were performed using IBM SPSS Statistics, version 19.0. Pearson correlation was used to determine the association between percent methylation at baseline (5–7 years) and percent methylation at subsequent ages. A longitudinal tracking coefficient was computed for each CpG, where the measurement at baseline (5–7 years) was regressed on all other measurements from 9 to 14 years simultaneously. In order to take into account the correlations between repeated measurements on the same children, we used generalized estimating equations (23) for determination of the association between methylation at baseline (5–7 years) and adiposity from 9 to 14 years of age. Age was included in the model as a categorical variable, and covariates in the models included sex, APHV, and minutes per week spent in moderate-to-vigorous physical activity. All relevant two-way interactions were tested. Associations between leukocyte cell numbers and methylation of individual CpG loci were investigated by calculation of Pearson correlation coefficient. Because of the focused study design, the statistical analysis did not include correction for multiple testing in order to reduce the risk of type II errors (24).

Of 40 children, 34 had data for adiposity, moderate-to-vigorous physical activity, and APHV at five or more time points between 9 and 14 years of age. The proportion of children who had a measurement of methylation at baseline and at five or more time points between 9 and 14 years of age was 30 of 37 for CpG –41, 34 of 39 for CpG –816, 38 of 39 for CpG –783, 35 of 38 for CpG –652, 26 of 35 for CpG –617, 38 of 39 for CpG –521, and 38 of 39 for CpG –515.

RESULTS

Temporal Stability of the Methylation of CpG Loci in the PGC1 α Promoter Between 5 and 14 Years

Forty subjects (20 boys, 20 girls) were selected from the EarlyBird cohort (15) (Table 1). Data collected at 5–7 years and 8–9 years were combined for statistical analysis in order to ensure complete longitudinal data sets. Seven CpG loci were sequenced (located between –841 to –515 bases relative to the transcription start site) (Fig. 1), which have been shown previously to be hypermethylated and associated with decreased PGC1 α expression in pancreatic islet cells from overweight subjects with type 2 diabetes compared with normal-weight control subjects (26). Methylation of individual CpG loci in the PGC1 α promoter varied from $20.4 \pm 3.5\%$ (CpG –521) to $64.9 \pm 2.8\%$ (CpG –841) across all subjects and years (Fig. 2) and did not differ between sexes ($P \geq 0.05$). Longitudinal tracking coefficients were high for all CpG loci (CpG –515, 0.93; –521, 0.83; –617, 0.97; –652, 0.99; –783, 0.95; –816, 0.96; and –841, 0.91; all $P < 0.001$) such that methylation at 5–7 years predicted between 77 and 88% of the variation at 14 years. There were no significant associations at any age between the proportions of neutrophils or lymphocytes in the blood samples from which the DNA was isolated and the level of methylation of any of the CpG loci

that were measured (all $P > 0.1$; neutrophils $r = -0.002$ to 0.34, lymphocytes 0.001–0.23).

Methylation of Specific CpG Loci in the PGC1 α Promoter at 5–7 Years and Predicted Percent Body Fat

Having established that methylation of these CpG loci tracked from 5–7 to 14 years of age, we next used generalized estimating equations to model the association between methylation at 5–7 years and adiposity (percent body fat) measured annually by dual-energy X-ray absorptiometry from 9 to 14 years of age. Age, sex, APHV, and physical activity and all relevant two-way interactions were included in this model. As expected, there were significant interactions between adiposity and age and sex ($P < 0.001$) and between age and APHV ($P < 0.001$) and physical activity ($P < 0.005$). Methylation of specific CpG loci in the PGC1 α promoter at 5–7 years was significantly associated with future adiposity (Fig. 3). For each 10% difference in methylation at 5–7 years, percent body fat differed by 12.5 (95% CI 4.7–20.3; adjusted 95% CI 2.2–22.7) at CpG locus –841 ($P = 0.002$), 7.5 (2.6–12.4; 1.1–13.9) at CpG –816 ($P = 0.003$), 6.3 (0.9–11.7; –0.8 to 13.4) at CpG –783 ($P = 0.02$), and 7.6 (1.0–14.0; –2.1 to 16.1) at CpG –521 ($P = 0.03$). There were no significant interactions between methylation at any of these loci and sex ($P \geq 0.52$), APHV ($P \geq 0.06$), physical activity ($P \geq 0.23$), or age (all $P \geq 0.21$, except for CpG –521, which showed a significant interaction with age ($P < 0.001$)). There were no significant associations between adiposity and methylation at CpG loci –652 ($\beta = 0.7$ [95% CI –3.3 to 4.6, $P = 0.75$], –617 (2.9 [–1.0 to 6.8], $P = 0.14$), or –515 (1.3 [–1.8 to 4.3], $P = 0.42$) bases.

