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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 the clinical condition named “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.

Ibuprofen | endocrine disruption | reproduction | hypogonadism | endocrinology

Much concern has been raised over declining male reproductive health, and the disruption of male endocrinology has been suggested to play a central role (1, 2). Male reproduction and general health rely on androgens, as well as on other hormones, which are mainly produced by testicular Leydig and Sertoli cells. In addition to the testis, the androgens act in many somatic organs, e.g., producing anabolic effects on muscle mass and influencing cognitive functions (3). Luteinizing hormone (LH) produced by the pituitary is the primary stimulator of testosterone production, and the testosterone/LH ratio is routinely used as a clinical marker of Leydig cell function. When Leydig cell function is compromised, normal or nearly normal testosterone levels can often be sustained by augmented LH levels, as observed in the clinical entity termed “compensated hypogonadism” (4). The essential importance of the pituitary–gonadal axis is emphasized by the recent association of hypogonadism with a wide range of risk factors and all-cause mortality in men (4, 5).

The so-called “over-the-counter” mild analgesics (hereafter simply called “analgesics”), such as acetaminophen/paracetamol, acetylsalicylic acid/Aspirin, and ibuprofen, are among the most commonly used pharmaceutical compounds worldwide (6, 7). Increasing evidence from recent years shows that exposure to analgesics can generate negative endocrine and reproductive effects during fetal life (6). Nonetheless, no in-depth studies have analyzed the effect of mild analgesics on the human pituitary–gonadal axis. In this context, ibuprofen is especially interesting because of its increasing use in the general population and in particular by elite athletes (8–12).

Therefore in this study we focused on how ibuprofen, used in the general population for aches, pains, fever, and arthritis and heavily used by athletes (13), affects the pituitary–testis axis. Because of the intrinsic great challenge in identifying endocrine-disrupting effects of chemicals in the adult human, we performed a unique combination of three interconnected approaches: (i) a randomized, controlled clinical trial; (ii) an ex vivo organ model using adult human testis explants; and (iii) a standardized in vitro

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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model system based on a steroidogenic cell line of human origin to complement the ex vivo approach. The complementary results revealed that ibuprofen induces a state of compensated hypogonadism by modifying hormonal profiles through selective repression of gene expression.

**Results**

Ibuprofen Affects the Hormonal Balance in Adult Men. We conducted a randomized, controlled clinical trial of ibuprofen administration to identify its possible effects on pituitary–gonadal feedback in young men. During administration, ibuprofen levels in plasma ranged on average from 25 to 35 μg/mL (1.2–1.7 × 10⁻⁴ M); the highest level measured was 100 μg/mL (4.85 × 10⁻⁴ M). The mean of this ibuprofen concentration was in the range measured after administration of 600 mg of ibuprofen to healthy volunteers (14). Samples drawn before administration showed that there were no initial differences between the placebo and ibuprofen groups for hormones or sex hormone-binding globulin (SHBG), a liver protein that specifically binds a substantial part of circulating testosterone (Fig. S1).

We investigated the levels of total testosterone and its direct downstream metabolic product, 17β-estradiol. Administration of ibuprofen did not result in any significant changes in the levels of these two steroid hormones after 14 d or at the last day of administration at 44 d (Fig. 1 A and C). The levels of free testosterone were subsequently analyzed by using the SHBG levels. Neither free testosterone nor SHBG levels were affected by ibuprofen during the administration (Fig. 1 A and C).

The pituitary gonadotropin hormones LH and FSH regulate the production of testosterone and peptide hormones by acting on Leydig and Sertoli cells, respectively. The levels of LH in the ibuprofen group had increased by 23% after 14 d of administration (P = 0.05) (Fig. 1A). This increase was even more pronounced at 44 d, at 33% (P = 0.01) (Fig. 1C). While a slight, nonsignificant increase in the average FSH concentration was observed at 14 d (+5%) (Fig. 1B), no difference in the average value of this hormone was seen at 44 d (Fig. 1D). These data suggested a link between pituitary LH levels and ibuprofen exposure. This assumption was confirmed when we investigated ibuprofen and LH levels in plasma and found they were significantly and positively correlated at 14 d (r = 0.73; P = 0.003) (Fig. 1E).

We next calculated the free testosterone/LH ratio in the men. We found an 18% decrease (P = 0.056) in the ibuprofen group compared with the placebo group at 14 d (Fig. 1A) and a 23% decrease (P = 0.02) after 44 d (Fig. 1C). Taken together, these in vivo data suggest that ibuprofen induced a state of compensated hypogonadism during the trial, which occurred as early as 14 d and was maintained until the end of the trial at 44 d.

