Original Research Article

Cortisol and Testosterone in Filipino Young Adult Men: Evidence for Co-regulation of Both Hormones by Fatherhood and Relationship Status

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Objectives: Although cortisol (CORT) may suppress testosterone (T) production under stress, in many species males' T and CORT are co-elevated during mate acquisition or conspecific competition. It is presently unknown how CORT co-varies with T in relation to fatherhood/relationship status in men. Here we evaluate associations between waking (AM) and pre-bed (PM) salivary CORT and T, and with plasma total T and luteinizing hormone. We also test whether co-elevation or co-downregulation of CORT and T are present in men who are mating-oriented (non-pairbonded, non-fathers) and parenting-oriented (pairbonded and/or fathers), respectively.

Methods: Data come from 630 of young adult Filipino males (21–23 years) enrolled in the Cebu Longitudinal Health and Nutrition Survey, a population-based birth cohort study in Cebu City, Philippines.

Results: T and CORT were positively related in AM ($r = 0.37$) and PM ($r = 0.30$) saliva samples (both $P < 0.001$). The positive relationship between AM measures was strengthened as caloric intake improved (interaction $P < 0.05$). Mating-oriented men were more likely to have co-elevated PM CORT and T ($P < 0.05$), defined as being in the highest tertile for both hormones, while parenting-oriented men were more likely to have co-downregulated (lowest tertile for both hormones) AM ($P < 0.05$) and PM ($P < 0.001$) CORT and T.

Conclusions: CORT and T are positively related upon waking and before bed and are more likely to be co-elevated in mating-oriented men and co-downregulated in parenting-oriented men. Our findings support the interpretation that CORT and T serve complementary roles in facilitating men's mating effort. Am. J. Hum. Biol. 00:00–00, 2011.

Organisms are constrained by finite energy, which leads to trade-offs between the competing functions of growth, maintenance and reproduction (Stearns, 1989). Hormones help mediate these trade-offs by influencing energy partitioning via pleiotropic effects on physiological processes and behavior (Bribiescas and Ellison, 2008; Finch and Rose, 1995; Worthman, 1999). Among male vertebrates, testosterone (T) is a primary reproductive steroid that facilitates energetic investment in metabolic and behavioral components of male reproductive strategy (Bribiescas, 2001; Gettler et al., 2010; Hau, 2007). T is often reduced when organisms are acutely or chronically stressed, which is viewed as helping shift priorities away from reproductive expenditures in favor of functions more essential to immediate survival (Sapolsky et al., 2000). This trade-off is partially mediated in humans by the glucocorticoid cortisol (CORT), which is produced by the hypothalamic-pituitary-adrenal (HPA) axis and shunts energy to functions critical during stress, such as skeletal muscle and the cardiovascular system. In general, CORT helps regulate metabolism and blood sugar by mobilizing stored energy for use (e.g., adipose tissue and glycogen) and by stimulating the production of glucose in the liver (gluconeogenesis) (Sapolsky et al., 2000).

There is evidence for direct suppressive effects of CORT on testicular steroid production in both rodents and primates (Rivier and Rivest, 1991; Sapolsky et al., 2000). CORT may also reduce T by suppressing gonadotropin-releasing hormone (GnRH) or LH production (Tilbrook et al., 2002). In humans, imposed stressors such as hypoglycemia (Cumming et al., 1983), rigorous physical activity (Hoogeveen and Zonderland, 1996), and psychosocial stress (Morgan et al., 2000) have been linked to increased CORT and reduced T. Cushing's disease, which is characterized by chronic glucocorticoid excess, is associated with reduced T (Vierhapper et al., 2000) as is administration of exogenous glucocorticoids (MacAdams et al., 1986). There is also a small but growing body of evidence, primarily from rodent models, that androgens can attenuate activity of the HPA axis (Lund et al., 2004; Viau and Meaney, 1996; Williamson and Viau, 2007), although studies on human subjects show mixed results (Muniyappa et al., 2010; Rubinow et al., 2005). These studies corroborate theoretical expectations of a stress-reproduction trade-off mediated in part through the effects of CORT on T, with preliminary evidence that higher T may partially buffer males from such inhibitory effects.

Despite these documented antagonistic effects of CORT on T production, multiple lines of evidence point to more complex relationships between the two hormones, including their tendency to positively co-vary under certain circumstances. Most obviously, the two hormones follow a

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common pattern of circadian change in humans, reaching lowest concentrations late in the evening and rising during sleep to reach peak levels at or soon after waking, before beginning a gradual decline across the day (Faiman and Winter, 1971; Vitzthum et al., 2009; Worthman, 1999). These parallel circadian changes suggest that the two hormones may routinely serve complementary rather than antagonistic functions under day-to-day conditions. While they have not specifically explored the hormones' diurnal associations, a small number of studies have found moderate, positive correlations between T and CORT under non-stimulated conditions in the absence of experimentally induced stress (Muehlenbein et al., 2010; Liening et al., 2010; Popma et al., 2007).

In addition, studies of mammalian males exposed to social challenge and competition provide conflicting evidence for an antagonistic relationship between the two hormones. For instance, in chimpanzees (Muller and Wrangham, 2004a,b) and cynomolgus monkeys (Czoty et al., 2009) socially dominant males have elevated T and CORT, and in tufted-capuchin monkeys (Lynch et al., 2002) and red-fronted lemurs (Ostner et al., 2008) males experience increases in T and CORT during the breeding season. Similar concurrent elevations of T and glucocorticoid hormones have been documented in other nonhuman primate (Dittami et al., 2008; van Schaik et al., 1991), non-primate mammalian (Mooring et al., 2004; Boonstra et al., 2001; Creel et al., 1997; Mooring et al., 2006), and non-mammalian species (Lance et al., 2001; Mateos, 2005; Moore et al., 2000).

These findings have been interpreted as evidence that CORT and T may cooperatively enhance males' breeding preparedness and, specifically, may allow for repeated mating over a short period of time (T) and more rapid behavioral responses when mating opportunities arise (CORT) (Lynch et al., 2002). Alternatively, high T may serve to enhance mating behaviors while elevated CORT may be related to increased energetic costs imposed by mating and/or maintaining high social rank (Boonstra et al., 2001; Muller and Wrangham, 2004b; Ostner et al., 2008). Although men have been shown to experience short-term, concurrent rises in T and CORT during some forms of competition (Elias, 1981; Mehta et al., 2008; Salvador et al., 2003), it is unclear whether mating-oriented men would benefit from concurrently high levels of CORT and T, as may be the case in these other mammalian species where breeding opportunities are more punctuated.

Humans are a long-lived species that produce slow-maturing, highly dependent offspring, often in the context of pairbonds that can last many years and in which males and females often cooperate to raise young (Gettler, 2010; Gray and Anderson, 2010; Quinlan, 2008). It is known that in many cultural settings T is generally higher in non-pairbonded, non-fathers compared with pairbonded, fathers (reviewed in Gray and Campbell, 2009), including the sample analyzed here (Kuzawa et al., 2009). Although comparably few past studies have reported men's CORT in relation to mating status, one study found fathers' CORT to be significantly lower than non-father controls (Berg and Wynne-Edwards, 2001), whereas another did not (Gray et al., 2007), and a third study found lower CORT among married men relative to unwed men (Mazur and Michalek, 1998). If CORT and T complementarily enhance human males' mating effort, we would expect non-pairbonded, non-fathers to be more likely to exhibit co-elevation of the two hormones, particularly in comparison with men who have committed to a pairbond or are invested in fatherhood. However, if CORT and T stimulate potentially competing expenditures, the ability of men to elevate both hormones simultaneously might be compromised under adverse energetic conditions.

Here, we seek to clarify the relationship between T and CORT in human males (age 21–23 years, $n = 630$) using data and samples from healthy young men living in Cebu City, the Philippines. To that end, we first evaluate the direction of the relationship between T and CORT measured in the same saliva sample collected at waking or before bed. Although it is well known that both hormones follow a similar circadian pattern, it is less clear whether men who have high levels of CORT at waking, compared with their peers measured at the same time of day, will tend to have relatively higher or lower T concurrently. We hypothesized that there would be a negative relationship between CORT and T among men with low daily caloric intake, reflecting prioritization of survival over reproduction. Second, building from the nonhuman primate studies noted above, we hypothesized that men who were neither pairbonded or fathers (men who were "mating-oriented") would be more likely to show co-elevated CORT and T, particularly in the context of high caloric intake, as a result of their presumed greater investment in mating effort, whereas men who were pairbonded and/or fathers ("parenting-oriented") would be more likely to show co-downregulation of the two hormones.