Exemplification of the Effect of Differential Methylation on Transcription Factor Binding

We used electrophoretic mobility shift assays to determine whether differential methylation at CpG –783, which is located within a putative HoxB9/PBX-1 response element (Fig. 1), altered transcription factor binding. A biotin-labeled double-stranded oligonucleotide probe corresponding to a region of the PGC1 α promoter from –797 to –764 containing either an unmethylated or methylated cytosine base at –783 was incubated with nuclear extracts from the liposarcoma cell line SW-872. Two complexes of similar mobility were seen binding to both the unmethylated and methylated probes, the binding of which (Fig. 3A) was reduced markedly by coincubation with 500-fold excess of the unlabeled probe (specific competitor) but not with a 500-fold excess of an unlabeled nonspecific competitor indicating specific protein binding to this region of the PGC1 α promoter. For determination of whether methylation at CpG –783 affected binding to this sequence, the unmethylated biotin-labeled probe was incubated with nuclear extracts from the liposarcoma cells with a 50-, 100-, and 500-fold excess of either the unmethylated or methylated specific competitor. While binding to the biotin-labeled unmethylated probe was markedly reduced in the presence of a 500-fold excess of the unmethylated

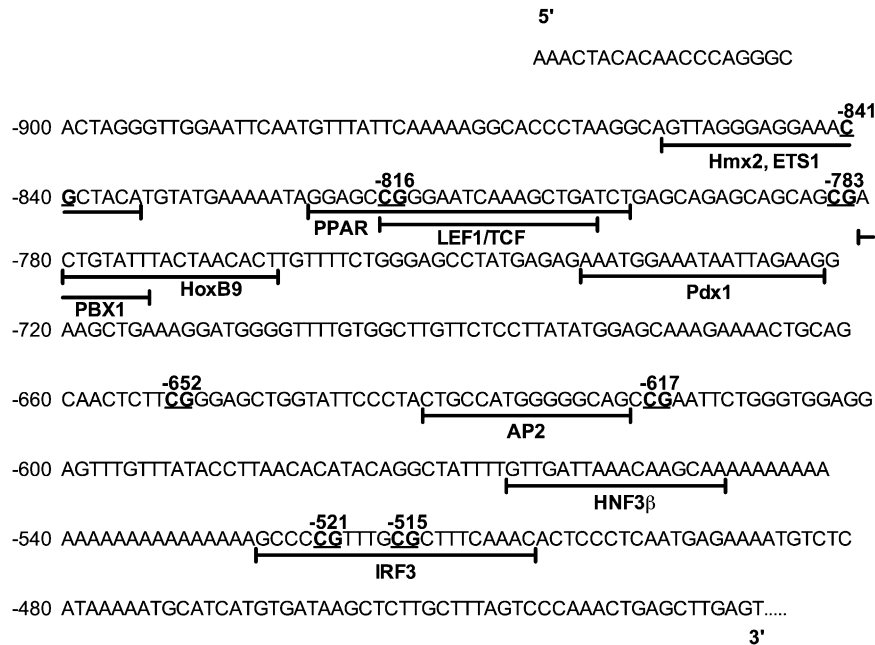


Figure 1—Locations of CpG dinucleotides within the PGC1 α promoter. Locations are defined by bp relative to the transcription start site (25). Putative transcription factor response elements (underlined) were identified by MatInspector (<http://www.genomatix.de/cgi-bin/matinspector>). AP2, adapter-related protein complex-2 β subunit; ETS1, human and murine v-ets avian erythroblastosis virus E26 oncogene homolog 1 factors; Hmx2, H6 family homeobox-2; HNF3 β , hepatocyte nuclear factor 3 β (Foxa-2); IRF3, interferon regulatory factor-3; LEF1/TCF, lymphoid enhancer-binding factor-1; Pdx1, pancreatic and duodenal homeobox-1; PPAR, peroxisome proliferator-activated receptor.

specific competitor, only a 50-fold excess of the methylated specific competitor was required to effectively compete out binding (Fig. 4B). This finding suggests that methylation at CpG -783 enhances binding to the PGC1 α promoter sequence. Increased binding to the methylated sequence was

also observed when the labeled methylated probe was incubated with increasing concentrations of the non-biotin-labeled unmethylated or methylated competitors (data not shown).

