Age-associated changes in hypothalamic–pituitary–testicular function in middle-aged and older men are modified by weight change and lifestyle factors: longitudinal results from the European Male Ageing Study

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Abstract

Objective: Health and lifestyle factors are associated with variations in serum testosterone levels in ageing men. However, it remains unclear how age-related changes in testosterone may be attenuated by lifestyle modifications. The objective was to investigate the longitudinal relationships between changes in health and lifestyle factors with changes in hormones of the reproductive endocrine axis in ageing men.

Design: A longitudinal survey of 2736 community-dwelling men aged 40–79 years at baseline recruited from eight centres across Europe. Follow-up assessment occurred mean (±s.d.) 4.4 ± 0.3 years later.

Results: Paired testosterone results were available for 2395 men. Mean (±s.d.) annualised hormone changes were as follows: testosterone −0.1 ± 0.95 nmol/l; free testosterone (FT) −3.83 ± 16.8 pmol/l; sex hormone-binding globulin (SHBG) 0.56 ± 2.5 nmol/l and LH 0.08 ± 0.57 U/l. Weight loss was associated with a proportional increase, and weight gain a proportional decrease, in testosterone and SHBG. FT showed a curvilinear relationship to weight change; only those who gained or lost ≥15% of weight showed a significant change (in the same direction as testosterone). Smoking cessation was associated with a greater decline in testosterone than being a non-smoker, which was unrelated to weight change. Changes in number of comorbid conditions or physical activity were not associated with significant alterations in hypothalamic–pituitary–testicular (HPT) axis function.

Conclusions: Body weight and lifestyle factors influence HPT axis function in ageing. Weight loss was associated with a rise, and weight gain a fall, in testosterone, FT and SHBG. Weight management appears to be important in maintaining circulating testosterone in ageing men, and obesity-associated changes in HPT axis hormones are reversible following weight reduction.

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Introduction

The age-related decline in testosterone in men has been well documented in cross-sectional studies (1, 2). More recently, longitudinal studies have also confirmed that testosterone declines as individuals age (3, 4, 5, 6, 7, 8). Despite the ill-defined aetiological mechanism(s) and clinical significance associated with this phenomenon, or the continuing uncertainties surrounding the risks vs benefits of testosterone treatment in older men (9),
these findings have fuelled a substantial worldwide increase in testosterone prescription (10, 11, 12, 13). Testosterone decline may not be an inevitable part of ageing, being related to adverse health and lifestyle factors, such as obesity; it may, therefore, be potentially preventable and reversible (5, 6, 7, 14).

Few studies have investigated the relationships between age-related transitions in testosterone and health or lifestyle changes, which could provide a greater understanding of the directionality of these associations and elucidate potential underlying mechanisms. The Massachusetts Male Aging Study (MMAS) reported that a 4–5 kg/m² increase in BMI had a comparable negative impact on testosterone as 10 years of ageing (7). MMAS also reported that weight gain was associated with subsequently lower levels of testosterone than remaining non-obese (5, 6). In obese diabetic patients, interventional weight loss regimes resulted in increased testosterone (15). However, it is not known whether ‘unsupervised’ weight loss in the general population would have a similar impact on testosterone. If so, there may be potentially important clinical and public health implications.

While the concentration of testosterone is often the sole focus of clinical decisions, it is important to consider a broader ensemble of changes in the endocrine reproductive axis. Individual hormones of the hypothalamic–pituitary–testicular (HPT) axis are tightly regulated by feedback / feedforward relationships (16). Different components of HPT function may ‘age’ differently and/or respond differentially to health and lifestyle modifications. The age-related increase in sex hormone-binding globulin (SHBG) (17), and its fluctuation in response to changes in metabolic status, can influence bioavailability of testosterone and contribute to alterations in HPT axis function (18, 19, 20, 21, 22).

We have previously investigated the cross-sectional relationships of HPT axis hormones with age, and health and lifestyle factors, in a sample of community-dwelling middle-aged and elderly men (1). Obesity and comorbidity were found to be linked to multiple alterations in HPT axis function. To extend these findings, we now report the longitudinal relationships between hormone changes with alterations in health status and lifestyle factors. The aim was to elucidate the aetiological mechanism(s) of the age-related decline in testosterone by determining whether and to what extent lifestyle factors could impact on HPT axis function. In addition, we aimed to investigate whether the directionality of these relationships could be established.

