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Ibuprofen alters human testicular physiology to produce a state of compensated hypogonadism

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Concern has been raised over increased male reproductive disorders in the Western world, and the disruption of male endocrinology has been suggested to play a central role. Several studies have shown that mild analgesics exposure during fetal life is associated with antiandrogenic effects and congenital malformations, but the effects on the adult man remain largely unknown. Through a clinical trial with young men exposed to ibuprofen, we show that the analgesic resulted in a state of compensated hypogonadism, a condition prevalent among elderly men and associated with reproductive and physical disorders. In the men, luteinizing hormone (LH) and ibuprofen plasma levels were positively correlated, and the testosterone/LH ratio decreased. Using adult testis explants exposed or not exposed to ibuprofen, we demonstrate that the endocrine capabilities from testicular Leydig and Sertoli cells, including testosterone production, were suppressed through transcriptional repression. This effect was also observed in a human steroidogenic cell line. Our data demonstrate that ibuprofen alters the endocrine system via selective transcriptional repression in the human testes, thereby inducing compensated hypogonadism.

Significance

Concern has been raised over declining male reproductive health in humans. Our study addresses this issue by extending data showing antiandrogenic effects of analgesics and suggests that such compounds may be involved in adult male reproductive problems. Using a unique combination of a randomized, controlled clinical trial and ex vivo and in vitro approaches, we report a univocal depression of important aspects of testicular function, including testosterone production, after use of over-the-counter ibuprofen. The study shows that ibuprofen use results in selective transcriptional repression of endocrine cells in the human testis. This repression results in the elevation of the stimulatory pituitary hormones, resulting in a state of compensated hypogonadism, a disorder associated with adverse reproductive and physical health disorders.


The authors declare no conflict of interest.

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Ibuprofen Inhibits Steroidogenesis ex Vivo and in Vitro. To determine the direct effect of ibuprofen on the testis, we next exposed adult testis explants from donors to doses of $10^{-6}$–$10^{-8}$ M, which corresponded to the oral doses producing mean plasma levels of 1.2–1.7 $\times$ 10$^{-4}$ M used among the men in the trial (see above). We first investigated testosterone production after 24 and 48 h of ibuprofen exposure to assess its effects on Leydig cell steroidogenesis. Inhibition of testosterone levels was significant and dose-dependent ($\beta = -0.405, P = 0.01$ at 24 h and $\beta = -0.664, P < 0.0001$ at 48 h) (Fig. 2A) and was augmented over time ($10^{-5}$ M at 24 h and $10^{-5}$–$10^{-6}$ M at 48 h, $-40\%$) (Fig. 2A). Examination of the effect of ibuprofen exposure on both the $\Delta 4$ and $\Delta 5$ steroid pathways (Fig. 2B) showed that it generally inhibited all steroids from pregnenolone down to testosterone and $17\beta$-estradiol; the production of each steroid measured decreased at doses of $10^{-5}$–$10^{-6}$ M. Under control conditions, production of androstenedione and dehydroepiandrosterone (DHEA) was below the limit of detection except in one experiment with DHEA (Fig. 2B).

We next examined the gene expression involved in testicular steroidogenesis ex vivo and found that levels of expression of every gene that we studied except CYP19A1 decreased after exposure for 48 h compared with controls (Fig. 2C). Suppression of gene expression concerned the initial conversion of cholesterol to the final testosterone synthesis. Hence, expression of genes involved in cholesterol transport to the Leydig cell mitochondria was impaired: Compared with controls, TSPO/BZRP fell significantly after exposure to $10^{-6}$ M; StAR expression was suppressed at both doses of $10^{-6}$ and $10^{-5}$ M (Fig. 2C); CYP11A1, CYP17A1, and HSD17B3 were suppressed by 40–50% at doses of $10^{-6}$–$10^{-7}$ M; and HSD3B2 was reduced by about 90%.