Binding to the biotin-labeled unmethylated or methylated probe was markedly diminished by coinubation with 100- and 500-fold excess of an unlabeled oligonucleotide containing the consensus sequence for the HoxB9/PBX-1 heterodimer (Fig. 4C). For confirmation of the identity of the proteins binding to this sequence, antibodies specific to PBX-1 and HOXB9 were incubated with the protein extract prior the addition of the probe. While the addition of the antibody against PBX-1 substantially reduced binding of both complexes to the unmethylated probe (Fig. 5A), an antibody against HOXB9 probe had little effect on protein binding to the unmethylated probe (Fig. 5A). In contrast, antibodies against PBX-1 or HOXB9 both substantially reduced protein binding to the methylated probe (Fig. 5A). To confirm that the transcription factor PBX-1 can regulate PGC1 α promoter activity, we transfected the PGC1 α promoter construct together with increasing concentrations of an expression vector containing PBX-1. We found that the addition of PBX-1 led to a marked decrease in PGC1 α promoter activity in liposarcoma cells, thus confirming that PBX-1 can regulate PGC1 α expression (Fig. 5B).

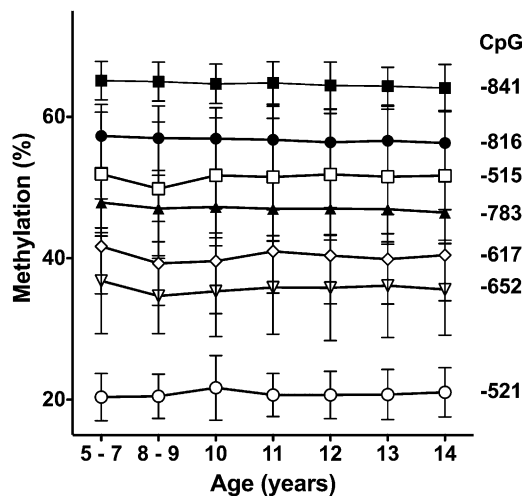


Figure 2—Methylation of specific CpG loci at the PGC1 α promoter in blood is temporally stable from 5–7 to 14 years of age. Data are means \pm SD percent methylation at individual loci, indicated from the transcription start site for boys and girls ($n = 40$). CpG loci are bases from the transcription start site.

DISCUSSION

In order to contribute causally to disease risk and have utility as biomarkers of disease risk, differentially methylated loci