Study design and population sampling

Briefly, 3369 men aged 40–79 years were recruited using stratified random sampling from eight European centres: Manchester (UK), Leuven (Belgium), Malmö (Sweden), Tartu (Estonia), Lodz (Poland), Szeged (Hungary), Florence (Italy) and Santiago de Compostela (Spain). Of the men recruited, 193 died and the remaining 3176 men were invited to attend for follow-up 4.4 ± 0.3 years (range 3.0–5.7 years) later (24). A total of 2736 (86.1%) men participated in the follow-up study, with 334 having been lost to follow-up (unrecorded reasons) and 106 having been institutionalised/too frail. Ethical approval for the study was obtained for each centre, as per the regulations of the local institutions.

Hormone measurements

A single fasting morning (before 1000 h) venous blood sample was obtained at baseline and follow-up. Testosterone was measured by liquid chromatography–tandem mass spectrometry (LC–MS/MS) (25), with paired baseline and follow-up samples analysed simultaneously. LH and SHBG were measured by the E170 platform electrochemiluminescence immunoassay (Roche Diagnostics). Free testosterone (FT) was calculated from testosterone, SHBG and albumin, using the Vermeulen formula (26). Intra- and inter-assay coefficients of variation were as follows: testosterone 4.0 and 5.6%; SHBG 1.7 and 3.2% and LH 1.9 and 3.0% respectively (1, 25). Stability of samples during long-term storage was established with no evidence of any systematic drift with time.

Other measurements and data collection

Data on medical conditions, medications, smoking, alcohol consumption and physical activity (Physical Activity Scale for the Elderly (PASE) (27)) were collected by self-completed and interviewer-assisted questionnaires (23). Standing height, weight and waist circumference (WC) were measured as described before (23). Briefly, body weight was measured to the nearest 0.1 kg using an electronic scale (SECA, model no. 8801321009, SECA UK Ltd, Birmingham, UK) and height to the nearest 1 mm using a stadiometer (Leicester Height Measure, SECA UK Ltd). BMI was calculated as body weight (kg) divided by the square of height (m). Each centre’s electronic scales and stadiometers were calibrated on a monthly basis. WC was recorded with an anthropometric tape measure – the median of three measurements was used. The impact of 10% change in weight or WC was initially explored, as this was regarded as ‘moderate’ weight loss in previous studies (28, 29). Participants were classified as having either none or ≥1 comorbidity at each visit (1). Change in physical activity was investigated as tertiles of change.

Materials and methods

The methodology of phase 1 and 2 of the European Male Ageing Study (EMAS) has been described in detail elsewhere (23, 24).

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Table 1 Change in health and lifestyle factors and mean (95% CI) hormone changes. Data generated using multivariate (multiple outcomes) regression. Values represent mean estimated hormone change within each group, for example men who lost ≥10% weight had a mean estimated increase in testosterone of 2.92 nmol/l, following adjustment for covariates (listed below).

<table>
<thead>
<tr>
<th>Weight changea</th>
<th>Testosterone (nmol/l)</th>
<th>FT (pmol/l)</th>
<th>SHBG (nmol/l)</th>
<th>LH (U/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥10% decrease (n=83)</td>
<td>2.92 (1.27, 4.58)†</td>
<td>9.43 (−7.88, 26.74)*</td>
<td>13.59 (8.09, 19.10)†</td>
<td>0.82 (−0.87, 2.51)</td>
</tr>
<tr>
<td>Within 10% (referent) (n=2104)</td>
<td>−0.35 (−0.84, 0.14)</td>
<td>−16.46 (−25.68, −7.23)</td>
<td>2.52 (1.03, 4.01)</td>
<td>0.24 (0.04, 0.44)</td>
</tr>
<tr>
<td>≥10% increase (n=86)</td>
<td>−2.35 (−3.27, −1.43)†</td>
<td>−22.28 (−41.39, −3.17)</td>
<td>−4.70 (−8.86, −0.53)†</td>
<td>−0.21 (−0.78, 0.35)</td>
</tr>
<tr>
<td>P value (multiple test)c</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

| Waist circumference changea | 2.05 (−0.90, 4.99) | 10.54 (−38.74, 58.83) | 8.35 (−4.35, 21.06) | 1.09 (−0.48, 2.66) |
| Within 10% (referent) (n=2127) | −0.29 (−0.70, 0.13) | −16.21 (−24.28, −8.14) | 2.87 (1.37, 4.36) | 0.25 (0.03, 0.47) |
| ≥10% increase (n=124) | −1.08 (−2.31, 0.16) | −12.34 (−29.77, 5.09) | −2.23 (−4.54, 0.09)† | −0.02 (−0.40, 0.37) |
| P value (multiple test)c | <0.001 | 0.001 | 0.001 | 0.001 |