The data from the ex vivo testis model showed suppression of both the $\Delta 4$ and $\Delta 5$ steroid pathways. A previous study reported androstenedione levels decreased by 63% among men receiving 400 mg of ibuprofen every 6 h for 4 wk (15), suggesting a possible inhibitory effect on CYP17A1. We therefore exposed the NCI-H295R cells of human origin (which, although derived from the adrenal gland (instead of testis) and from a cancer originating in the cortex, are considered the best in vitro model of human steroidogenesis according to the Organization for Economic Co-operation and Development (OECD) (16)) to ibuprofen and, as a positive control, to the CYP17A1 antagonist abiraterone. The latter compound is clinically used as an androgen biosynthesis inhibitor (17). Before testing ibuprofen’s action on steroidogenesis, we verified that none of the doses used had a toxic effect on the NCI-H295R cell line (Fig. S2A and B). This in vitro work confirmed the global inhibitory effect of abiraterone on CYP17A1 (Fig. 3A and B). In contrast, ibuprofen significantly decreased androstenedione and other sex steroid levels downstream from the CYP17A1 lyase activity, including testosterone (Fig. 3A and Table S1), complementing the results in the ex vivo testis model. These data therefore reveal that ibuprofen, unlike abiraterone, is not a general CYP17A1 antagonist. It is noteworthy that the NCI-295R cell line was less sensitive to ibuprofen than were the ex vivo cells in the organ model, likely due to its different origin (6, 18).

Measuring the mRNA expression of genes involved in steroidogenesis in vitro showed that ibuprofen had a profound inhibitory effect on the expression of these genes (Fig. 3B–D), consistent with that seen above in our ex vivo organ model. Taken together, these data examining effects on the endocrine cells confirm that ibuprofen-induced changes in the transcriptional machinery were the likely reason for the inhibition of steroidogenesis.

Ibuprofen Inhibits Leydig Cell Insulin-like Factor 3 in the Adult Human Testis ex Vivo. In addition to steroids, Leydig cells also produce insulin-like factor 3 (INSL3) (19). Its production increased at 24 h at the $10^{-6}$ M dose and subsequently decreased at the $10^{-7}$ M dose (Fig. 2D). These variations were transient, with no significant effect of ibuprofen observed after 48 h. INSL3 expression decreased by 50% at a dose of $10^{-4}$ M, but expression of the LH receptor, luteinizing hormone/choriogonadotropin receptor (LHCGR), which is also Leydig cell specific, was not repressed (Fig. 2E). Nonetheless, overall the changes in gene expression indicate that the transcriptional machinery behind the endocrine action of Leydig cells was most likely impaired by ibuprofen exposure.
Ibuprofen Impairs Sertoli Cell Function in the Adult Human Testis ex Vivo. Data from the trial showed that ibuprofen affected Sertoli cells, inhibiting AMH and decreasing the inhibin B/FSH ratio. Ex vivo, increasing doses of ibuprofen resulted in an inverse correlation with inhibin B after 24 h ($\beta = -0.467; P = 0.01$), although none of the individual ibuprofen concentrations significantly inhibited this hormone (Fig. 4A). After 48 h of exposure, however, ibuprofen doses of $10^{-7}$–$10^{-4}$ M significantly decreased inhibin B production, resulting in a further significant negative association between ibuprofen concentrations and inhibin B ($\beta = -0.739, P < 0.0001$). AMH production was also negatively correlated with increasing ibuprofen concentration ($\beta = -0.451; P = 0.01$) (Fig. 4B). Accordingly, a dose of $10^{-4}$ M repressed gene expression of AMH and INHBB by $\sim 35\%$ (Fig. 4C). Together, these data show that ibuprofen also directly impairs Sertoli cell function ex vivo by inhibiting transcription. Of note, no significant changes were found in the gene expression of the Sertoli cell-specific FSH receptor (FSH-R) or of LAMAS5 (Fig. 4C).

Ibuprofen Selectively Affects Peritubular Cells’ Gene Expression in the Adult Human Testis ex Vivo. Peritubular cells lining the seminiferous wall play an important role in sustaining seminiferous tubule function (20). The peritubular cells are not broadly characterized in terms of specific markers. Nevertheless, we investigated the expression of a few genes that are assigned to these cells. We found that ibuprofen selectively repressed ACTA2 and MYH-11 by $50\%$, but two other peritubular cell markers, THY1 and KCNIP4, did not change significantly (Fig. 5A).