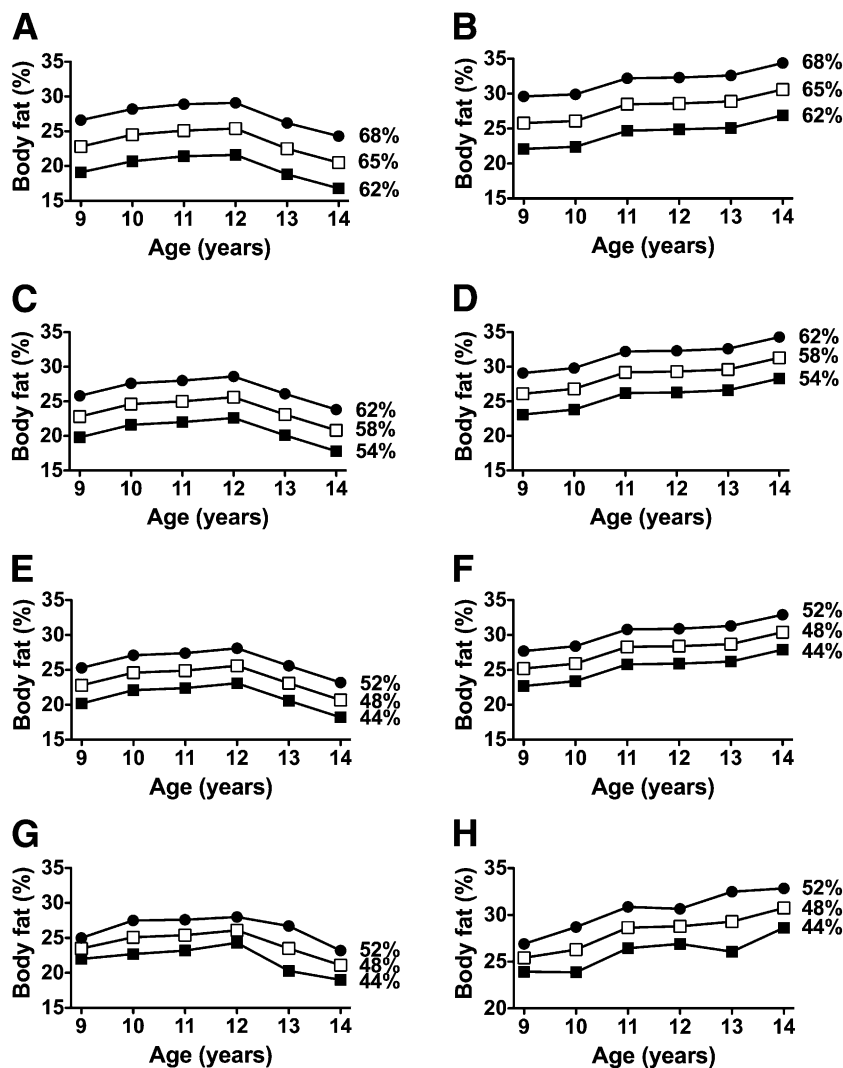


Figure 3—Modeled trajectories of adiposity in boys and girls from 9 to 14 years of age. Trajectories were modeled according to mean (□), -1 SD (■), and $+1$ SD (●) percent methylation for CpG loci for which methylation at 5–7 years was associated significantly with adiposity (percent body fat) from 9 to 14 years in boys (A, C, E, and G) and girls (B, D, F, and H). A and B: CpG -841 . C and D: CpG -816 . E and F: CpG -783 . G and H: CpG -521 .

induced early in life must be stable in the face of subsequent environmental change and have clinical relevance. Our findings provide the first direct evidence that specific epigenetic marks measured in childhood can satisfy these criteria in relation to obesity.

The level of methylation of the seven CpG loci that were measured in the PCG1 α promoter in leukocyte DNA showed significant year-on-year associations between 5–7 and 14 years of age. Heterogeneity in blood cell populations has been identified as a potential confounder for measuring DNA methylation marks in blood (27), although the proportion of variation in methylation explained by leukocyte heterogeneity appears to differ between genes. For example, the proportion of neutrophils accounted for 50% of the variation in interleukin-10 methylation in blood samples collected from adults 11–20 years apart (28). However, the variation in methylation explained by

the proportion of neutrophils was less for imprinted (IGF2, 3.5%; GNASAS, 0.8) and nonimprinted (FTO, 0.1%; LEP, 7.4%) metabolism-associated genes (28). Corresponding differential leukocyte counts were available for all the samples that we analyzed for DNA methylation. There were no significant associations between the proportions of the major circulating leukocyte populations, neutrophils, and lymphocytes and the methylation of the seven CpG loci measured in the PCG1 α promoter. Together, our findings with those of Talens et al. (28) suggest that the impact of variations in leukocyte populations on the methylation status of individual CpG loci measured in whole blood is related to the nature of the gene of interest both in children and in adults and is not a primary concern for the interpretation of this study.

The DNA methylome differs markedly between centenarians and infants (29), which implies either continuous

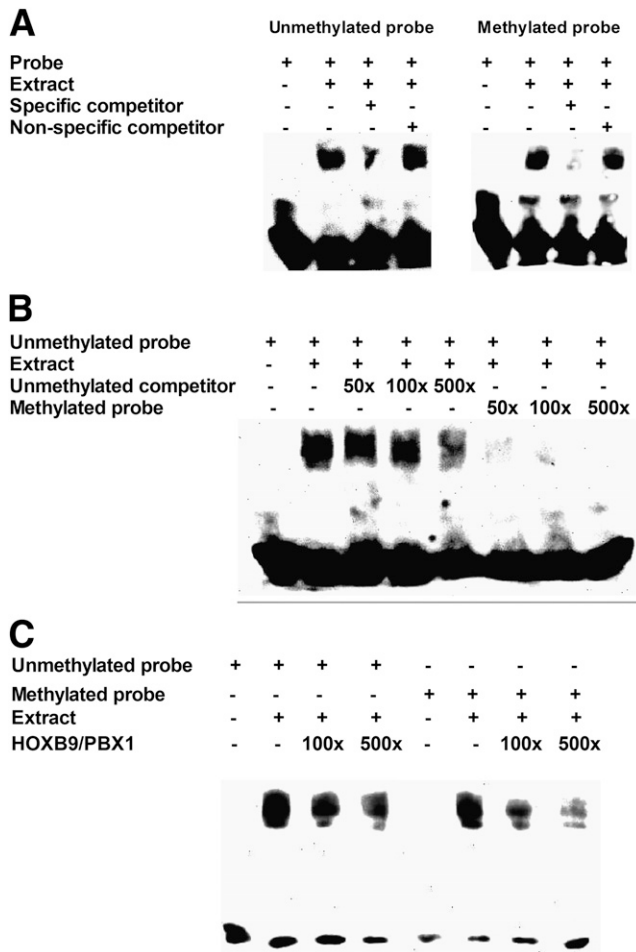


Figure 4—Analysis of the effect of methylation of CpG –783 on transcription factor binding to the PGC1 α promoter sequence by electrophoretic mobility shift assay. The results are typical of three analyses. *A*: The unmethylated and methylated probes showed a strong shift upon incubation with the extract, and this shift was markedly reduced by coincubating with 500-fold excess of the unlabeled specific competitor but not with 500-fold excess of an unlabeled nonspecific competitor. *B*: The unmethylated biotin-labeled probe was incubated with nuclear extracts from the liposarcoma cells with a 50-, 100-, and 500-fold excess of the unmethylated or methylated specific competitor. Binding to the unmethylated probe was competed out with 50-fold excess of the methylated specific competitor compared with 500-fold excess of the unmethylated specific competitor. *C*: Binding to the methylated labeled probe was markedly diminished by coincubation with 100- and 500-fold excess of an unlabeled oligonucleotide containing the consensus sequence for the HoxB9/PBX-1 heterodimer.