| Smoking statusb | Non-smoker (referent) (n=1759) | −0.34 (−0.69, 0.01) | −15.04 (−22.96, −7.12) | 2.39 (1.25, 3.53) | 0.40 (0.15, 0.64) |
| Stopped smoking (n=112) | −2.01 (−2.81, −1.22)† | −34.83 (−50.60, −19.09)* | −1.07 (−2.92, 0.79) | 0.002 (−0.43, 0.44) |
| Started smoking (n=53) | 1.02 (−0.37, 2.40) | −3.23 (−33.37, 26.91) | 4.76 (1.77, 7.76) | −0.02 (−0.86, 0.82) |
| Smoker (n=339) | −0.47 (−1.28, 0.34) | −18.85 (−29.37, −8.34) | 3.12 (0.34, 5.89) | 0.16 (−0.17, 0.49) |
| P value (multiple test)c | 0.03 | 0.03 | 0.03 | 0.03 |

| Alcohol consumptionb | Inrequent (<1 x/wk) (referent) (n=524) | −0.25 (−0.92, 0.42) | −15.30 (−30.90, 0.30) | 2.79 (1.86, 3.73) | 0.37 (0.09, 0.65) |
| Increased to frequent (n=332) | −0.63 (−1.09, −0.17) | −16.75 (−20.41, −13.09) | 2.05 (0.04, 4.07) | 0.56 (0.27, 0.84) |
| Reduced to infrequent (n=135) | 0.16 (−0.39, 0.72) | −13.53 (−27.38, 0.32) | 4.94 (3.07, 6.80)* | 0.07 (−0.41, 0.55) |
| Frequent at both (n=1027) | −0.42 (−1.05, 0.20) | −17.01 (−25.73, −8.28) | 2.41 (0.93, 3.89) | 0.23 (−0.07, 0.54) |
| P value (multiple test)c | 0.17 | 0.17 | 0.17 | 0.17 |

| Comorbiditiesb | Never ≥1 (referent) (n=830) | −0.43 (−0.97, 0.12) | −16.61 (−24.29, −8.94) | 2.12 (0.82, 3.43) | 0.09 (−0.16, 0.34) |
| ≥1 at baseline only (n=90) | −0.20 (−1.30, 0.90) | −11.72 (−28.05, 4.61) | 2.20 (−0.35, 4.76) | 0.44 (0.26, 0.61) |
| ≥1 at follow-up only (n=293) | −0.08 (−0.93, 0.76) | −13.37 (−29.20, 2.37) | 2.63 (0.19, 5.06) | 0.37 (−0.08, 0.83) |
| ≥1 at both (n=808) | −0.42 (−0.62, −0.23) | −17.39 (−23.95, −10.83) | 2.66 (1.11, 4.21) | 0.47 (0.23, 0.74) |
| P value (multiple test)c | 0.64 | 0.64 | 0.64 | 0.64 |

| Physical activity: change in PASE scoreb | Tertile 1 (decreased activity) (referent) (n=672) | −0.38 (−0.88, 0.12) | −14.78 (−21.27, −8.29) | 2.19 (0.68, 3.69) | 0.23 (−0.04, 0.50) |
| Tertile 2 (stable) (n=672) | −0.39 (−0.83, 0.04) | −17.53 (−30.57, −4.49) | 2.61 (0.54, 4.69) | 0.26 (−0.07, 0.59) |
| Tertile 3 (increased activity) (n=672) | −0.45 (−0.95, 0.05) | −18.37 (−24.89, −11.85) | 2.53 (1.38, 3.68) | 0.40 (0.11, 0.69) |
| P value (multiple test)c | 0.65 | 0.65 | 0.65 | 0.65 |

| Physical activity: change in exercise frequencyb | Increased (n=672) | −0.18 (−0.70, 0.34) | −12.94 (−21.57, −4.31) | 2.54 (1.34, 3.73) | 0.23 (−0.003, 0.47) |
| No change (referent) (n=921) | −0.51 (−0.83, −0.18) | −19.15 (−27.50, −10.80) | 2.66 (1.15, 4.17) | 0.46 (0.24, 0.67) |
| Decreased (n=639) | −0.59 (−1.06, −0.12) | −18.08 (−26.69, −9.46) | 1.82 (−0.10, 3.73) | 0.28 (0.03, 0.52) |
| P value (multiple test)c | 0.61 | 0.61 | 0.61 | 0.61 |