Ibuprofen Spares the Spermatogenic Cells in the Adult Human Testis ex Vivo. Turning our attention to germ cells in the explants, we found no significant changes in the expression of genes involved specifically with spermatogenesis (Fig. 5B). The absence of a change in the germ cell complement by ibuprofen was confirmed by staining for caspase 3 after 48 h of exposure: Apoptosis did not increase significantly in the testis after exposure (Fig. 5C and D), and the histopathology of the testis at the highest doses did not differ from that of controls (Fig. 5D).

Ibuprofen Suppresses Prostaglandin Production in the Adult Human Testis ex Vivo and in Vitro. As ibuprofen acts specifically on COX sites of prostaglandin H2 synthase (prostaglandin endoperoxide synthase or prostaglandin G/H synthase and cyclooxygenase, PTGS), and because prostaglandin receptors and synthesizing
enzymes are widely distributed within the testis (21), we investigated prostaglandin D2 (PGD2) and E2 (PGE2) in our culture system. Ibuprofen produced a significant dose-dependent reduction of PGD2 ($\beta = -0.781; P < 0.0001$ at 24 h and $\beta = -0.797; P < 0.0001$ at 48 h) (Fig. 6A) and of PGE2 ($\beta = -0.707; P < 0.0001$ and $\beta = -0.627; P < 0.0001$, respectively) (Fig. 6B). PTGS1 and PTGS2 gene expression decreased similarly: PTGS1 mRNA levels fell significantly by 24 and 48 h (Fig. 6C), and PTGS2 mRNA was significantly repressed after 48 h of exposure. These ex vivo data show that ibuprofen suppressed both PTGS enzyme activity and PTGS gene expression in the adult testis.

To complement our ex vivo model system, we next screened the human NCI-H295R cell line for prostaglandin production. This screen showed that the NCI-H295R cells produced detectable levels of prostaglandins, which were decreased dose dependently with ibuprofen (Fig. 7A). As also shown in the experiments presented above, ibuprofen decreased the expression of PTGS1 and PTGS2 in the NCI-H295R cell line (Fig. 7B).

**Discussion**

The pituitary–gonadal axis plays key roles in growth, sex development, metabolism, musculoskeletal build-up, strength, mood, energy, immune system, libido, and reproduction (22–24). Fluctuations in or impaired fine-tuning of the axis can result in a wide range of endocrine disorders that may be local but severe, e.g., infertility (25), or affect the entire body, as seen with adverse outcomes involving this axis such as sexual symptoms (4), depression (26), coronary heart disease/heart attack (27), autoimmune diseases such as arthritis (28), and diabetes (29, 30). Testosterone forms a negative feedback loop that inhibits the production of both LH and gonadotropin-releasing hormone (GnRH) in the hypothalamus (31). While testosterone plays multiple roles outside the testes, the

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**Fig. 2.** Ibuprofen inhibits Leydig cell hormone production in human testicular explants. (A) Dose effect of ibuprofen for 24 and 48 h on testosterone production by the adult human testis. Values are means ± SEM of five independent experiments from different donors. Dose responses were analyzed for significance with the Mann–Whitney U test. The slopes and $P$ values of these results were calculated with Spearman correlation. (B) Effect of $10^{-5}$ and $10^{-4}$ M ibuprofen on the Δ4 and Δ5 steroidogenic pathways. Steroid precursors were measured by GC-MS/MS. Values are means ± SEM of three independent experiments from different donors. Dose effects were analyzed for significance with the Mann–Whitney U test. DHEA, dehydroepiandrosterone. (C) Effect of $10^{-5}$ and $10^{-4}$ M ibuprofen on the gene expression of steroidogenic enzymes after 48-h exposure. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (D) Dose effect of ibuprofen for 24 and 48 h on INSL3 production by the adult human testis. Values are means ± SEM of three independent experiments from different donors. Dose responses were analyzed for significance with the Mann–Whitney U test. (E) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (F) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (G) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (H) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (I) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (J) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (K) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (L) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (M) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (N) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (O) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (P) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (Q) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (R) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test. (S) Specific Leydig cell hormone gene expression. Values are means ± SEM of five independent experiments from different donors. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes $BZW1$ and $GUSB$. Dose responses were analyzed for significance with the Mann–Whitney U test.
extratesticular actions of inhibin B are more subtle, working primarily to decrease FSH (32). Nonetheless, inhibin B is a key clinical marker of reproductive health (32). The function of AMH, also secreted by Sertoli cells, and its regulation through FSH remain unclear in men (33). It has, however, been shown that the AMH concentrations are lower in seminal plasma from patients with azoospermia than from men with normal sperm levels (32).