plasticity or periods of increased variation in DNA methylation across the life course. Little is known about the plasticity of DNA methylation marks during childhood and puberty, although infancy and puberty have been proposed to be periods of increased epigenetic change (30). Recent studies in mono- and dizygotic twins showed that the methylation of specific CpG loci in genes associated with neurological function in buccal cells differed by up to 40% between 5 and 10 years of age (11). This is in marked contrast to our findings where there was no

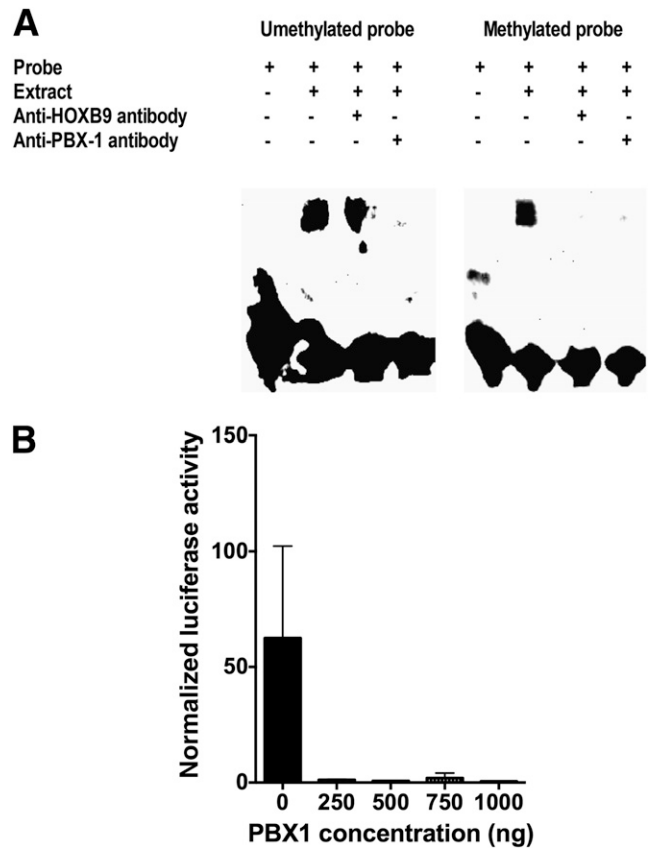


Figure 5—*A*: Analysis of the effect of methylation of CpG –783 on PBX-1 and HOXB9 binding to the PGC1 α promoter sequence by electrophoretic mobility shift assay. The results are typical of three analyses. Antibodies against PBX-1 and HOXB9 were incubated with the nuclear extract for 20 min prior to the addition of the probe. Binding to the unmethylated-labeled probe was markedly diminished by incubation with the PBX-1 antibody, with the HOXB9 antibody having little effect on protein binding. Binding to the methylated-labeled probe was markedly diminished by incubation with both the PBX-1 and the HOXB9 antibodies. *B*: Overexpression of PBX-1 represses PGC1 α expression. The PGC1 α promoter construct was transfected with 0, 250, 500, 750, and 1,000 ng expression vector containing the full-length cDNA of PBX-1. The amount of transfected DNA for all transfections was equalized with the addition of empty expression vector.

significant change in the methylation of the PGC1 α promoter during childhood and puberty. This suggests that, at least for some loci, methylation patterns are established by early childhood, in this case by 5 years, and are not subsequently influenced significantly by environmental factors such as exercise (12), pollution (13), or puberty and is consistent with the paradigm that epigenetics thus is a causal process that links the early life environment to the future phenotype.

Four of the CpG loci that were measured in the PGC1 α promoter predicted adiposity irrespective of sex, pubertal timing, or levels of physical activity, even though the percent body fat of the boys fell sharply and girls diverged in temporal trends in fat mass in the peri-pubertal period. The magnitude of the association suggested that 10%

difference in methylation at these loci predicted up to 12% difference in fat mass. Since body fat is associated causally with insulin resistance in children (31), a major underlying risk factor for CMD (32), our findings imply that differential methylation in mid-childhood of CpG loci that exhibit relatively strong temporal stability may be able to predict differences in patterns of adiposity that have longer-term clinical relevance. Thus, these findings are in agreement with, but also extend substantially, previous findings (3,5,9) by providing direct evidence that supports an assumption on which these studies were based: that methylation of specific CpG loci that are induced early in life can be maintained essentially independent of lifestyle, growth, and development during childhood and predicts health-related outcomes.