Specific models included the following covariates: aweight, waist circumference – baseline age and centre, changes in smoking status, alcohol consumption comorbidities and physical activity; bsmoking, alcohol, comorbidities, physical activity – baseline age and centre, and weight change. Change in PASE score: tertile 1 = −388 to −55 (decreased); tertile 2 = −55 to 13 (stable); tertile 3 = 13 to 482 (increased). Significantly different from (referent): *P<0.05, †P<0.01. A total of 23 outliers with SHBG ≥120 nmol/l, LH ≥60 UI or FT ≥800 pmol/l were excluded from the regression analysis. cP value for multivariate regression analysis: null hypothesis is that the four β-coefficients (testosterone, FT, SHBG and LH) for each covariate are all simultaneously equal to zero; therefore, P<0.05 for multiple test indicates at least one component of the HPT axis associated with covariate.
in PASE score and participants assigned to one of three groups accordingly (increased, decreased or no change).

**Statistical analysis**

Differences in cohort characteristics between baseline and follow-up were determined using the paired t-test or \( \chi^2 \) test – as appropriate to the data. Hormone changes were treated as continuous variables and calculated as follow-up measurement – baseline measurement. Linear (age as a continuous variable) and non-linear (age (2)) trends between hormone changes and baseline age were investigated using linear regression. Unadjusted relationships between hormone changes and each of the health/lifestyle changes across the four baseline age bands (40–49, 50–59, 60–69 and 70–79 years) were initially evaluated graphically. To reflect the functional links between the components of the HPT axis under investigation, multivariate (multiple outcomes) linear regression was used to jointly regress the four outcome variables (changes in testosterone, FT, SHBG and LH) simultaneously, as described previously (1). This extension to simple linear regression generates a ‘multiple test statistic’ denoting whether the four coefficients (one for each hormone) obtained are simultaneously equal to zero. A \( P \) value of <0.05 for the multiple test statistic suggests that at least one of the four hormones is significantly associated with the independent variable. Separate multivariate regression models were then carried out to investigate the relationships between changes in each of the health/lifestyle factors (as categorical variables) and changes in the four hormones. Referent categories in each model are denoted in Table 1. Results were expressed as mean hormone changes and 95% CIs and considered statistically significant if the null hypothesis could be rejected at the 0.05 (two-tailed) level. Each regression model was adjusted for potential confounders: baseline age, centre and BMI, where relevant. Additional adjustments for confounders included changes in weight, smoking status, alcohol consumption, comorbidities and physical activity (see Tables 1 and 2 footnotes for further details). To obtain a broader overview of the relationship between weight change and HPT axis function, a multivariate regression model (as described earlier) was used to investigate changes in hormones at seven mutually exclusive levels of weight change (\( \pm >15\% \), \( \pm 10\% \), \( \pm 5\% \) and ‘no change’ (within 5% of baseline)). The independent variable denoting levels of weight change was a single categorical variable; men in the ‘no change’ group were the referent category. These relationships were also evaluated graphically. Sub-analyses, using multivariate regression models as described earlier, were also carried out after stratifying by baseline obesity. Multinomial logistic regression was used to investigate the relationships between (continuous) baseline hormone levels and the likelihood of a subsequent change in weight compared with the likelihood of having ‘stable’ weight; this was then repeated for WC change. Statistical analyses were conducted using STATA SE version 10 (StataCorp, College Station, TX, USA).

**Results**

**Cohort characteristics**

Men who had diagnosed medical conditions or were on medications known to affect pituitary–testicular function or hormone clearance at baseline (\( n=106 \)) or during follow-up (\( n=155 \)) were excluded from this analysis, using the same criteria as our previous cross-sectional analysis (1). Men who did not have testosterone one results at both time points were also excluded (\( n=80 \)). Characteristics of the analysis sample are summarised in Table 3. Mean (s.d.) age of the analysis sample at study recruitment was 58.4 (10.5) years. Twenty-four per cent of men were obese (BMI \( \geq 30 \text{ kg/m}^2 \)) at baseline and 27% at follow-up. There were fewer smokers (17 vs 20%) but a greater percentage of frequent drinkers (67 vs 59%) at follow-up. The proportion of men reporting \( \geq 1 \) comorbidity increased from 45 to 55%.