MATERIALS AND METHODS

Study population

Data come from the Cebu Longitudinal Health and Nutrition Survey (CLHNS), a community-based birth cohort study of mothers and their infants born in 1983–1984 (Adair et al., 2010). Men were a mean of 21.5 years old (range 20.8–22.6 years) at the time of data and sample collection. Socioeconomic, demographic, health, and general behavioral data were collected using questionnaire-based, in-home interviews administered by Cebuano-speaking interviewers (Adair et al., 1993; Kuzawa and Adair, 2003). Men were defined as pairbonded if they were legally married or cohabitating. Men were defined as fathers if they were living with one or more son or daughter. Men did not differentiate biological offspring from step-children. Because our sample is limited to young adults from a population in which divorce and remarriage are uncommon, particularly for men in this sample's age range, the presence of step-children is likely small (Kuzawa et al., 2009). Weight (kg) and height (cm), and triceps, suprailiac, and subscapular skinfold thicknesses (mm) were measured using standard anthropometric techniques (Lohman et al., 1988). Skinfolds were included in analyses as a summation of the three measures (sum of skinfolds). The body mass index (BMI) was calculated as the ratio of weight (kg)/height (m^2). Dietary intake was measured using two 24-h recalls on consecutive days and the mean was used in analyses. Energy intake was calculated using Philippines Food Composition Tables produced by the Food and Nutrition Research Institute of the Philippines (FNRI 1997). General health was self-reported as poor, good or excellent. Estimates of daily energetic expenditure in domestic and employment related labor were constructed from self-reports of effort exerted in

labor, body weight (kg), and previously validated metabolic estimates for occupational activities (Ainsworth et al., 2000). Self-reported psychosocial stress in the month preceding sampling was quantified via a modified version of the 10-item perceived stress-scale (PSS) (Cohen et al., 1983). This research was conducted under conditions of informed consent with human subjects clearance from the Institutional Review Boards of the University of North Carolina, Chapel Hill, and Northwestern University.

Salivary T and CORT measurement

Each participant was provided with instructions and two polypropylene tubes for saliva collection. The first sample was collected immediately before bed (PM). After collection, they sealed the tube and kept it at room temperature. Mean PM sampling time was 10:13 PM ± 1:38 (SD). They were instructed to place the second tube next to their bed and to collect the second sample immediately upon waking the following morning (AM). Respondents reported time of saliva collection, wake time, and usual wake time. Mean AM sampling time was 6:29 AM ± 1:16. Men reported their self-rated sleep quality from the prior night when providing the AM sample. Participants also provided ratings of their self-perceived psychosocial stress on the day of PM sampling in response to the question "How stressful was your day today?" using a 5-point scale, ranging from "Not stressful at all" to "Very stressful." Saliva tubes were collected later the second day by an interviewer, who placed the tubes on ice packs in a cooler while in transit to freezer storage at −35°C. They were shipped on dry ice to Northwestern University, where they were stored at −80°C. They were thawed, centrifuged, supernatant separated, and aliquoted into smaller tubes for analysis of individual analytes.

Salivary T. Salivary testosterone assays were run at the Laboratory for Human Biology Research at Northwestern University. Concentrations of T were determined using an enzyme immunoassay protocol developed for use with saliva samples (Salimetrics, State College, PA; Kit No. 1-2402). The inter-assay coefficients of variation were 13.7% and 11.5% for high and low control samples, respectively.

Salivary CORT. CORT was assayed in saliva samples sent to a laboratory in Trier, Germany. Samples were assayed in duplicate using a time-resolved immunoassay with fluorometric detection (DELFIA). The inter-assay coefficients of variation range from 7.1% to 9.0%.

Plasma total T and LH

During a separate sample collection, participants were asked to fast overnight for 12 h, and blood samples were collected in the participants' homes the following morning using EDTA-coated tubes. Mean time of blood draw was 7:10 AM ± 0:37 (SD). After separation, samples were frozen and shipped on dry ice to Northwestern University for analysis. Plasma total T was analyzed with a commercially available enzyme immunoassay protocol (Diagnostic Systems Laboratories #DSL-10-4000, Webster, TX), as was plasma LH (Immuno-Biological Laboratories #IB19104, Minneapolis, MN). For plasma T, the inter-assay coefficients of variation were 13.3% and 5.8% for low and high controls, respectively. For plasma LH, the inter-assay coefficients of variation were 5.7% and 8.0% for low and high controls, respectively. All samples remained frozen at −80°C until thawed for analysis.

C-reactive protein (CRP). Blood samples were collected into EDTA-coated vacutainer tubes in the participants' homes in the morning after an overnight fast. Blood samples were kept in coolers on ice packs for no more than 2 h and were then centrifuged to separate plasma before freezing at −70°C. Samples were shipped to Northwestern University on dry ice and stored frozen at −80°C until analysis. CRP concentrations were determined using a high sensitivity immunoturbidimetric method (Synchron LX20, lower detection limit: 0.1 mg/L) (McDade et al., 2010).

Sample selection

During the 2005 survey, 1,008 males of the original cohort of 1,633 liveborn males, with an average age of 21.5 years (range 20.8–22.7 years), were located and interviewed. Of these, a final sample of 630 individuals agreed to participate in saliva collection, had sufficient sample for analysis and complete questionnaire data and biomarker assessments (Table 1). A total of 45 men were excluded from this analysis because they were nightshift workers, had sleep patterns consistent with night shift work, or spent less than 8 h or greater than 20 h awake, all of which increase the likelihood of disrupted circadian rhythms for CORT and T (Axelsson et al., 2005; Touitou et al., 1990; Weibel et al., 1996). One subject was excluded as an outlier based on his AM CORT value of 61.01 nmol/L compared with a mean of 7.03 ± 3.9 (SD) nmol/L. Individuals with CRP > 10 mg/L ($n = 17$), meeting the American Heart Association and the Centers for Disease Control and Prevention's criterion for active infection, were removed from the analyses (Pearson et al., 2003). We assessed whether subjects in the analysis differed from excluded men using unpaired, two-tailed t-tests. Excluded individuals were born to parents who were more educated ($P < 0.05$). However, there were no significant differences between the analysis subsample here and the original baseline cohort in birth weight, birth length, birth order, household income, parental height, or mother or father's age at baseline (all $P > 0.3$).

Statistical analysis

All analyses were conducted using version 10 of Stata (Stata Corporation, College Station, TX). AM T (pg/mL), PM T (pg/mL), AM CORT (nmol/L), PM CORT (nmol/L), plasma total T (ng/mL), plasma LH (mIU/mL), household income, daily food intake (kcal), and PSS were all analyzed as continuous variables. Salivary and plasma hormones, energy intake, sum of skinfolds, and income were all right-skewed and were therefore log-transformed before analysis. Men who were in the highest tertile for CORT and T, sampled at the same time of day, were considered to have co-elevated CORT and T. Using these criteria, dichotomous variables were created that distinguished men with co-elevated AM and PM CORT/T, respectively, from those without co-elevation of both hormones. By these criteria, 13% of men had co-elevated AM

TABLE 1. Characteristics of sample, stratified by mating status[a]

	All (n = 630)	Mating-oriented (n = 484)[b]	Parenting-oriented (n = 146)[b]	P-value[b]
Hormones[c]				
Waking T (pg/mL)	190.3 ± 74.4	195.5 ± 77.0	173.1 ± 62.4	0.00
Evening T (pg/mL)	115.6 ± 50.3	119.6 ± 51.1	102.4 ± 45.2	0.00
Waking CORT (nmol/L)	7.0 ± 3.7	7.1 ± 3.9	6.5 ± 3.0	0.08
Evening CORT (nmol/L)	2.2 ± 2.6	2.3 ± 2.6	1.8 ± 2.4	0.08
Waking plasma total T[d] (ng/mL)	7.9 ± 2.8	8.1 ± 2.9	7.3 ± 2.7	0.00
Plasma LH[d] (mIU/mL)	10.4 ± 4.8	10.9 ± 5.0	8.8 ± 3.9	0.00
Anthropometry and diet				
Height (cm)	163.0 ± 5.8	162.9 ± 6.0	163.3 ± 4.8	0.50
Weight (kg)	55.9 ± 9.3	55.9 ± 9.5	55.9 ± 8.4	0.96
BMI (kg/m^2)	21.0 ± 3.0	21.0 ± 3.1	20.9 ± 2.8	0.75
Tricep skinfold (mm)	10.9 ± 5.6	11.1 ± 5.7	10.4 ± 5.4	0.16
Energy intake (kcal/day)	2195 ± 933	2215 ± 970	2129 ± 793	0.33
Sociodemographic factors				
Age (years)	21.5 ± 0.3	21.5 ± 0.3	21.5 ± 0.3	0.11
Weekly household income (pesos/resident)	90.5 ± 118.5	96.1 ± 128.2	71.9 ± 75.6	0.03
Education (highest grade)	10.3 ± 4.0	10.7 ± 4.0	9.0 ± 3.9	0.00

[a]Mean ± SD unless otherwise noted.
[b]Test for significant differences by mating status (unpaired, two-tailed t-test).
[c]Raw (unadjusted) values.
[d]Sub-sample of n = 612.