Because of the tissue-specific nature of the level of methylation at many CpG loci (33), it is not possible to infer directly from the present findings that the level of methylation of CpG loci in whole blood reflects differential methylation of those CpGs in adipose tissue or that they are involved in the regulation of fat mass by PGC1 α in adipose. However, significant associations have been reported between individual CpG loci in human cells from different embryonic tissue lineages (28). Furthermore, three CpG loci with stable methylation status predictive of future adiposity at positions -783, -816, and -841 have been shown previously to be hypermethylated in pancreatic islet cells and associated with variation in mRNA levels in overweight subjects (26). Because it was not possible to collect adipose tissue from children, we have cautiously sought to exemplify the plausibility that differential methylation of CpGs measured in blood that predict adiposity may reflect variation in the epigenetic regulation of PGC1 α in adipose tissue. We investigated the effect of methylation at one locus in the PGC1 α promoter, position -783, that predicted adiposity on transcription factor binding. The findings showed that in human liposarcoma cells, one complex of similar mobility bound to this region of the PGC1 α promoter, but binding was stronger when the cytosine at -783 was methylated. This CpG lies within a predicted PBX-1/HOXB9 response element. PBX-1 is a TALE (three amino acid loop extension) homeodomain transcription factor, which promotes the early commitment of stem cells to the adipocyte lineage such that PBX-1-null mice are unable to generate adipocytes (34). PBX-1 alone has been reported to exhibit little or no intrinsic DNA binding affinity but can interact with other homeodomain transcription factors including members of the HOX gene family, for example, HOXB4, -B6, -B7, and -B9, and Meis homeobox 1 to form heterodimeric transcriptional complexes that bind DNA (35). Consistent with PBX-1 binding to this region of the PGC1 α promoter, we show that binding was competed out by the consensus sequence for HOXB9/PBX-1 and that antibodies against PBX-1 blocked binding to both the unmethylated and methylated sequences. In contrast, antibodies against HOXB9 had no effect on binding to the unmethylated

sequence but blocked binding to the methylated sequence. Because the antibodies were added prior to the addition of the probe, this suggests that the failure of the HOXB9 antibody to block binding to the unmethylated probe does not reflect a difference in conformation of the PBX-1/HOXB9 heterodimer bound to the DNA and a masking of the epitope. Instead, these data suggest that while both PBX-1 and HOXB9 bound to the methylated sequence, PBX-1 may be bound to the unmethylated sequence with a different partner.

Methylation of DNA has generally been associated with a reduction in transcription factor binding (36-39); however, there is increasing evidence that mCpG-binding activity is widespread among specific transcription factor families, such as homeodomain transcription factors (40), of which PBX1 and HOXB9 are members. Our data provide the first evidence that suggests methylation of a specific CpG locus may induce the binding of alternative PBX-1-containing heterodimers to the EMSA probes, potentially adding a further layer of complexity to regulation by PBX-1. However, whether this occurs *in vivo* at the PGC1 α promoter requires confirmation in intact cells. Consistent with a role of PBX-1 in the regulation of PGC1 α expression, overexpression of PBX-1 led to a marked decrease in PGC1 α transcription in the luciferase reporter construct in liposarcoma cells, although whether this occurs in intact cells remains to be determined. Thus, it is possible that methylation at this locus within the promoter of PGC1 α may alter PGC1 α transcription and exert downstream effects on adipocyte development that are consistent with, but do not demonstrate directly, greater methylation leading to increased adiposity, although further experiments are required to determine whether PBX1 binds to the PGC1 α promoter and regulates endogenous PGC1 α expression *in vivo* to demonstrate this conclusively. Thus, our findings provide evidence to support the view that the methylation status of specific CpG loci in blood may mark the level of methylation of these CpG dinucleotides in adipocytes. If so, these findings suggest that methylation at this locus may have been induced during early development before the divergence of mesodermal stem cells into adipocyte and hematopoietic lineages. However, these findings cannot rule out the possibility that differential adiposity between children was driven primarily by differences in caloric intake or another environmental factor—or genetic predisposition. Furthermore, differential methylation of PGC1 α is a consequence rather than a determining factor of adiposity in children. Nevertheless, whether such associations reflect cause or consequence of variation in adiposity, these epigenetic loci retain utility as potential predictive biomarkers of risk of inappropriate weight gain in children.