**Hormone levels**

Mean (s.d.) testosterone was 16.9 (6.0) nmol/l at baseline, and decreased to 16.5 (6.1) nmol/l at follow-up

<table>
<thead>
<tr>
<th>(( n=2395 ))</th>
<th>Mean testosterone change (nmol/l)</th>
<th>Mean FT change (pmol/l)</th>
<th>Mean SHBG change (nmol/l)</th>
<th>Mean LH change (U/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lost ( \geq 15% ) ( n=22 )</td>
<td>5.75 (1.32, 10.18)*</td>
<td>51.78 (1.71, 101.85)*</td>
<td>14.77 (2.39, 27.15)*</td>
<td>2.21 (–0.58, 5.01)</td>
</tr>
<tr>
<td>Lost 10 to &lt;15% ( n=61 )</td>
<td>1.96 (–0.47, 4.39)</td>
<td>–5.06 (–39.17, 29.06)</td>
<td>13.19 (7.06, 19.32)*</td>
<td>0.34 (–1.51, 2.20)</td>
</tr>
<tr>
<td>Lost ( \geq 5% ) to &lt;10% ( n=288 )</td>
<td>0.28 (–0.22, 0.77)$^\dagger$</td>
<td>–13.94 (–21.40, 6.68)</td>
<td>5.32 (3.40, 7.24)$^\dagger$</td>
<td>0.87 (0.17, 1.60)</td>
</tr>
<tr>
<td>Within 5% (referent) ( n=1554 )</td>
<td>–0.33 (–0.79, 0.13)</td>
<td>–16.85 (–27.02, 4.56)</td>
<td>2.61 (1.06, 1.45)</td>
<td>0.16 (–0.06, 0.37)</td>
</tr>
<tr>
<td>Gained ( \geq 5% ) to &lt;10% ( n=262 )</td>
<td>–1.20 (–2.07, –0.33)*</td>
<td>–16.92 (–29.66, 6.18)</td>
<td>–1.26 (–2.90, 0.58)$^\ddagger$</td>
<td>–0.005 (–0.27, 0.26)</td>
</tr>
<tr>
<td>Gained 10 to &lt;15% ( n=69 )</td>
<td>–1.89 (–3.14, –0.63)*</td>
<td>–16.55 (–46.45, 13.35)</td>
<td>–3.84 (–8.63, 0.95)$^\ddagger$</td>
<td>–0.26 (–1.10, 0.57)</td>
</tr>
<tr>
<td>Gained ( \geq 15% ) ( n=17 )</td>
<td>–4.35 (–6.97, –1.73)*</td>
<td>–47.10 (–136.91, 42.72)</td>
<td>–8.41 (–18.73, 1.90)*</td>
<td>–0.004 (–1.00, 0.99)</td>
</tr>
</tbody>
</table>

Significantly different from (referent): *\( P<0.05 \), $^\dagger$\( P<0.01 \). Models included the following covariates: baseline age and centre, changes in smoking status, alcohol consumption, comorbidities and physical activity. A total of 23 outliers with SHBG \( \geq 120 \text{ nmol/l} \), LH \( \geq 60 \text{ U/l} \) or FT \( \geq 800 \text{ pmol/l} \) were excluded from the regression analysis.
### Weight

The relationships between change in weight and hormonal changes are shown in Fig. 2. Following adjustment for potential confounders, men whose weight decreased by ≥10% (mean decrease of 13.7 kg) showed an increase in testosterone (2.9 nmol/l) and SHBG (13.6 nmol/l), which were significantly different from the respective changes among men whose weight remained within 10% of baseline: testosterone −0.4 nmol/l and SHBG 2.5 nmol/l (P < 0.01 for both) (Table 1). An increase of ≥10% in weight (mean increase of 12.3 kg) was associated with a decrease in testosterone (−2.4 nmol/l) and SHBG (−4.7 nmol/l), which were significantly different from the respective changes in men with ‘stable’ weight (P < 0.01 for both).

### Waist circumference

Multiple testing showed a strong association between change in WC and changes in HPT axis function (P < 0.001) (Table 1). The relationships between a decrease in WC and hormone changes were similar to those for weight loss in direction and magnitude. The hormone changes associated with WC increase were more modest, although in the same direction, than those associated with weight gain.

### Smoking

Men who stopped smoking showed a greater decrease than non-smokers in testosterone (−2.0 vs −0.3 nmol/l; P < 0.01) and FT (−34.8 vs −15.0 pmol/l; P < 0.05) (Table 1). Starting smoking was not significantly associated with hormone changes.

### Alcohol

Multiple testing indicated that there was no significant relationship between change in alcohol consumption and change in HPT axis function (P = 0.17). However, frequent drinkers who decreased their frequency of alcohol consumption during follow-up showed a significantly greater increase in SHGB than men who remained infrequent drinkers at both time points (4.9 vs 2.8 nmol/l; P < 0.05) (Table 1).

### Other health and lifestyle factors

There was no association between changes in number of comorbidities, physical activity or exercise frequency (Table 1) with hormone changes.