TABLE 2. Correlation coefficients (r) relating salivary hormones, nutritional status, and self-reported stress (n = 630)

	Waking T	Evening T	Waking CORT	Evening CORT
Waking T[a]	–			
Evening T[a]	0.29***	–		
Waking CORT[a]	0.37***	0.10*	–	
Evening CORT[a]	0.03	0.33***	0.11**	–
BMI (kg/m^2)	0.04	0.03	−0.01	−0.08*
Sum of skinfolds	0.08*	0.02	0.04	−0.10*
Daily caloric intake (kcal)	0.05	−0.03	−0.01	−0.08^
Self-reported stress (day of sampling)	0.02	−0.07^	0.10*	0.0004
Self-reported stress (month of sampling)	−0.04	0.01	−0.04	−0.001

[a]Adjusted for time of sample collection, wake time that day (AM), and usual wake time (AM).
^$P < 0.10$.
$^{*}P < 0.05$.
$^{**}P < 0.01$.
$^{***}P < 0.001$.

CORT and T and 17% men had co-elevated PM values. Conversely, men who were in the lowest tertile for CORT and T, sampled at the same time of day, were considered to have co-downregulated CORT and T. 17% of men had co-downregulated AM CORT and T and 16% of men had co-downregulated PM values. We first tested for correlations between AM and PM T in relation to AM and PM CORT [adjusted for wake time, usual wake time (AM models), and time of saliva collection (AM, PM models)] as well as energetic status and psychosocial stress. We also assessed correlations between salivary hormone measures and plasma total T and LH. We then used multiple linear regression to evaluate relationships between AM and PM CORT and AM and PM T, adjusting for covariates and potential confounders. We next used one-way analysis of variance (ANOVA) to test for differences in CORT and T between "mating-oriented" (non-pairbonded, non-fathers) compared with "parenting-oriented" men (pairbonded and/or fathers), with a Bonferroni *post-hoc* multiple comparison test. We then tested whether these groups differed in the strength of the relationship between CORT and T. Using linear regression, we evaluated whether the strength of the relationship between the two hormones differed significantly by mating/parenting groups by interacting mating-status with CORT in models predicting T. Finally, we used logistic regression to predict whether men showed greater likelihood of having co-elevated CORT and T if they were "mating-oriented" versus "parenting-oriented," controlling for covariates, and we further tested for interactions between mating status and daily caloric intake in separate models predicting co-elevated CORT and T or co-downregulated CORT and T. Statistical significance was set at $P < 0.05$ with relationships between $P > 0.05$ and $P < 0.10$ interpreted as a borderline statistical trend.

RESULTS

CORT and T were positively correlated in AM and PM samples (Table 2). Figures 1a, b show the linear positive relationship between salivary CORT and T. PM CORT was significantly negatively associated with BMI and sum of skinfolds, while AM T was positively correlated to sum of skinfolds (Table 2). Plasma T was positively correlated to salivary AM (r = 0.13; $P < 0.01$) and PM T (r = 0.18; $P < 0.0001$). There were significant positive relationships between PM CORT and plasma T (r = 0.09; $P < 0.05$) and borderline significant positive relationships between AM CORT and plasma T (r = 0.07; $P < 0.10$) and LH (r = 0.07; $P < 0.10$).

Men reporting higher stress on the day of PM saliva collection had lower PM T and higher AM CORT the next morning. In light of these findings, we ran multiple linear regression models, adjusting for age, usual

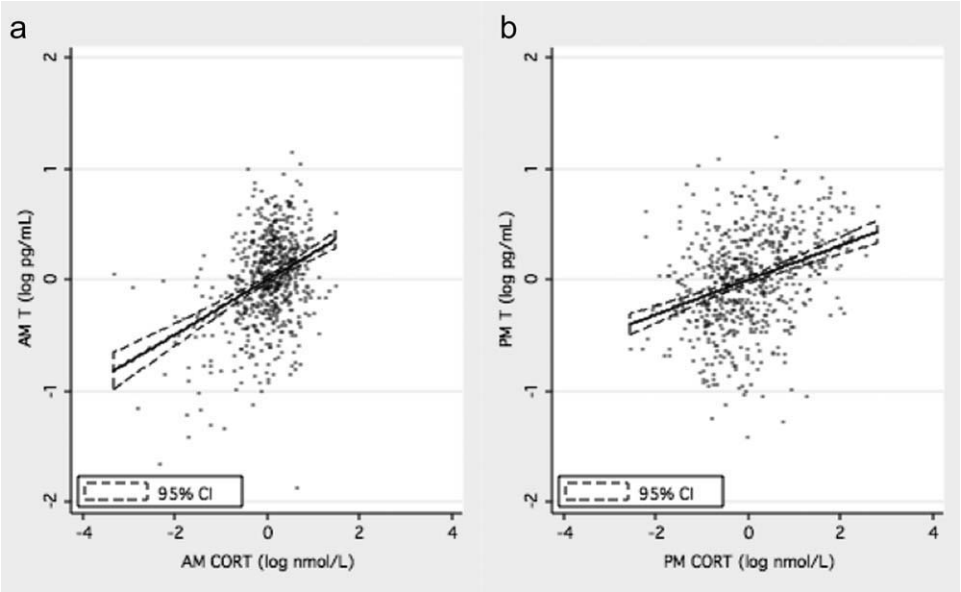

Fig. 1. (a) Scatter plot of logged residuals of AM T regressed on AM CORT. Residuals derived from separate regressions adjusting for time of saliva collection, wake time, and usual wake time. Dark line = best fit linear relationship between T and CORT ($\beta = 0.245 \pm 0.02$, $P < 0.001$). Dotted line = 95% CI. (b) Scatter plot of logged residuals for PM T regressed on PM CORT. Residuals derived from separate regressions adjusting for time of saliva collection. Dark line = best fit linear relationship between T and CORT ($\beta = 0.155 \pm 0.02$, $P < 0.001$). Dotted line = 95% CI.

TABLE 3. Multiple regression models predicting waking T[a,b]

	Model 1	Model 2	Model 3
Waking CORT	$0.25 \pm 0.02^{***}$	$0.24 \pm 0.02^{***}$	$0.25 \pm 0.02^{***}$
Self-reported sleep quality		$-0.04 \pm 0.01^{**}$	$-0.04 \pm 0.01^{*}$
General health		-0.01 ± 0.04	-0.02 ± 0.02
Weekly household income (pesos/resident)		-0.02 ± 0.02	-0.03 ± 0.04
Daily food intake (kcal)			0.04 ± 0.04
Sum of skinfolds			0.07 ± 0.04
Daily energetic expenditure[c] (kcal)			-0.00003 ± 0.02
Model adjusted R^2	0.135	0.142	0.146

[a]Values are $\beta \pm$ SE of log-transformed T.
[b]Adjusted for age, time of saliva collection, wake time that day, and usual wake time.
[c]Converted to z-score, coefficient reflects the effects of a 1 SD change.
$^{*}P < 0.05$.
$^{**}P < 0.01$.
$^{***}P < 0.001$.

wake time (AM models), wake time that day (AM models), and time of saliva collection, to assess whether the relationship between T and stress might be mediated by CORT. The regression coefficient relating self-perceived stress and PM T ($\beta = -0.0244 \pm 0.01$, $P = 0.085$) was virtually unchanged when PM CORT was added to the model ($\beta = -0.0243 \pm 0.01$, $P = 0.070$). Stress self-reported on the first evening of sampling was unrelated to AM T the following morning ($P > 0.64$); the addition of AM CORT to the model did not affect the relationship (not shown).

We next used multiple linear regression to evaluate relationships between T and CORT adjusting for covariates (Tables 3 and 4). Building from a base model that adjusted for usual wake time (AM models), wake time that day (AM models), and time of saliva collection, we evaluated the possible confounding influence of sleep quality, general health, and a measure of socioeconomic status (per capita household income), followed by energetic variables (caloric intake, sum of skinfold thicknesses, and daily energetic expenditure in labor). Relationships between CORT and T were not substantially changed after adjusting for any of these sets of variables (Tables 3 and 4).

To evaluate whether the relationship between CORT and T varies in relation to energetic condition, we tested for interactions between CORT and both energy intake (kcal) and physical activity (daily energetic expenditure in labor) in models predicting T, with models adjusted for usual wake time (AM models only), wake time that day (AM models only), and time of saliva collection. The continuous interaction between AM CORT and daily caloric intake was significant ($P = 0.006$, model adjusted R^2 0.15; Fig. 2). Other energy X CORT interactions in models predicting concurrent T were not significant (results not shown).