Overall, these findings support the view that epigenetic marks measured in childhood that exhibit temporal stability may have utility in predicting future disease risk. Identification of such marks in blood may increase the number of individuals in whom such associations can

be tested beyond those for whom fetal tissue is available (3) and provide opportunities for further investigation of longitudinal associations and the impact of therapeutic interventions.

Acknowledgments. The authors thank Val Morgan (Plymouth Hospital National Health Service [NHS] Trust, Plymouth, U.K.) and Karen Brookes (Plymouth Hospital NHS Trust) for their technical skills and the EarlyBird children and their parents for their remarkable commitment.

Funding. The EarlyBird Diabetes Study received financial support from the Bright Future Trust, Bupa Health Foundation, Kirby Laing Foundation, Peninsula Foundation, and EarlyBird Diabetes Trust. The laboratory analyses were supported by the National Institute for Health Research Southampton Biomedical Research Centre in Nutrition, which also provided salary support for R.C.-H. and K.M.G. R.C.-H., K.M.G., K.A.L., and G.C.B. are members of the EpiGen Consortium.

Duality of Interest. No potential conflicts of interest related to this article were reported.

Author Contributions. R.C.-H., A.N.J., and B.S.M. performed the experiments and contributed to the first draft of the manuscript. T.J.W. conceived and designed the laboratory experiments and the cohort study and provided substantial input for the first draft of the manuscript. J.H. analyzed data, carried out the mathematical modeling, and provided substantial input into the first draft of the manuscript. J.P. and K.M.G. contributed to discussions and to editing the manuscript and contributed to the first draft of the manuscript. L.D.V. conceived of and designed the cohort study, performed the experiments, and contributed to the first draft of the manuscript. K.A.L. conceived and designed the laboratory experiments and provided substantial input for the first draft of the manuscript. G.C.B. conceived and designed the laboratory experiments and wrote the first draft of the manuscript. K.A.L. is the guarantor of this work and, as such, had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