Our trial showed that ibuprofen use in men led to (i) elevation of LH; (ii) a decreased testosterone/LH ratio and, to a lesser degree, a decreased inhibin B/FSH ratio; and (iii) a reduction in the levels of the Sertoli cell hormone AMH. The decrease in the free testosterone/LH ratio resulted primarily from the increased LH levels, revealing that testicular responsiveness to gonadotropins likely declined during the ibuprofen exposure. Our data from the ex vivo experiments support this notion, indicating that the observed elevation in LH resulted from ibuprofen’s direct antiandrogenic action. Accordingly, in the trial the average inhibin B levels did not differ significantly in the ibuprofen-treated men and the control group. This is consistent with a previous report that men who volunteered to take another nonsteroidal antiinflammatory drug (NSAID), acetylsalicylic acid, coadministered with human chorionic gonadotropin (hCG), which mimics LH, had lower levels of steroidal hormones than controls exposed to hCG but not to the analgesic (34).

AMH levels were consistently suppressed by ibuprofen both in vivo and ex vivo, indicating that this hormone is uncoupled from gonadotropins in adult men. The ibuprofen suppression of AMH further demonstrated that the analgesic targeted not only the Leydig cells but also the Sertoli cells, a feature encountered not only in the human adult testis but also in the fetal testis (35). It is noteworthy that ibuprofen repressed the expression of both AMH and INHBB as well as genes encoding essential proteins and enzymes involved in both cholesterol transport and steroidogenesis. Thus, ibuprofen displayed broad transcription-repression abilities involving steroidogenesis, peptide hormones,
and prostaglandin synthesis. However, these repressive abilities were selective, as a number of gene-expression patterns were spared by ibuprofen, namely prostaglandin inhibition in Leydig cells (CYP19A1 and LHCRY), Sertoli cells (LAMA5 and FSHR), peritubular cells (KCNIP4 and THY1), and all those investigated in germ cells. Of note, the absence of an effect of ibuprofen on the expression levels of gonadotropin receptor genes (LHCGR and FSHR) indicates that the responsiveness of Leydig cells and Sertoli cells to the action of LH and FSH is likely not affected by ibuprofen. However, more investigation is required at this level.

Several compounds have been found to have unintentional antiandrogenic effects, and these are normally investigated in connection with fetal male development using rodent models (36, 37). Our approach, using ibuprofen as an example, demonstrates how a chemical compound, through its effects on the signaling compounds, can result in changes in the testis at gene level, resulting in perturbations at higher physiological levels in the adult human. The analgesics acetaminophen/paracetamol and ibuprofen have previously been shown to inhibit the post-exercise response in muscles by repressing transcription (38–40). However, the striking dual effect of ibuprofen observed here on both Leydig and Sertoli cells makes this NSAID the chemical compound, of all the chemical classes considered, with the broadest endocrine-disturbing properties identified so far in men. Previous ex vivo studies on adult testis have indeed pointed to an antiandrogenicity, only on Leydig cells, of phthalates (41), aspirin, indomethacin (42), and bisphenol A (BPA) and its analogs (43).
However, ibuprofen’s effects were not restricted to Leydig and Sertoli cells, as data showed that the expression of genes in peritubular cells was also affected. Previous studies have shown that long-term fetal exposure to acetaminophen and acetylsalicylic acid in mice and rats targets primordial germ cell proliferation by blocking RNA synthesis and thus leads to reduced follicle reservoir and subsequent decreased fertility in adulthood (44–46). By contrast, in the present study using human testes, germ cells were the only cell category not altered by this analgesic in our ex vivo culture conditions. However, it must be noted that our ex vivo model systems can be used only for short-term exposure. Therefore, determining the effect on men that sustained exposure to ibuprofen would generate in terms of sperm production and fertility would require designing specific and challenging experiment(s). It is noteworthy that exposure to analgesics in men has been associated with increased time to pregnancy (47).