TABLE 4. Multiple regression models predicting evening T[a,b]

	Model 1	Model 2	Model 3
Evening CORT	0.16 ± 0.02***	0.16 ± 0.02***	0.16 ± 0.02***
General health		0.01 ± 0.04	0.003 ± 0.04
Weekly household income (pesos/resident)		0.02 ± 0.02	0.01 ± 0.02
Daily food intake (kcal)			−0.02 ± 0.04
Sum of skinfolds			0.05 ± 0.04
Daily energetic expenditure[c] (kcal)			−0.004 ± 0.02
Model adjusted R^2	0.112	0.110	0.108

[a]Values are β ± SE of log-transformed T.
[b]Adjusted for age and time of saliva collection.
[c]Converted to z-score, coefficient reflects the effects of a 1 SD change.
***$P < 0.001$.

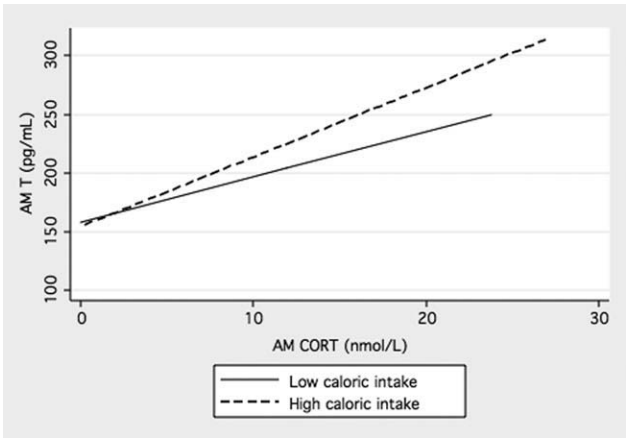

Fig. 2. AM T regressed on AM CORT, both adjusted for time of saliva collection, wake time, and usual wake time. Solid line = best fit linear trend resulting from regression of T on CORT for men with daily caloric intake below median. Dashed line = best fit linear trend resulting from regression of T on CORT for men with daily caloric intake above median.

We then tested for differences in CORT and T based on men's relationship and parenting status (see Fig. 3). Pair-bonded fathers had lower AM and PM T compared with non-pairbonded, non-fathers (ANOVA, both $P < 0.01$). Both pairbonded fathers and pairbonded non-fathers also had significantly lower PM CORT relative to non-pair-bonded, non-fathers ($P < 0.05$), while AM CORT was not significantly different across the groups. To evaluate whether the coupling of CORT and T varies by mating status, we then assessed the extent to which the strength of correlations between CORT and T were different in men who were "mating-oriented" ($n = 484$) compared with men who were "parenting-oriented" (n = 146) (see Materials and Methods section). The correlation between AM CORT and T was highly significant for both groups, and there was little evidence for differences by relationship status: mating-oriented men ($r = 0.38$; $P < 0.0001$); parenting-oriented men ($r = 0.34$; $P < 0.001$). Correlations linking PM CORT and T were also significant and similar in strength among mating-oriented ($r = 0.31$; $P < 0.0001$) and parenting-oriented men ($r = 0.26$; $P < 0.001$). In linear regression models predicting T, interactions between CORT and relationship status were highly non-significant at both times of day (both $P > 0.66$).

Finally, logistic regression revealed that mating-oriented men were significantly more likely to have co-elevated PM CORT and T (Table 5; Fig. 4). When we added household income (per capita), caloric intake, sum of skinfolds, physical activity, and self-reported psychosocial stress to the model, these relationships were strengthened (OR 1.85; $P = 0.034$). In contrast, models predicting co-elevated hormone levels in the AM were not significant (results not shown). In the AM model, men with higher scores on the perceived stress-scale showed a trend toward lower likelihood of co-elevated hormones (OR 0.95; $P = 0.067$). All other covariates for AM and PM models were not significant ($P > 0.11$). To evaluate possible effects of energetic status on men's ability to maintain heightened levels of the two hormones, we tested for a mating status X caloric intake interaction term in models predicting co-elevated CORT and T, which was not significant in AM or PM models (both $P > 0.3$).

Parenting-oriented men showed a trend towards greater likelihood of having co-downregulated AM CORT and T ($P < 0.10$) and were significantly more likely to have co-downregulated PM values ($P < 0.001$; Table 6; Fig. 4). When the covariates listed above were added to the models, parental orientation became a significant predictor of co-downregulation for AM (OR 1.62; $P = 0.045$) while the PM model was essentially unchanged.

DISCUSSION

In the Filipino young adult men studied here, both AM and PM T were positively related to CORT measured from the same saliva sample. These relationships appeared to be present irrespective of several measures of energy status, with the exception of the finding that men who consumed more calories and had higher AM CORT generally had greater AM T. Because CORT and T have been shown to positively co-vary during the breeding season and in the context of competition for mates or social dominance in a variety of nonhuman primate species (Czoty et al., 2009; Lynch et al., 2002; Muller and Wrangham, 2004a,b), we tested whether men who we interpreted as likely to employ a reproductive strategy oriented around mating effort (non-pairbonded non-fathers) would show greater co-elevation of CORT and T compared with men whose reproductive strategy likely oriented around parenting (pairbonded and/or fathers). Confirming our hypotheses, mating-oriented men were more likely to have co-elevated CORT and T in the evening, while parenting-oriented men were more likely to have co-downregulated levels of both hormones at both waking and in the evening. These findings suggest that CORT and T serve complementary roles under day-to-day conditions,

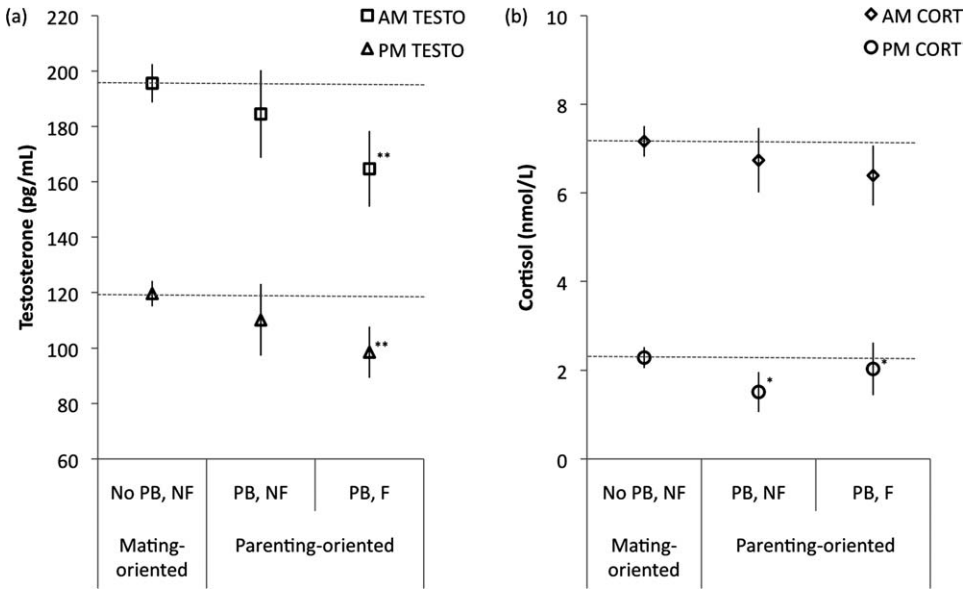

Fig. 3. Mean values of AM and PM T (a) and CORT (b), stratified according to relationship and parenting status. Values adjusted for time of saliva collection, wake time (AM only), and usual wake time (AM only). PB: pairbonded; NF: not a father; F: father. Dashed horizontal lines indicate mean value among non-PB, NF. *$P < 0.05$; **$P < 0.01$. Statistical comparisons reflect one-way ANOVA of logged hormonal values, with Bonferroni multiple comparison tests. Error bars = 95% CI.

TABLE 5. Predicting co-elevation or co-downregulation of CORT and T from mating status

	Co-elevated[a]		Co-downregulated[b]	
	OR (95% CI)	*P*-value	OR (95% CI)	*P*-value
Mating-oriented (AM)[c]	1.64 (0.76, 2.41)	0.308		
Mating-oriented (PM)[c]	1.76 (1.01, 3.06)	0.046		
Parenting-oriented (AM)[d]			1.57 (0.99, 2.48)	0.055
Parenting-oriented (PM)[d]			3.01 (1.92, 4.71)	0.000

[a]Men with co-elevated CORT and T defined as being in the highest tertile for both hormones.
[b]Men with co-downregulated CORT and T defined as being in the lowest tertile for both hormones.
[c]Excluded comparison group: parenting-oriented men (pairbonded and/or fathers).
[d]Excluded comparison group: mating-oriented men (non-pairbonded, non-fathers).

and that the two hormones are co-regulated in parallel fashion by fatherhood/relationship status in human males, much as seen in other mammalian and primate species with more acute changes in mating and breeding status.