### Levels of weight change

The weight/hormone relationship was further investigated at seven different incremental levels of weight change.

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**Table 3** Cohort characteristics at baseline and follow-up.

<table>
<thead>
<tr>
<th>Age (years)*</th>
<th>Baseline n/N (%)</th>
<th>Follow-up n/N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40–49</td>
<td>641/2395 (26.8)</td>
<td>314/2395 (13.1)</td>
</tr>
<tr>
<td>50–59</td>
<td>706/2395 (29.5)</td>
<td>752/2395 (31.4)</td>
</tr>
<tr>
<td>60–69</td>
<td>607/2395 (25.3)</td>
<td>649/2395 (27.1)</td>
</tr>
<tr>
<td>≥ 70</td>
<td>441/2395 (18.4)</td>
<td>680/2395 (28.4)</td>
</tr>
</tbody>
</table>

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*P < 0.001. P value for difference calculated using t-test (continuous) or χ² test (categorical); BMI (kg/m²); WC, waist circumference (cm). Smoking status: current smoker (cigarettes), otherwise ‘non-smoker’ (ex-smoker or never smoked). Alcohol intake: frequent (>5 drinks/week), otherwise ‘infrequent’ (<1 drink/week or one to four drinks/week).

*Mean (±SEM).
change (>15% loss, 10–15% loss, 5–10% loss, within 5%, 5–10% gain, 10–15% gain, >15% gain). Figure 3 summarises the overall dose–response relationships between weight and hormone changes. Both testosterone and FT showed a curvilinear (cubic) relationship. However, there were differences between testosterone and FT. Losing 5% of weight was associated with a significant increase in testosterone, which increased further with additional weight loss. Weight gain mirrored this pattern with progressive decline in testosterone. By contrast, there appeared to be a threshold relationship with FT whereby only a weight

Figure 1 Unadjusted and adjusted relationships between hormone changes and age. This shows the mean hormone changes at 10-year age bands with 95% CI (vertical bars) in 2395 men. Testosterone and FT appeared to show a greater decrease beyond 50 years, SHBG showed an increase that was relatively stable across the age bands and LH showed a progressive increase after 50 years, with an apparent inflection point around 70 years. Testosterone (P<0.03) and LH (P<0.001) showed a significant non-linear trend with age. Adjustment for potential confounders (BMI, smoking status and centre) did not alter these relationships. Dashed lines represent adjusted values.

Figure 2 Relationships between age, weight changes and hormone changes. Values represent the unadjusted mean hormone change at 10-year age bands with 95% CI (vertical bars). A total of 23 outliers with SHBG ≥120 nmol/l, LH ≥60 U/l or FT ≥800 pmol/l were excluded from these graphs. The cohort was stratified according to weight change into three groups: lost ≥10% weight (closed square), stable weight (within 10% of baseline, closed circle) and gained ≥10% weight (closed triangle). Testosterone and SHBG increased by significantly more among men whose weight decreased than men whose weight did not change by ≥10%. Men whose weight increased showed a greater decline in testosterone, FT and SHBG than men with stable weight.
loss or gain of ≥15% was associated with a notable change in FT. Men who lost ≥15% weight showed a significant increase in FT (51.8; 95% CI 1.7, 101.9 pmol/l), in contrast to the decrease among men with stable weight (−16.9; 95% CI −27.0, −6.7 pmol/l), and those whose weight increased by ≥15% showed a greater decline in FT (−47.1; 95% CI −136.9, 42.7 pmol) (Table 2). SHBG change showed a linear relationship with weight change (Fig. 3) – men who lost the most weight showed the greatest increase and men who gained the most weight showed the greatest decline. The relationship between weight change and LH change was curvilinear (Fig. 3) – weight loss appeared to be associated with an exponential increase in LH whereas weight gain was not associated with LH change. Men who lost ≥15% of weight showed a tenfold greater increase in LH (2.2; 95% CI −0.6, 5.0 U/l) than men with stable weight (0.2; 95% CI −0.1, 0.4 U/l) (Table 2).

Baseline obesity and weight change

Men who were obese at baseline showed a marginally greater increase in testosterone with ≥10% weight loss compared with non-obese men (3.0 vs 1.2 nmol/l) (data not shown). Losing weight also appeared to have greater influence on FT change in obese compared with non-obese men (7.8 vs −13.5 pmol/l). However, these differences did not reach statistical significance (testosterone \(P=0.07\); FT \(P=0.17\)). Weight gain was associated with similar changes in testosterone and FT for obese and non-obese men. However, weight gain was associated with a greater decline in SHBG in non-obese compared with obese men (−6.3 vs −3.5 nmol/l), this difference also did not reach statistical significance.