References

- Gluckman PD, Hanson MA, Cooper C, Thornburg KL. Effect of in utero and early-life conditions on adult health and disease. *N Engl J Med* 2008;359:61–73
- Burdge GC, Lillycrop KA. Nutrition, epigenetics, and developmental plasticity: implications for understanding human disease. *Annu Rev Nutr* 2010;30:315–339
- Godfrey KM, Sheppard A, Gluckman PD, et al. Epigenetic gene promoter methylation at birth is associated with child's later adiposity. *Diabetes* 2011;60:1528–1534
- Harvey NC, Lillycrop KA, Garratt E, et al. Evaluation of methylation status of the eNOS promoter at birth in relation to childhood bone mineral content. *Calcif Tissue Int* 2012;90:120–127
- Relton CL, Groom A, St Pourcain B, et al. DNA methylation patterns in cord blood DNA and body size in childhood. *PLoS ONE* 2012;7:e31821
- Heijmans BT, Tobi EW, Stein AD, et al. Persistent epigenetic differences associated with prenatal exposure to famine in humans. *Proc Natl Acad Sci U S A* 2008;105:17046–17049
- Tobi EW, Lumey LH, Talens RP, et al. DNA methylation differences after exposure to prenatal famine are common and timing- and sex-specific. *Hum Mol Genet* 2009;18:4046–4053
- Huang RC, Galati JC, Burrows S, et al. DNA methylation of the IGF2/H19 imprinting control region and adiposity distribution in young adults. *Clin Epigenetics* 2012;4:21
- Perkins E, Murphy SK, Murtha AP, et al. Insulin-like growth factor 2/H19 methylation at birth and risk of overweight and obesity in children. *J Pediatr* 2012;161:31–39
- Heyn H, Esteller M. DNA methylation profiling in the clinic: applications and challenges. *Nat Rev Genet* 2012;13:679–692
- Wong CCY, Caspi A, Williams B, et al. A longitudinal study of epigenetic variation in twins. *Epigenetics* 2010;5:516–526
- Barrès R, Yan J, Egan B, et al. Acute exercise remodels promoter methylation in human skeletal muscle. *Cell Metab* 2012;15:405–411
- Baccarelli A, Wright RO, Bollati V, et al. Rapid DNA methylation changes after exposure to traffic particles. *Am J Respir Crit Care Med* 2009;179:572–578
- Puigserver P, Spiegelman BM. Peroxisome proliferator-activated receptor-gamma coactivator 1 alpha (PGC-1 alpha): transcriptional coactivator and metabolic regulator. *Endocr Rev* 2003;24:78–90
- Voss LD, Kirkby J, Metcalf BS, et al. Preventable factors in childhood that lead to insulin resistance, diabetes mellitus and the metabolic syndrome: the EarlyBird diabetes study 1. *J Pediatr Endocrinol Metab* 2003;16:1211–1224
- Levy JC, Matthews DR, Hermans MP. Correct homeostasis model assessment (HOMA) evaluation uses the computer program. *Diabetes Care* 1998;21:2191–2192
- Gungor N, Saad R, Janosky J, Arslanian S. Validation of surrogate estimates of insulin sensitivity and insulin secretion in children and adolescents. *J Pediatr* 2004;144:47–55
- Cole TJ, Freeman JV, Preece MA. Body mass index reference curves for the UK, 1990. *Arch Dis Child* 1995;73:25–29
- Metcalf BS, Curnow JS, Evans C, Voss LD, Wilkin TJ. Technical reliability of the CSA activity monitor: The EarlyBird Study. *Med Sci Sports Exerc* 2002;34:1533–1537
- Puyau MR, Adolph AL, Vohra FA, Butte NF. Validation and calibration of physical activity monitors in children. *Obes Res* 2002;10:150–157
- Lillycrop KA, Phillips ES, Torrens C, Hanson MA, Jackson AA, Burdge GC. Feeding pregnant rats a protein-restricted diet persistently alters the methylation of specific cytosines in the hepatic PPAR alpha promoter of the offspring. *Br J Nutr* 2008;100:278–282
- Harris RG, White E, Phillips ES, Lillycrop KA. The expression of the developmentally regulated proto-oncogene Pax-3 is modulated by N-Myc. *J Biol Chem* 2002;277:34815–34825
- Twisk J. *Applied Longitudinal Data Analysis for Epidemiology*. Cambridge, U.K., Cambridge University Press, 2013
- Rothman KJ. No adjustments are needed for multiple comparisons. *Epidemiol* 1990;1:43–46
- Gemma C, Sookoian S, Alvarías J, et al. Maternal pregestational BMI is associated with methylation of the PPARGC1A promoter in newborns. *Obesity (Silver Spring)* 2009;17:1032–1039
- Ling C, Del Guerra S, Lupi R, et al. Epigenetic regulation of PPARGC1A in human type 2 diabetic islets and effect on insulin secretion. *Diabetologia* 2008;51:615–622
- Adalsteinnsson BT, Gudnason H, Aspelund T, et al. Heterogeneity in white blood cells has potential to confound DNA methylation measurements. *PLoS ONE* 2012;7:e46705
- Talens RP, Boomsma DI, Tobi EW, et al. Variation, patterns, and temporal stability of DNA methylation: considerations for epigenetic epidemiology. *FASEB J* 2010;24:3135–3144
- Heyn H, Li N, Ferreira HJ, et al. Distinct DNA methylomes of newborns and centenarians. *Proc Natl Acad Sci U S A* 2012;109:10522–10527
- Szyf M. The dynamic epigenome and its implications in toxicology. *Toxicol Sci* 2007;100:7–23
- Hosking J, Metcalf BS, Jeffery AN, Voss LD, Wilkin TJ. Direction of causality between body fat and insulin resistance in children—a longitudinal study (EarlyBird 51). *Int J Pediatr Obes* 2011;6:428–433
- Ferrannini E, Cushman WC. Diabetes and hypertension: the bad companions. *Lancet* 2012;380:601–610
- Bird A. DNA methylation patterns and epigenetic memory. *Genes Dev* 2002;16:6–21
- Bertolino E, Reimund B, Wildt-Perinic D, Clerc RG. A novel homeobox protein which recognizes a TGT core and functionally interferes with a retinoid-responsive motif. *J Biol Chem* 1995;270:31178–31188

35. Knoepfler PS, Kamps MP. The pentapeptide motif of Hox proteins is required for cooperative DNA binding with Pbx1, physically contacts Pbx1, and enhances DNA binding by Pbx1. *Mol Cell Biol* 1995;15:5811–5819
36. Kovtsi I, Reichel R, Nevins JR. Role of an adenovirus E2 promoter binding factor in E1A-mediated coordinate gene control. *Proc Natl Acad Sci U S A* 1987; 84:2180–2184
37. Gaston K, Fried M. CpG methylation has differential effects on the binding of YY1 and ETS proteins to the bi-directional promoter of the Surf-1 and Surf-2 genes. *Nucleic Acids Res* 1995;23:901–909
38. Comb M, Goodman HM. CpG methylation inhibits proenkephalin gene expression and binding of the transcription factor AP-2. *Nucleic Acids Res* 1990; 18:3975–3982
39. Jane SM, Gumucio DL, Ney PA, Cunningham JM, Nienhuis AW. Methylation-enhanced binding of Sp1 to the stage selector element of the human gamma-globin gene promoter may regulate development specificity of expression. *Mol Cell Biol* 1993;13:3272–3281
40. Hu S, Wan J, Su Y, et al. DNA methylation presents distinct binding sites for human transcription factors. *eLife* 2013;2:e00726