An important question is the exact relationship between the prostaglandin-inhibitory actions of ibuprofen and its effects on testosterone and gene expression. This has been investigated previously in studies on rodent and human testicular development, which showed no correlation between the endocrine-disruptive effects of analgesics and their prostaglandin-inhibitory actions (6, 48, 49). However, in the present study using testes from adult men, the suppression of androgens and prostaglandins occurred in parallel, and, because for several decades prostaglandins have been known to be involved in male reproduction (50), a link between the endocrine-disruptive properties of ibuprofen and the prostaglandin-inhibitory action of NSAIDs in the adult testis cannot be excluded.

In the clinical setting, compromised Leydig cell function resulting in increased insensitivity to LH is defined as compensated hypogonadism (4), an entity associated with all-cause mortality (5). Therefore, investigating ibuprofen-induced compensatory hypogonadism is crucial, as this clinical state is generally associated with smoking and aging (4, 51). Moreover, compensated hypogonadic men present with an increased likelihood of reproductive, cognitive, and physical symptoms (4, 52–54). Further characterizations of the state of compensated hypogonadism induced by ibuprofen, which was already established after 14 d of ibuprofen administration, are therefore important in determining the potential effects on healthy young men. Several reports have stressed the high level of long-term analgesic use among both amateur (55) and professional athletes; ibuprofen has been favored in this use and abuse (56–59). Of note, an inverse relationship was recently reported between
endurance exercise training and male sexual libido, but the possibility that medication uptake might interfere in this observation could not be totally excluded (22). Moreover, ibuprofen appears to be the preferred pharmaceutical analgesic for long-term chronic pain and arthritis (60). Therefore it is also of concern that men with compensated hypogonadism may eventually progress to overt primary hypogonadism, which is characterized by low circulating testosterone and prevalent symptoms including reduced libido, reduced muscle mass and strength, and depressed mood and fatigue (4, 60).

Materials and Methods

In Vivo Intervention Trial. Design and participants. The in vivo study was designed as a double-blinded, placebo-controlled, randomized intervention trial in which ibuprofen or placebo was administered to subjects for 2 wk before and 30 d after a single exercise session. Staff not involved in the project prepared and distributed the medication in boxes weekly. Study personnel and participants were blinded to treatment, and all later analyses were performed blinded to the treatment type, participant, and time point. The study was part of a broader investigation also focusing on muscle biopsies, collected on days 0, 2, 7, and 30 postexercise, a subset of which is described elsewhere (62).

The study protocol was in compliance with the Helsinki Declaration, was approved by the Regional Scientific Ethical Committees of Copenhagen in Denmark (Ref: HD-2008-074), and was registered at ClinicalTrials.gov (no. NCT00832663). The study recruited 31 healthy white men, age 18-35 y. Subjects were included after an interview, a questionnaire assessing physical activity status, and the results of a screening blood sample. Exclusion criteria included body mass index above 30, knee injuries, pepitic ulcers, signs of liver or kidney dysfunction, and participation in regular physical activity (especially strength training) apart from cycling as a means of transport. All individuals provided written informed consent to participate in the study. Subsequently, the subjects were assigned to either a placebo (17 subjects) or ibuprofen (14 subjects) group; the groups were matched for age, height, and weight.

Supplementation. One group of subjects received ibuprofen, 2 × 600 mg/d, (ibumetin; Nycomed Denmark Aps) for a period of 6 wk, from 14 d before to 4 wk after the electrical stimulation exercise. Ibuprofen was detected only in participants to whom ibuprofen was distributed and only after administration began. The second group received placebo pills (which were visually indistinguishable from the ibuprofen pills) over the same period. Subjects received the medication in Medidos No. 1 boxes (KIBodan A/S), which were refilled every week. To verify compliance, ibuprofen levels in the blood were indistinguishable from the ibuprofen pills (no. 62). Subjects were provided written informed consent to participate in the study. Subsequently, the subjects were assigned to either a placebo (17 subjects) or ibuprofen (14 subjects) group; the groups were matched for age, height, and weight.