Inhibin B and anti-Müllerian hormone (AMH) are peptide hormones secreted to the blood from the Sertoli cells. The administration of ibuprofen did not change mean inhibin B levels (Fig. 1 B and D). To examine the stimulatory action of FSH on the Sertoli cells, we next examined the inhibin B/FSH ratio and found that it decreased by 4% after 14 d (Fig. 1B) and by 12% at the end administration at 44 d (Fig. 1D). Importantly, further investigation of Sertoli cell activity showed that AMH levels decreased significantly with ibuprofen administration, by 9% (P = 0.02) after 14 d (Fig. 1B) and by 7% (P = 0.05) after 44 d compared with the placebo group (Fig. 1D). The AMH data show that the hypogonadism affected not only Leydig cells but also Sertoli cells and also occurred as early as 14 d of administration.

Ibuprofen Inhibits Steroidogenesis ex Vivo and in Vitro. To determine the direct effect of ibuprofen on the testes, we next exposed adult testis explants from donors to doses of 10⁻⁶–10⁻⁴ M, which corresponded to the oral doses producing mean plasma levels of 1.2–1.7 × 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 (β = −0.405, P = 0.01 at 24 h and β = −0.664, P < 0.0001 at 48 h) (Fig. 2A) and was augmented over time (10⁻³ 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 Δ4 and Δ5 steroid pathways (Fig. 2B) showed that it generally inhibited all steroids from pregnenolone down to testosterone and 17β-estradiol; the production of each steroid measured decreased at doses of 10⁻⁵–10⁻⁶ M. Under control conditions, production of androstenediol 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/BZIP fell significantly after exposure to 10⁻³ M; StAR expression was suppressed at both doses of 10⁻⁵ and 10⁻⁴ M (Fig. 2C); CYP11A1, CYP17A1, and HSD17B3 were suppressed by 40–50% at doses of 10⁻⁴–10⁻³ M; and HSD3B2 was reduced by about 90% (Fig. 2C). The data from the ex vivo testis model showed a reduction in the expression of both the Δ4 and Δ5 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 Cooperation 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. S2 A and B). This in vitro work confirmed the global antagonistic effect of abiraterone on CYP17A1 (Fig. 3A). In contrast, ibuprofen significantly decreased androstenedione and other sex steroid levels downstream from the CYP17A1 lyase activity, including testosterone (Fig. 3B 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. 3 C–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 10⁻⁴ M dose and subsequently decreased at the 10⁻³ 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 10⁻³ 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 LAMA5 (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

![Fig. 2](image-url)

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 $\Delta 4$ and $\Delta 5$ 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.

* $P \leq 0.05$, ** $P \leq 0.01$. E718 | www.pnas.org/cgi/doi/10.1073/pnas.1715035115

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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. Values are means ± SEM of three independent experiments analyzed with one-way ANOVA followed by a post hoc Dunnett’s test. CYP11A1, cytochrome P450 family 11 subfamily A member 1; CYP17A1, cytochrome P450 family 17 subfamily A member 1; CYP19A1, cytochrome P450 family 19 subfamily A member 1; HSD17B3, hydroxysteroid 17-β dehydrogenase 3; HSD3B2, hydroxy-β-5-steroid dehydrogenase 3 β- and steroid δ-isomerase 2; StAR, steroidogenic acute regulatory protein; TSPO, translocation protein. *P ≤ 0.05, **P ≤ 0.01, ***P ≤ 0.001.

Fig. 3. The steroid screen identifies ibuprofen as an inhibitor of steroidogenesis in the human NCI-H295R cell line. (A) Effects of ibuprofen (red trace; n = 9–18) and abiraterone (blue trace; n = 6–15) exposure on the relative steroidogenic hormone production in the dose ranges of 10−6–10−3 M and 3.15 × 10−11–3.15 × 10−8 M (x axis), respectively, in the human NCI-H295R cell line, according to OECD standards. The position of each graph corresponds to the position of that particular steroid hormone in steroidogenesis. Steroid concentrations (y axis; % of control) are depicted as mean ± SEM with key enzymes shown in blue boxes. For statistics see Table S1. (B–D) Quantitative RT-PCR screen of steroidogenic gene expression in NCI-H295R cells after 48 h of culture with 10−7–10−3 M ibuprofen. Values are means ± SEM of three independent experiments analyzed with one-way ANOVA followed by a post hoc Dunnett’s test. CYP11A1, cytochrome P450 family 11 subfamily A member 1; CYP17A1, cytochrome P450 family 17 subfamily A member 1; CYP19A1, cytochrome P450 family 19 subfamily A member 1; HSD17B3, hydroxysteroid 17-β dehydrogenase 3; HSD3B2, hydroxy-β-5-steroid dehydrogenase 3 β- and steroid δ-isomerase 2; StAR, steroidogenic acute regulatory protein; TSPO, translocation protein. *P ≤ 0.05, **P ≤ 0.01, ***P ≤ 0.001.
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 LHCGR), 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).