Consistent with a role of stress in HPA activation and suppression of HPG function, men with higher self-reported stress during the day of PM saliva collection had lower PM T and elevated AM CORT. We found that the association between stress and T was modestly strengthened after adjusting for PM CORT, suggesting that CORT does not mediate the relationship between stress and lower T in these men. It is possible that T is mediated through a stress-related physiological pathway not evaluated here (Sapolsky, 1991). Alternatively, men with lower T at baseline could be more inclined to report feeling day-to-day psychosocial stress. Although we are not able to address this possibility with our cross-sectional data, past studies have reported that T is positively associated with mood and that men with lower T are at increased risk of depression (Booth et al., 1999a).

The expectation that CORT and T would be inversely related among men with low caloric intake emerges from the potentially competing functions stimulated by each hormone (survival/maintenance and reproduction, respectively), which both require resources derived from the body's finite energy pool (Stearns, 1989). Thus, it is expected that trade-offs will be greatest in men whose nutritional resources are most constrained. In our sample, evening CORT related negatively to caloric intake and adiposity, consistent with past suggestions of an association between nutritional or energetic stress and elevated CORT (Lukas et al., 2005). Although we did find a significant interaction between caloric intake and CORT, the nature of the relationship was not consistent with these expectations. Contrary to a simple suppressive effect of CORT on T under conditions of caloric stress, men who consumed more calories and had higher CORT showed the highest AM T.

Much of the evidence that CORT suppresses T comes from studies in which stressors, often extreme, are imposed (Tilbrook et al., 2002), but far less is known about the ways in which the two hormones interact under the day-to-day conditions represented in our study (McEwen and Wingfield, 2003, 2010). In addition to our own findings, there is some evidence that CORT and T positively

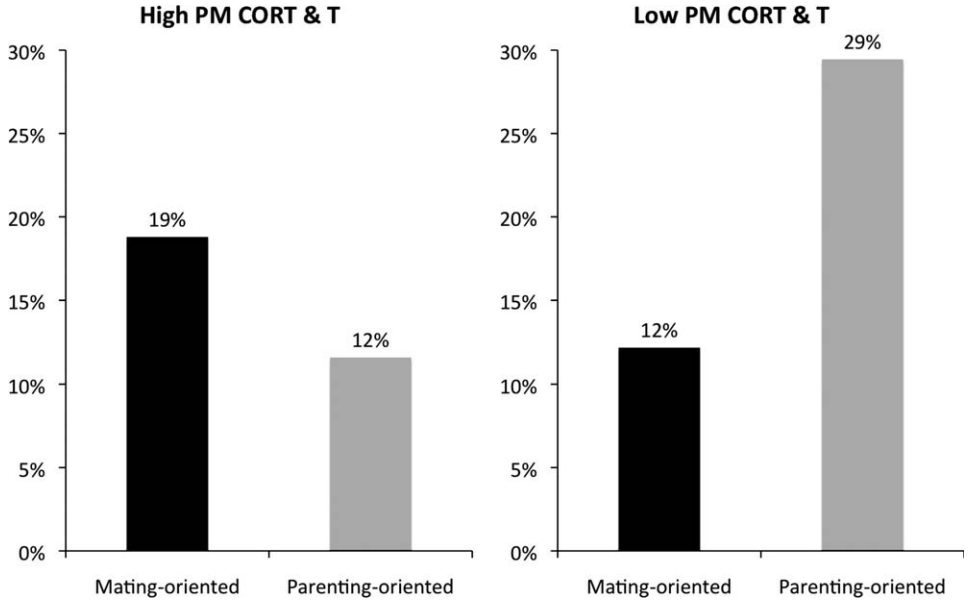

Fig. 4. Percentages of men with co-elevated PM CORT and T (being in the highest tertile of both) and co-downregulated PM CORT and T (being in the lowest tertile of both), stratified according to mating status.

co-vary under day-to-day conditions in humans (Liening et al., 2010; Popma et al., 2007). The most obvious example is the similar diurnal pattern of production of CORT and T, with their similar peaks (near waking) and nadirs (near sleep onset) (Faiman and Winter, 1971; Vitzthum et al., 2009; Worthman, 1999). However, despite these circadian parallels, we did not anticipate that individuals with greater CORT at a given time of day would also have higher T regardless of energetic status, as we document here. Although our sample is relatively lean (average BMI: 21.0), it is possible that these men are not energetically stressed enough for the expected trade-off between CORT and T to be evident (Sapolsky et al., 2000).

Based on cross-species evidence of higher CORT and T among males engaged in breeding and male-male competition, we hypothesized that mating-oriented men would be more likely to show co-elevated CORT and T compared with parenting-oriented men, and similarly, that parenting-oriented men would be more likely to show co-downregulation of CORT and T. Both expectations were confirmed in our data. These results build on previous findings that fathers/married men have lower CORT and T, assessed individually, compared with non-fathers/married men (Berg and Wynne-Edwards, 2001; Mazur and Michalek, 1998). In other species in which CORT and T are higher during the breeding season or periods of intrasexual social challenge, the elevation of CORT (coincident with T) has been interpreted as a physiological response to energetic strain (Muller and Wrangham, 2004b) and other stressors related to mating competition (Boonstra et al., 2001; Ostner et al., 2008). Contrary to our prediction, we did not find that the relationship between mating status and co-elevated CORT and T varied by energetic status, while adjusting models for socioeconomic status and psychosocial stress had essentially no effect on models. Although the limitations of our energetic and stress measures must be emphasized, this finding suggests that the maintenance of simultaneously high CORT and T during mating effort in these men is not contingent upon variation in energetic or psychosocial stress among these men.

One possible interpretation of these findings is that greater CORT and T play a facilitatory role in the behavioral patterns related to mating effort (Lynch et al., 2002). For example, the morning rise in CORT serves as a psychological and behavioral "boost" that prepares humans for anticipated challenges (Adam et al., 2006; Kunz-Ebrecht et al., 2004). CORT also relates positively to self-esteem in young adult males (Zorrilla et al., 1995) and can increase arousal and selective attention to emotionally salient stimuli (Erickson et al., 2003). Moreover, elevation of CORT during short-term interactions with a female relates positively to males' post-interaction mood rating (Roney et al., 2010). Although findings vary across studies, T has generally been shown to relate to aggressive behaviors and personality characteristics suggested to be relevant to dominance and social position (Archer, 2006). For instance, there is evidence that T increases attention paid to angry faces, while reducing the level of induced anxiety (van Honk et al., 1999; Wirth and Schultheiss, 2007). T has also been linked to sensation seeking and extraversion (Daitzman and Zuckerman, 1980; Gerra et al., 1999) and motivation to win during competition (Salvador et al., 2003; Suay et al., 1999).

As noted previously, men have also been reported to experience short-term, concurrent rises in T and CORT when participating in competitive events (Elias, 1981; Mehta et al., 2008; Salvador et al., 2003) and, among men placing a high value on masculinity and honor, in response to challenges to their status by other men (Cohen et al., 1996). Simultaneous increases in CORT and T have also been linked to increased unconscious attention to social threat, perhaps reflecting sub-cortical neuroendocrine response to dominance challenge (van Honk et al., 2000). Men have also been found to increase CORT and T

when interacting with females, particularly those they find attractive (Roney et al., 2010; van der Meij et al., 2010). If we presume that non-pairbonded, non-fathers engage in or anticipate what they perceive as greater daily male-male competition or dominance challenges, as well as interactions with potential mating partners (Booth and Dabbs, 1993; Mazur and Michalek, 1998), they may derive benefits from maintaining heightened day-to-day CORT and T, as our results indicate, rather than merely experiencing the transient hormonal increases documented in many of the studies above. In total, given that previous studies have demonstrated that females often privilege characteristics related to self-confidence, status, and dominance in choosing a mate (Buss, 1989; Buunk et al., 2002), the role of CORT and T in increasing men's self-esteem, competitiveness, and assertiveness in response to dominance challenges could increase the effectiveness of their mating effort. Notably, men with higher T have previously been shown to report more lifetime sexual partners and to have physical attributes deemed attractive by females (Dabbs and Morris, 1990; Roney et al., 2006). Moreover, dominance status is positively related to male reproductive success in many nonhuman primate species (Packer, 1979; Paul et al., 1993; Wroblewski et al., 2009).