Blood samples and hormonal analysis. A 40-mL blood sample was collected from the antecubital vein of the nondominant arm when subjects arrived at the laboratory for screening. Samples were also taken at 3 and 2 wk before exercise (days −21 and −14), on the day of exercise before the exercise (day 0), after exercise (+2 h; day 0.1), and subsequently at 2, 4, 7, and 30 d after exercise. Hence, ibuprofen and placebo administration was ongoing for samples drawn on day 0, 2 to 3, and 7, and 30 d in the present study. In the present study, we focused on samples drawn on day 0 after 14 d of supplementation. Plasma samples were stored at −80 °C until being assayed. The samples were analyzed for LH, FSH, testosterone, 17α-estradiol, AMH, inhibin B, and SHBG, as previously described in Aksglaede et al. (63), and inhibin B as previously described in Farrar et al. (64). Of note, the LH measurements of one subject in the placebo group were aberrant and were discarded, thus decreasing the n value from 17 to 16.

Ex Vivo Organ Model: Testis Explant Assay. To determine the direct effect of ibuprofen on adult human testis physiology, we used a validated organ model assay (Testis Explant Assay) (65). Testes were obtained from prostate cancer patients who had not undergone any antihormonal treatment or from multiorgan donors (average age 46.9 ± 4.4 y). The protocol was approved by the local ethics committee (Agence de la Biomédine; authorization no. PF59-015), and informed consent was obtained from all donors or their next of kin.

After collection of each testis, the organ was placed at 4 °C and rapidly processed for experimentation. Observation by transillumination allowed us to discard the rare testes not displaying spermatogenesis. Four 3-mm² testis explants were placed onto a polyethylene terephthalate insert (Falcon Labware) at the interface of air in 1 mL of DMEM (Sigma-Aldrich) in a well of a 12-well plate. The medium for exposure experiments contained 0.1% DMSO as a control and ibuprofen at different concentrations (purity >99%) (Sigma-Aldrich) in 0.1% DMSO. Four wells were analyzed for each condition. Exposures lasted 24 or 48 h, with a total medium change at 24 h, in a humidified atmosphere containing 5% CO₂ at 34 °C. The culture medium was then collected and stored at −80 °C. On the day of collection, three testis explants for each culture condition were randomly selected and fixed in 4% neutral buffered formaldehyde, or Bouin’s fixative for 2 h at 4 °C. Embedded in paraffin, sliced into 5.0-μm-thick sections, and stored at 4 °C until immunostaining.

Hormone levels were assayed in duplicate in the culture medium. Testosterone levels were assayed with a specific RIA (Beckman Coulter). The intra- and interassay coefficients of variation were ≤8.6 and 11.9%, respectively. Control testis explants produced an average of 10.26 ± 2.50 ng testosterone per milliliter of explant after 24 h of culture and 8.47 ± 2.16 ng testosterone per milliliter of explant after 48 h of culture. INSL3 production was assayed with a commercial ELISA kit (Phoenix France). Each sample was diluted twofold in RIA buffer before RIA. The intra- and interassay coefficients of variation were ≤15 and 7%, respectively, and the lower limit of detection was 20.17 pg/mL. Control testis explants produced an average of 0.29 ± 0.20 ng INSL3 per milliliter of explant after 24 h of culture and 0.11 ng INSL3 per milliliter of explant after 48 h of culture. Inhibin B was assayed with a commercial ELISA kit (Beckman Coulter) according to the manufacturer’s instructions. Each sample was diluted twofold in sample diluent solution before reactions. The intra- and interassay coefficients of variation for serum samples were ≤5.6 and 7.6%, respectively. Control testis explants produced an average of 570.43 ± 78.50 ng inhibin B per milliliter of explant after 24 h of culture and 528.44 ± 79.17 ng inhibin B per milliliter of explant after 48 h of culture. PGD2 and prostaglandin E2 (PGE2) were assayed by an ELISA method (Cayman Chemical Company), as was AMH (Immunootech).