![Fig. 4](ibuprofen affects Sertoli cell activity in human testicular explants. (A and B) Dose effect of ibuprofen on the production of inhibin B after 24 and 48 h (A) and anti-Müllerian hormone (AMH) after 48 h (B) by the adult human testis. Values are means ± SEM of three independent experiments from different donors. Slopes and P values of Spearman correlation are indicated. (C) Quantitative RT-PCR performed after 48 h of culture treated with 10⁻⁵ and 10⁻⁴ M ibuprofen for specific Sertoli cell 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. AMH, anti-Müllerian hormone; BZW1, basic leucine zipper and W2 domains 1; FSHR, follicle-stimulating hormone receptor; GUSB, β-glucuronidase; INHBB, inhibin B subunit B; LAMA5, laminin subunit α5. *P ≤ 0.05, **P ≤ 0.01.

![Fig. 5](ibuprofen decreases gene expression in peritubular cells but does not affect germ cells or morphology in human testicular explants. (A and B) Quantitative RT-PCR performed after 48 h of culture treated with 10⁻⁵ and 10⁻⁴ M ibuprofen for gene expression in peritubular cells (A) and germ cells (B). Each bar represents the mean ± SEM of five independent experiments from different donors. A Mann–Whitney U test was performed. (C) Number of apoptotic germ cells. Values are means ± SEM of five independent experiments from different donors. A Mann–Whitney U test was performed. (D) Immunostaining of apoptotic germ cells in testis explants cultured for 48 h in the presence of DMSO (control) or 10⁻⁵ or 10⁻⁴ M ibuprofen. Each micrograph shows representative areas of ibuprofen-induced morphology compared with corresponding area. (Scale bars: 50 μm.) ACTA2, actin α2 smooth muscle aorta; ALPP, alkaline phosphatase, placental; BZW1, basic leucine zipper and W2 domains 1; GUSB, β-glucuronidase; KCNIP4, potassium voltage-gated channel interacting protein 4; MYH11, myosin heavy polypeptide 11, smooth muscle; PGK2, phosphoglycerate kinase 2; PRM2, protamine 2; THY1, Thy-1 cell-surface antigen. **P ≤ 0.01.
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

Fig. 6. Ibuprofen decreases PGE2 and PGD2 production and PTGS gene expression in human testicular explants. (A and B) Dose effect of ibuprofen exposure after 24 and 48 h on PGD2 (A) and PGE2 (B) production by adult human testicular explants. Values are means ± SEM of five independent experiments from different donors. Dose responses were analyzed for significance with the Mann–Whitney U test. Slopes and P values of Spearman correlation are indicated. (C) Quantitative RT-PCR was performed after 48 h of culture treated with 10⁻³ and 10⁻⁴ M ibuprofen. Each bar represents the mean ± SEM of the fold change in target gene expression relative to the reference genes BZW1 and GUSB. Values are means ± SEM of five independent experiments from different donors. Differences in gene expression were analyzed with a Mann–Whitney U test. BZW1, basic leucine zipper and W2 domains 1; GUSB, β-glucuronidase; PTGS, prostaglandin-endoperoxide synthase. *P ≤ 0.05, **P ≤ 0.01.

Fig. 7. Ibuprofen dose-dependently reduces prostaglandin levels and mRNA expression in human endocrine NCI-H295R cells. (A) Effects of ibuprofen on general prostaglandin production from NCI-H295R cells after 24 h. Values are means ± SEM of three independent experiments analyzed with one-way ANOVA followed by a post hoc Dunnett’s test. (B) Quantitative RT-PCR screen of steroidogenic and PTGS gene expression in NCI-H295R cells after 48 h of culture with 10⁻⁷–10⁻³ M ibuprofen. Values are means ± SEM of three independent experiments analyzed with one-way ANOVA followed by a post hoc Dunnett’s test. PTGS, prostaglandin-endoperoxide synthase. *P ≤ 0.05, **P ≤ 0.01.
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).
Research Chemicals, and derivatization quality-control standards (7b-17β-estradiol-17-acetate), instrument control standards (estrone-3-methyl ether), and derivatization reagents (N,N-dimethyl-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’s t tests were used to compare the placebo and ibuprofen groups after 14 and 44 d 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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