For parenting-oriented men, downregulation of CORT and T could provide benefits when reproductive strategy shifts to maintaining a stable pairbond and/or raising children, as the time invested in and behavioral patterns associated with mating effort may conflict with effective pairbond maintenance and caregiving. For example, among married US men, T has been found to positively relate to the likelihood of divorce (Mazur and Michalek, 1998) or a history of having been divorced, physically abusive to a partner, and unfaithful (Booth and Dabbs, 1993). Conversely, men who care for their children have been shown to have the lowest T in connection with fatherhood (Kuzawa et al., 2009; Muller et al., 2009). Moreover, as in other species (Boonstra et al., 2001), there are likely health costs to long-term co-elevation of CORT and T, (Booth et al., 1999b; Muehlenbein and Watts, 2010; Sapolsky, 2004), consistent with a prioritization of reproduction over survival and maintenance.

The physiologic mechanisms that might moderate the relationship between CORT and T and thereby determine whether they negatively or positively covary remain unclear. In rats, two enzymes, 11-β hydroxysteroid dehydrogenase (11β-HSD) types 1 and 2, are expressed in the testes where they convert the biologically active form of glucocorticoids to inert metabolites, thus preventing them from suppressing T (Gao et al., 1997; Monder et al., 1994). When stressors increase CORT above a threshold the oxidative capacity of these enzymes is saturated and T synthesis is inhibited (Hu et al., 2008). In human samples, significant interindividual variability in 11β-dehydrogenase activity has been documented (Cooper et al., 2000), suggesting that subjects may vary in the threshold at which elevated CORT inhibits T production.

In addition, minor increases in unbound T, which is the form measured in saliva, may result from effects of CORT on carrier protein binding. Both hormones are partially bound by albumin and corticosteroid binding globulin. Hence, an AM rise in unbound T may be observed in men with relatively greater AM CORT due to its competitive binding to these carrier proteins (Cooke et al., 1993, 1996). Acute increases in CORT may also reduce the production of sex hormone binding globulin, which binds T with a high affinity, possibly leading to greater unbound T with elevated CORT (Hautanen et al., 1993). Other possible relevant mechanisms include changes in receptor affinity or density, which may be modulated through circadian and context-sensitive effects (Tomlinson et al., 2004; Yang et al., 2006).

In light of the positive association between LH and CORT in our sample, it is also possible that the trophic factors responsible for stimulating production of CORT in the adrenal cortex (ACTH) and T in the testis (LH) serve as secretagogues for steroidogenesis in the opposing site. Although to our knowledge there is no evidence that ACTH upregulates leydig cell production of T, human adrenal cells in the zona fasciculata, where CORT is primarily produced, have been shown to express the LH receptor (Pabon et al., 1996), albeit likely at a low level (Bernichtein et al., 2008). Positive relationships between CORT and LH have been demonstrated among post-menopausal women as well as in subjects with adrenal pathologies, such as forms of ACTH-independent Cushing's syndrome (Bertherat et al., 2005; Lacroix et al., 1999). However, LH has not been shown to increase CORT under physiological conditions in adult males (Bernichtein et al., 2008). Disentangling the physiologic bases for such HPA-HPG cross talk merits further attention in future studies.

Several limitations of this study are worth noting. Similar to much previous work on human male reproductive ecology, the cross-sectional nature of our biological samples prevents us from making causal determinations about changes in the relationship between CORT and T over time. In addition, the reliability of our biomarker data would have been enhanced by sampling across several days and using the average in analyses rather than analyzing estimates from single samples (Dabbs, 1990). Our single measurements of saliva and blood do not introduce bias, but merely reduce the reliability of our biomarker measures and thereby limit our ability to detect relationships between hormones as well as with other variables. To compensate for these limitations, we collected saliva samples at carefully standardized times in a sample of men that exceeds the size of most prior similar studies. The significant positive relationships between CORT and T that we document, despite the limitations of single samples, speak to the tight coupling of the circulating concentrations of these two hormones.

In sum, we find moderate, positive associations between CORT and T measured in the same saliva samples collected at waking and before bed. These associations were positive regardless of an individual's physical activity or self-reported psychosocial stress. The positive relationship between CORT and T present at waking increased among men with greater caloric intake. Commensurate with findings in nonhuman species, we show that mating-oriented men were more likely to have co-elevated CORT and T at waking and in the evening. We also found that parenting-oriented men were more likely to have co-downregulated CORT and T. These results were not affected by men's energetic condition and other relevant covariates related to status and psychosocial stress. Our findings suggest that CORT and T may be co-regulated as complementary components of reproductive strategy in human males, as has been shown previously among males of other species representing a range of mating strategies and breeding systems.

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LITERATURE CITED

Adair LS, Popkin BM, Akin JS, Guilkey DK, Gultiano S, Borja J, Perez L, Kuzawa CW, McDade T, Hindin MJ. 2010. Cohort profile: the Cebu Longitudinal Health and Nutrition Survey. Int J Epidemiol (in press).

Adair LS, Popkin BM, Guilkey DK. 1993. The duration of breast-feeding: how is it affected by biological, sociodemographic, health sector, and food-industry factors. Demography 30:63–80.

Adam EK, Hawkley LC, Kudielka BM, Cacioppo JT. 2006. Day-to-day dynamics of experience-cortisol associations in a population-based sample of older adults. PNAS 103:17058–17063.

Ainsworth BE, Haskell WL, Whitt MC, Irwin ML, Swartz AM, Strath SJ, O'Brien WL, Bassett DR, Schmitz KH, Emplaincourt PO, Jacobs DR, Leon AS. 2000. Compendium of physical activities: an update of activity codes and met intensities. Med Sci Sports Exerc 32:S498–S516.

Archer J. 2006. Testosterone and human aggression: an evaluation of the challenge hypothesis. Neurosci Biobehav Rev 30:319–345.

Axelsson J, Ingre M, Akerstedt T, Holmback U. 2005. Effects of acutely displaced sleep on testosterone. J Clin Endocrinol Metab 90:4530–4535.

Berg SJ, Wynne-Edwards KE. 2001. Changes in testosterone, cortisol, and estradiol levels in men becoming fathers. Mayo Clinic Proceedings 76:582–592.

Bernichtein S, Alevizaki M, Huhtaniemi I. 2008. Is the adrenal cortex a target for gonadotropins? Trends Endocrinol Metab 19:231–238.

Bertherat J, Contesse V, Louiset E, Barrande G, Duparc C, Groussin L, Emy P, Bertagna X, Kuhn J-M, Vaudry H, Lefebvre H. 2005. In vivo and in vitro screening for illegitimate receptors in adrenocorticotropin-independent macronodular adrenal hyperplasia causing cushing's syndrome: identification of two cases of gonadotropin/gastric inhibitory polypeptide-dependent hypercortisolism. J Clin Endocrinol Metab 90: 1302–1310.

Boonstra R, McColl CJ, Karels TJ. 2001. Reproduction at all costs: the adaptive stress response of male Arctic ground squirrels. Ecology 82:1930–1946.

Booth A, Dabbs JM. 1993. Testosterone and men's marriages. Social Forces 72:463–477.

Booth A, Johnson DR, Granger DA. 1999a. Testosterone and men's depression: the role of social behavior. J Health Social Behav 40:130–140.

Booth A, Johnson DR, Granger DA. 1999b. Testosterone and men's health. J Behav Med 22:1–19.

Bribiescas RG. 2001. Reproductive ecology and life history of the human male. Yearb Phys Anthropol 44:148–176.

Bribiescas RG, Ellison PT. 2008. How hormones mediate trade-offs in human health and disease. In: Stearns SC, Koella JC, editors. Evolution in health and disease,2nd ed. Oxford University Press. p77–93.

Buss DM. 1989. Sex differences in human mate preferences: evolutionary hypotheses tested in 37 cultures. Behav Brain Sci 12:1–14.

Buunk BP, Dijkstra P, Fetchenhauer D, Kenrick DT. 2002. Age and gender differences in mate selection criteria for various involvement levels. Personal Relationships 9:271–278.

Cohen S, Kamarck T, Mermelstein R. 1983. A global measure of perceived stress. J Health Soc Behav 24:385–396.

Cohen D, Nisbett RE, Bowdle BF, Schwarz N. 1996. Insult, aggression, and the southern culture of honor: an "Experimental ethnography." J Pers Soc Psychol 70:945–960.

Cooke RR, McIntosh JE. 1996. Murray-McIntosh RP. Effect of cortisol on percentage of non-sex- hormone-bound steroid: implications for distribution of steroids on binding proteins in serum. Clin Chem 42:249–254.