RNA was extracted from testes with the NucleoSpin RNA ll kit (Macherey-Nagel) according to the manufacturer’s instructions and then was precipitated. Each total RNA sample (250 ng) was reverse transcribed with the Iscript cDNA Synthesis Kit (Bio-Rad). Quantitative PCR was performed using the manufacturer’s instructions with the TaqMan Gene Expression Master Mix Supermix (Bio-Rad) and a 2.5-μL cDNA template in a CFX384 Touch Real-Time PCR Detection System (Bio-Rad). The amplification program was as follows: an initial denaturation of 3 min at 95 °C; 40 cycles of 10-s denaturation at 95 °C, 30 s at 62 °C for annealing and extension. Dissociation curves were performed with the thermal melting profile performed after the last PCR cycle. To avoid amplification of contaminating genomic DNA, primer pairs were selected on two different exons. B2m and Gusb mRNA were used as internal controls for normalization. Results were calculated by the ΔΔCT method as n-fold differences in target gene expression with respect to the reference gene and the calibration sample.

To analyze steroidogenesis in the explants, we performed solid-phase extraction (SP) with C18 cartridges, reagents, and solvents from Solvent Documentation Synthesis. Standard reference steroids were from Sigma. Reference steroids were from Steraloids. Toxicity characterization procedures and measurements in GC-MS/MS in electronization mode were performed as previously described (66, 67).

Cells were labeled with the primary rabbit antibody directed against cleaved caspase-3 (1/100; Cell Signaling) (41, 42) to enable detection of cells undergoing apoptosis in the explants. Slides were then scanned with a NanoZoomer slide scanner (Hamamatsu Photonics). Caspase-3 cells were counted by ImageJ software, and the results were expressed as percentages of the control values.

In Vitro: NCI-H295R Cell Line. The NCI-H295R human adrenocortical carcinoma cell line was obtained from ATCC (CRL-2128), and experiments aiming at completing the in vivo experiments using human adult testis explants were conducted in accordance with OECD guidelines their next of kin after exposure to ibuprofen, abiraterone, and PGD2 (Sigma-Aldrich). Toxicity was evaluated with the Alamar Blue assay (Sigma-Aldrich). Deuterated steroid analogs were obtained for analysis from CDN Isotopes and Toronto
Research Chemicals, and derivatization quality-control standards (7b-17αestradiol-17-ace), instrument control standards (estrone-3-methyl ether), and derivatization reagents (dimethylsilylimidazole, N-methyl-N-(trimethylsilyl)-trifluoroacetamide, and 1,4-dithioerythritol) were obtained from Sigma-Aldrich. Steroid extraction and the subsequent quantification of steroid hormones were performed according to Holm et al. (68).

For prostaglandin secretion analysis, the NIC-H295R cells were plated in 12-well plates and were exposed overnight; the global prostaglandin synthesis was evaluated immediately afterward with a Prostaglandin Screening ELISA Kit (Cayman Chemical Company).

For transcriptional analysis with RT-qPCR, RNA was isolated from cells with the All Prep DNA/RNA kit (Qiagen). RNA integrity was measured on a NanoDrop ND-1000 spectrophotometer (Thermo Scientific), and only 260/280 and 260/230 ratios >2.0 were accepted for further processing. Quantitative PCR was performed as previously described.

Statistical Analysis. For the trial, each individual’s samples were normalized by division by the mean of the baseline samples drawn before the intervention. Hence, samples from each volunteer were normalized with the individual’s own baseline values before the administration. Unpaired Student t tests were used to compare the placebo and ibuprofen groups after 14 and 44 df of administration. For the ex vivo experiments, data were compared using the Mann-Whitney U test and slopes with P values and Spearman correlation when indicated. For in vitro cell experiments, analysis was performed with one-way ANOVA followed by a post hoc Dunnett’s multiple comparison test. All data are expressed as mean ± SEM, and differences were considered statistically significant when P ≤ 0.05.

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