Baseline hormones and weight change

None of the baseline hormone levels showed any consistent associations with subsequent weight change (data not shown). For each 10 pmol/l increase in baseline FT, there was a very small decrease in the likelihood of losing ≥10% weight compared with having ‘stable’ weight (relative risk ratio 0.96; 95% CI 0.94, 0.99). The likelihood of an increase in body weight, or a change in WC in either direction, was not associated with baseline levels of testosterone, FT, SHBG, or LH (\(P>0.05\) for each).

Discussion

This prospective study of community-dwelling men in Europe showed that weight gain was associated with suppression of testosterone, FT and SHBG, while weight loss was associated with an increase in testosterone, FT, SHBG and LH. These reciprocal changes displayed a robust dose–response relationship between weight change and reproductive hormones, which emphasises the functional liability (and reversibility) in the HPT axis in ageing men.
In agreement with our previous cross-sectional findings, and other longitudinal studies (1, 3, 4, 5, 6, 7, 8, 30, 31, 32), the present results confirm that testosterone and FT declined while SHBG and LH increased with age, with the mean hormone levels remaining well within the physiological range. The overall pattern of changes in the HPT axis was consistent with a progressive age-related impairment of testicular function, partially compensated for by an increase in LH. The decline in FT with age is exaggerated by the concurrent rise in SHBG. The magnitude of the observed change in testosterone (−0.1 nmol/l per year) was modest and similar to that in previous longitudinal studies (3, 14, 30, 32).

The present longitudinal data were in agreement with other prospective studies showing that weight gain was associated with a decline in testosterone and SHBG (5, 6, 7, 8). LH was largely unchanged with weight gain, despite the significant decrease in testosterone. Weight gain (and obesity) appears to be associated with hypothalamic dysfunction, leading to blunted LH secretion and secondary or hypoandrotrophic hypogonadism (33). Reversal of this hypothalamic suppression with weight loss may thus be expected to result in a rise in testosterone through increased LH stimulation. Indeed, the most notable novel finding in this study, which had not been reported previously in the general population, is the consistent relationship between weight loss and increased testosterone, FT and LH, which was not observed in men with stable weight. This is compatible with clinical interventional studies on weight reduction strategies in obese patients (with diabetes or the metabolic syndrome) (15, 34).

Our results also show, for the first time in a general population cohort, that SHBG increased with weight loss as well as decreased with weight gain, modulating not only circulating levels of testosterone but also buffering FT variations associated with more modest degrees of weight changes (vide infra). It is generally accepted that obesity is associated with lower SHBG (1, 4, 7) as a result of insulin resistance, with the high levels of circulating insulin inhibiting hepatic SHBG production (17). The present results suggest that the fluctuations in SHBG concentrations can provide robust metabolic signal-linking variations in adiposity to HPT axis function, thereby regulating androgen bioactivity through insulin signalling. This is supported by the recent finding that circulating SHBG is influenced by variations in genes involved in the regulation of lipid and carbohydrate metabolism (35). Delivery of bound hormones at target tissue sites (36) is a further possibility for an active role of SHBG in the regulation of sex steroid bioavailability.

The overall picture of HPT axis function with incremental levels of weight change (Fig. 3) shows that hormone levels varied bi-directionally in proportion to the degree of weight loss/gain. The impact of weight change (especially >10%) is much greater than that of ageing alone (Fig. 1). Furthermore, the apparent reversal of the age-related decline in testosterone and FT with weight loss, and its exaggeration with weight gain (Fig. 2), reaffirm our previous suggestion that decreasing testosterone with ageing is not inevitable but potentially preventable and reversible with weight management. The majority of men in this analysis showed stable weight or <15% change, as expected in a non-interventional study. However, a significant shift in FT was only observed with more substantial (≥15%) weight change. This apparent ‘threshold’ effect could be explained by the fact that FT is calculated from testosterone and SHBG concentrations (both of which varied independently with weight change). Thus, the significant increase in FT with ≥15% weight loss could reflect the steeper rise in testosterone, probably driven by a similar increase in LH. This LH-driven exponential increase in testosterone with more substantial weight loss exceeded the binding capacity and could therefore override the effects of a more modest linear increase in SHBG. With ≥15% weight gain, the greater fall in testosterone, associated with a lack of LH change (evidence for progressive hypothalamic suppression), may again explain the fall in FT despite the concurrent decrease in SHBG. In other words, any mitigating effect of SHBG changes on FT is overridden by simultaneous and greater changes in (total) testosterone. Direct measurement of FT, not currently available in this study, will be required to substantiate the current findings and allow more in-depth analyses of the contribution of changes in SHBG to changes in FT. These considerations may also account for the inconsistent relationship between FT and weight change in previous studies (3, 6, 7, 34, 37, 38).