Cooke RR, Mcintosh JEA, McIntosh RP. 1993. Circadian variation in serum, free, and non-shbg-bound testosterone in normal men: measurements, and simulation using a mass action model. Clin Endocrinol 39:163–171.

Cooper MS, Walker EA, Bland R, Fraser WD, Hewison M, Stewart PM. 2000. Expression and functional consequences of 11β-hydroxysteroid dehydrogenase activity in human bone. Bone 27:375–381.

Creel S, Creel N, Mills MGL, Monfort SL. 1997. Rank and reproduction in cooperatively breeding African wild dogs: behavioral and endocrine correlates. Behav Ecol 8:298–306.

Cumming DC, Quigley ME, Yen SSC. 1983. Acute suppression of circulating testosterone levels by cortisol in men. J Clin Endocrinol Metab 57:671–673.

Czoty PW, Gould RW, Nader MA. 2009. Relationship between social rank and cortisol and testosterone concentrations in male cynomolgus monkeys (*Macaca fascicularis*). J Neuroendocrinol 21:68–76.

Dabbs JM. 1990. Salivary testosterone measurements: reliability across hours, days, and weeks. Physiol Behav 48:83–86.

Dabbs JM, Morris R. 1990. Testosterone, social class, and antisocial behavior in a sample of 4,462 men. Psychol Sci 1:209–211.

Daitzman R, Zuckerman M. 1980. Disinhibitory sensation seeking, personality and gonadal hormones. Pers Individ Differences 1:103–110.

Dittami J, Katina S, Mostl E, Eriksson J, Machatschke IH, Hohmann G. 2008. Urinary androgens and cortisol metabolites in field-sampled bonobos (*Pan paniscus*). General and Comparative Endocrinology 155:552–557.

Elias M. 1981. Serum cortisol, testosterone, and testosterone binding globulin responses to competitive fighting in human males. Aggress Behav 7:215–224.

Erickson K, Drevets W, Schulkin J. 2003. Glucocorticoid regulation of diverse cognitive functions in normal and pathological emotional states. Neurosci Biobehav Rev 27:233–246.

Faiman C, Winter JSD. 1971. Diurnal cycles in plasma fsh, testosterone, and cortisol in men. J Clin Endocrinol Metab 33:186–192.

Finch CE, Rose MR. 1995. Hormones and the physiological architecture of life history evolution. Q Rev Biol 70:1–52.

FNRI. 1997. Food and nutrition research institute: food composition tables recommended for use in the philippines. Manila: Food and Nutrition Research Institute of the Philippines.

Gao HB, Ge R, Lakshmi V, Marandici A, Hardy MP. 1997. Hormonal regulation of oxidative and reductive activities of 11β-hydroxysteorid dehydrogenase in rat ledyig cells. Endocrinology 138:156–161.

Gerra G, Avanzini P, Zaimovic A, Sartori R, Bocchi C, Timpano M, Zambelli U, Delsignore R, Gardini F, Talarico E, Brambilla F. 1999. Neurotransmitters, neuroendocrine correlates of sensation-seeking temperament in normal humans. Neuropsychobiology 39:207–213.

Gettler LT. 2010. Direct male care and hominin evolution: why male-child interaction is more than a nice social idea. Am Anthropol 112:7–21.

Gettler LT, Agustin S, Kuzawa C. 2010. Testosterone and somatic outcomes among Filipino males. Am J Phys Anthropol 142:590–599.

Gray PB, Anderson KG. 2010. Fatherhood: evolution and human paternal behavior. Cambridge, MA: Harvard University Press. p304.

Gray PB, Campbell BC. 2009. Human male testosterone, pair bonding and fatherhood. In: Ellison PT, Gray PB, editors. Endocrinology of social relationships. Cambridge, MA: Harvard University Press. p270–293.

Gray PB, Parkin JC, Samms-Vaughan ME. 2007. Hormonal correlates of human paternal interactions: a hospital-based investigation in urban Jamaica. Horm Behav 52:499–507.

Hau M. 2007. Regulation of male traits by testosterone: implications for the evolution of vertebrate life histories. BioEssays 29:133–144.

Hautanen A, Sarna S, Pelkonen R, Adlercreutz H. 1993. Serum sex hormone binding globulin, cardiovascular risk factors, and adrenal cortisol responses to dexamethasone and corticotropin. Metabolism 42:870–874.

Hoogeveen AR, Zonderland ML. 1996. Relationships between testosterone, cortisol and performance in professional cyclists. Int J Sports Med 17:423–428.

Hu GX, Lian QQ, Lin H, Latif SA, Morris DJ, Hardy MP, Ge RS. 2008. Rapid mechanisms of glucocorticoid signaling in the leydig cell. Steroids 73:1018–1024.

Kunz-Ebrecht SR, Kirschbaum C, Steptoe A. 2004. Work stress, socioeconomic status and neuroendocrine activation over the working day. Soc Sci Med 58:1523–1530.

Kuzawa CW, Adair LS. 2003. Lipid profiles in adolescent Filipinos: relation to birth weight and maternal energy status during pregnancy. Am J Clin Nutr 77:960–966.

Kuzawa C, Gettler LT, Muller MN, McDade TW, Feranil AB. 2009. Fatherhood, pairbonding, and testosterone in the Philippines. Horm Behav 2009; 56:429–435.

Lacroix A, Hamet P, Boutin J-M. 1999. Leuprolide acetate therapy in luteinizing hormone-dependent cushing's syndrome. N Engl J Med 341:1577–1581.

Lance VA, Grumbles JS, Rostal DC. 2001. Sex differences in plasma corticosterone in desert tortoises, *gopherus agassizii*, during the reproductive cycle. J Exp Zool 289;285–289.

Liening SH, Stanton SJ, Saini EK, Schultheiss OC. 2010. Salivary testosterone, cortisol, and progesterone: two-week stability, interhormone correlations, and effects of time of day, menstrual cycle, and oral contraceptive use on steroid hormone levels. Physiol Behav 99:8–16.

Lohman TG, Roche AF, Martorell R. 1988. Anthropometric standardization reference manual. Champaign, IL: Human Kinetics Books.

Lukas WD, Campbell BC, Campbell KL. 2005. Urinary cortisol and muscle mass in Turkana men. Am J Hum Biol 17:489–495.

Lund TD, Munson DJ, Haldy ME, Handa RJ. 2004. Androgen inhibits, while oestrogen enhances, restraint-induced activation of neuropeptide neurones in the paraventricular nucleus of the hypothalamus. J Neuroendocrinol 16:272–278.

Lynch JW, Ziegler TE, Strier KB. 2002. Individual and seasonal variation in fecal testosterone and cortisol levels of wild male tufted capuchin monkeys, Cebus apella nigritus. Horm Behav 41:275–287.

MacAdams MR, White RH, Chipps BE. 1986. Reduction of serum testosterone levels during chronic glucocorticoid therapy. Ann Intern Med 104:648–651.

Mateos C. 2005. The subordination stress paradigm and the relation between testosterone and corticosterone in male ring-necked pheasants. Anim Behav 69:249–255.

Mazur A, Michalek J. 1998. Marriage, divorce, and male testosterone. Social Forces 77:315–330.

McDade TW, Adair L, Feranil AB, Kuzawa C. 2011. Positive antibody response to vaccination in adolescence predicts lower c-reactive protein concentration in young adulthood in the Philippines. Am J Hum Biol 23:313–318.

McEwen BS, Wingfield JC. 2003. The concept of allostasis in biology and biomedicine. Horm Behav 43:2–15.

McEwen BS, Wingfield JC. 2010. What is in a name? Integrating homeostasis, allostasis and stress. Horm Behav 57:105–111.

Mehta PH, Jones AC, Josephs RA. 2008. The social endocrinology of dominance: basal testosterone predicts cortisol changes and behavior following victory and defeat. J Pers Soc Psychol 94:1078–1093.

Monder C, Miroff Y, Marandici A, Hardy MP. 1994. 11β-hydroxysteroid dehydrogenase alleviates glucorticoid-mediated inhibition of steroidogenesis in rat leydig cells. Endocrinology 134:1199–1204.

Moore IT, Lerner JP, Lerner DT, Mason RT. 2000. Relationships between annual cycles of testosterone, corticosterone, and body condition in male red spotted garter snakes, Thamnophis sirtalis concinnus. Physiol Biochem Zool 73:307–312.

Mooring MS, Patton ML, Lance VA, Hall BM, Schaad EW, Fortin SS, Jella JE, McPeak KM. 2004. Fecal androgens of bison bulls during the rut. Horm Behav 46:392–398.

Mooring MS, Patton ML, Lance VA, Hall BM, Schaad EW, Fetter GA, Fortin SS, McPeak KM. 2006. Glucocorticoids of bison bulls in relation to social status. Horm Behav 49:369–375.