Of the 568 men who were obese at baseline, only a relatively small number showed a ≥10% weight change during follow-up (loss: n = 30; gain: n = 25). Thus, there was insufficient analytical power to detect a statistically significant difference of the impact of weight changes between obese and non-obese men. However, our data did suggest that obese men may experience a greater increase in testosterone with weight loss compared with non-obese men (data not shown). This highlights the value of weight loss in improving HPT axis function, especially in obese men.

It is important to note that we found little association between baseline hormone levels and subsequent weight changes. This is in agreement with recent findings from the BACH survey of middle-aged men (personal communication). Findings from a recent study of menopausal women also suggested that weight gain drives hormone changes (39). Although it is not possible to prove direct causality, changes in HPT hormones appear to be driven by changes in adiposity and not vice versa.

The reason for an individual’s weight change may potentially confound the relationships between weight change and hormone changes. Important reasons for
weight changes are changes in diet and/or physical activity, smoking, alcohol consumption, general health (comorbidity), cancer cachexia and other wasting diseases and bariatric surgery. Our results show that the relationships between weight and hormone changes were not attenuated by adjustment for changes in physical activity, smoking, alcohol consumption or comorbidities. Dietary data were not available, and no subject reported undergoing bariatric surgery. Excluding men who had incident cancer or heart disease did not influence the results (data not shown). The relationships between weight and hormone changes therefore appear to be robust. Apart from body weight, other health/lifestyle factors (e.g. comorbidity and physical activity) did not show much independent influence on hormone changes. Men who stopped smoking showed a greater decline in testosterone than non-smokers. More of the men who stopped smoking gained (>10%) weight during follow-up compared with non-smokers (16 vs 3%). However, the relationship between smoking and testosterone decline was independent of weight change.

A key strength of this study is the investigation of changes in health and lifestyle factors (as opposed to baseline predictors), with contemporaneous changes in circulating hormone levels; there are two major benefits of this approach. First, it provides a better understanding of the temporal relationship between health/lifestyle modifications and hormone changes. Secondly, the potential impact of positive lifestyle changes (e.g. weight loss) on HPT axis function can be assessed, highlighting the public health message. A further strength is consideration of the feedback-feed-forward regulatory nature of the HPT axis by examining multiple hormones, enabling differentiation between hypothalamic and testicular malfunctions. In our previous cross-sectional study, a gas chromatography–mass spectrometry method was used for measuring testosterone (1), which showed a high concordance correlation (\( R = 0.95, P < 0.001; \) data not shown) with the validated LC–MS/MS method (25) used in this analysis. In the present longitudinal study, parallel analyses of both baseline and follow-up samples, together in the same LC–MS/MS run (25), not only ensured optimal accuracy and precision (40) but also minimised inter-laboratory and methodological variations. The ability to use data from such a sizeable general population cohort in a real-world setting is another one of the study’s major strengths. One limitation, however, is the relative shortage of detailed information about individuals’ circumstances that could account for weight change, such as diet. It was not possible to investigate the relationship between weight and oestradiol change as mass spectrometry measurements of oestradiol were not available in the follow-up samples. Other limitations in the EMAS have been described in detail previously (1, 23). However, some specific issues should be highlighted when interpreting the current results. The overall retention rate of the cohort was 81.2%, with a mortality-adjusted participation rate of 86.2% (31). This is comparable to other longitudinal studies of ageing (24) whose findings, like ours, are inevitably subject to some survivor bias. Exclusion of men with diagnosed medical conditions known to affect pituitary–testicular function may have resulted in overrepresentation of healthier men, which may explain why an association between number of comorbid conditions and hormone changes was not observed. The average duration of follow-up of 4.4 years in EMAS is relatively short in the context of the ageing process; longer follow-up with additional rounds of assessment is required to define the trajectory of changes of interest more accurately.

In conclusion, our results show that longitudinal changes in HPT axis function in ageing men are modified by health and lifestyle factors, which can attenuate or reverse the apparent age-related testosterone-decline. We have shown, for the first time in the general population, that moderate weight loss was associated with an increase in testosterone and more substantial (>15%) weight loss with an increase in FT as well. This suggests that preventing obesity is important in maintaining HPT axis functioning in ageing, and furthermore, obesity-associated changes in reproductive hormones are reversible following weight reduction.

Declaration of interest

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