Morgan CA, Wang S, Mason J, Southwick SM, Fox P, Hazlett G, Charney DS, Greenfield G. 2000. Hormone profiles in humans experiencing military survival training. Biol Psychiatr 47:891–901.

Muehlenbein MP, Hirschtick JL, Bonner JZ, Swartz AM. 2010. Toward quantifying the usage costs of human immunity: Altered metabolic rates and hormone levels during acute immune activation in men. Am J Hum Biol 22:546–556.

Muehlenbein M, Watts D. 2010. The costs of dominance: testosterone, cortisol and intestinal parasites in wild male chimpanzees. Biopsychosoc Med 4:21.

Muller MN, Marlowe FW, Bugumba R, Ellison PT. 2009. Testosterone and paternal care in East African foragers and pastoralists. Proc R Soc B 276:347–354.

Muller MN, Wrangham RW. 2004a. Dominance, aggression and testosterone in wild chimpanzees: a test of the "challenge hypothesis." Anim Behav 67:113–123.

Muller MN, Wrangham RW. 2004b. Dominance, cortisol and stress in wild chimpanzees (*Pan troglodytes schweinfurthii*). Behav Ecol Sociobiol 55:332–340.

Muniyappa R, Veldhuis JD, Harman SM, Sorkin JD, Blackman MR. 2010. Effects of testosterone administration on nocturnal cortisol secretion in healthy older men. J Gerontol A Biol Sci Med Sci 65A:1185–1192.

Ostner J, Heistermann M, Kappeler P. 2008. Androgen and glucocorticoid levels reflect seasonally occurring social challenges in male redfronted lemurs (*Eulemur fulvus rufus*). Behav Ecol Sociobiol 62:627–638.

Pabon JE, Li X, Lei ZM, Sanfilippo JS, Yussman MA, Rao CV. 1996. Novel presence of luteinizing hormone/chorionic gonadotropin receptors in human adrenal glands. J Clin Endocrinol Metab 81:2397–2400.

Packer C. 1979. Male dominance and reproductive activity in *Papio anubis*. Anim Behav 27(Part 1):37–45.

Paul A, Kuester J, Timme A, Arnemann J. 1993. The association between rank, mating effort, and reproductive success in male Barbary macaques (*Macaca sylvanus*). Primates 34:491–502.

Pearson TA, Mensah GA, Alexander RW, Anderson JL, Cannon RO III, Criqui M, Fadl YY, Fortmann SP, Hong Y, Myers GL, Rifai N, Smith SC Jr, Taubert K, Tracy RP, Vinicor F. 2003. Markers of inflammation and cardiovascular disease: application to clinical and public health practice: a statement for healthcare professionals from the centers for disease control and prevention and the American heart association. Circulation 107:499–511.

Popma A, Vermeiren R, Geluk C, Rinne T, van den Brink W, Knol DL, Jansen LMC, van Engeland H, Doreleijers TAH. 2007. Cortisol moderates the relationship between testosterone and aggression in delinquent male adolescents. Biol Psychiatry 61:405–411.

Quinlan RJ. 2008. Human pair-bonds: evolutionary functions, ecological variation, and adaptive development. Evol Anthropol 17:227–238.

Rivier C, Rivest S. 1991. Effect of stress on the activity of the hypothalamic-pituitary-gonadal axis: peripheral and central mechanisms. Biol Reprod 45:523–532.

Roney JR, Hanson KN, Durante KM, Maestripieri D. 2006. Reading men's faces: women's mate attractiveness judgments track men's testosterone and interest in infants. Proc R Soc B 273:2169–2175.

Roney JR, Simmons ZL, Lukaszewski AW. 2010. Androgen receptor gene sequence and basal cortisol concentrations predict men's hormonal responses to potential mates. Proc R Soc B 277:57–63.

Rubinow DR, Roca CA, Schmidt PJ, Danaceau MA, Putnam K, Cizza G, Chrousos G, Nieman L. 2005. Testosterone suppression of crh-stimulated cortisol in men. Neuropsychopharmacology 30:1906–1912.

Salvador A, Suay F, Gonzalez-Bono E, Serrano MA. 2003. Anticipatory cortisol, testosterone and psychological responses to judo competition in young men. Psychoneuroendocrinology 28:364–375.

Sapolsky RM. 1991. Testicular function, social rank, and personality among wild baboons. Psychoneuroendocrinology 16:281–293.

Sapolsky RM. 2004. Social status and health in humans and other animals. Annu Rev Anthropol 33:393–418.

Sapolsky RM, Romero ML, Munck AU. 2002. How do glucocorticoids influence stress responses? Integrating permissive, suppressive, stimulatory, and preparative actions. Endocr Rev 21:55–89.

Stearns SC. 1989. Trade-offs in life history evolution. Funct Ecol 3:259–268.

Suay F, Salvador A, Gonzalez-Bono E, Sanchis C, Martinez M, Martinez-Sanchis S, Simon V, Montoro JB. 1999. Effects of competition and its outcome on serum testosterone, cortisol and prolactin. Psychoneuroendocrinology 24:551–566.

Tilbrook AJ, Turner AI, Clarke IJ. 2002. Stress and reproduction: central mechanisms and sex differences in non-rodent species. Stress 5:83–100.

Tomlinson JW, Walker EA, Bujalska IJ, Draper N, Lavery GG, Cooper MS, Hewison M, Stewart PM. 2004. 11beta-hydroxysteroid dehydrogenase type 1: A tissue-specific regulator of glucocorticoid response. Endocr Rev 25:831–866.

Touitou Y, Motohashi Y, Reinberg A, Touitou C, Bourdeleau P, Bogdan A, Auzéby A. 1990. Effect of shift work on the night-time secretory patterns of melatonin, prolactin, cortisol and testosterone. Eur J Appl Physiol Occup Physiol 60:288–292.

van der Meij L, Buunk AP, Salvador A. 2010. Contact with attractive women affects the release of cortisol in men. Horm Behav 58:501–505.

van Honk J, Tuiten A, van den Hout M, Koppeschaar H, Thijssen J, de Haan E, Verbaten R. 2000. Conscious and preconscious selective attention to social threat: different neuroendocrine response patterns. Psychoneuroendocrinology 25:577–591.

van Honk J, Tuiten A, Verbaten R, van den Hout M, Koppeschaar H, Thijssen J, de Haan E. 1999. Correlations among salivary testosterone, mood, and selective attention to threat in humans. Horm Behav 36:17–24.

van Schaik C, van Noordwijk M, van Bragt T, Blankenstein M. 1991. A pilot study of the social correlates of levels of urinary cortisol, prolactin, and testosterone in wild long-tailed macaques (*Macaca fascicularis*). Primates 32:345–356.

Viau V, Meaney M. 1996. The inhibitory effect of testosterone on hypothalamic-pituitary- adrenal responses to stress is mediated by the medial preoptic area. J Neurosci 16:1866–1876.

Vierhapper H, Nowotny P, Waldhäusl W. 2000. Production rates of testosterone in patients with Cushing's syndrome. Metabolism 49:229–231.

Vitzthum VJ, Worthman CM, Beall CM, Thornburg J, Vargas E, Villena M, Soria R, Caceres E, Spielvogel H. 2009. Seasonal and circadian variation in salivary testosterone in rural bolivian men. Am J Hum Biol 21:762–768.

Weibel L, Spiegel K, Follenius M, Ehrhart J, Brandenberger G. 1996. Internal dissociation of the circadian markers of the cortisol rhythm in night workers. Am J Physiol Endocrinol Metab 270:E608–E613.

Williamson M, Viau V. 2007. Androgen receptor expressing neurons that project to the paraventricular nucleus of the hypothalamus in the male rat. J Comp Neurol 503:717–740.

Wirth MM, Schultheiss OC. 2007. Basal testosterone moderates responses to anger faces in humans. Physiol Behav 90:496–505.

Worthman CM. 1999. Epidemiology of human development. In: Panter-Brick C, Worthman CM, editors. Hormones, health, and behavior. Cambridge: Cambridge University Press. p47–104.
Wroblewski EE, Murray CM, Keele BF, Schumacher-Stankey JC, Hahn BH, Pusey AE. 2009. Male dominance rank and reproductive success in chimpanzees, *Pan troglodytes schweinfurthii*. Anim Behav 77:873–885.
Yang X, Downes M, Yu RT, Bookout AL, He W, Straume M, Mangelsdorf DJ, Evans RM. 2006. Nuclear receptor expression links the circadian clock to metabolism. Cell 126:801–810.
Zorrilla EP, DeRubeis RJ, Redei E. 1995. High self-esteem, hardiness and affective stability are associated with higher basal pituitary-adrenal hormone levels. Psychoneuroendocrinology 20:591–601.