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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 analogics 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 tests, 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 analogics (hereafter simply called “analgesics”), such as acetaminophen/paracetamol, acetysalicylic acid/aspirin, and ibuprofen, are among the most commonly used pharmaceutical compounds worldwide (6, 7). Increasing evidence from recent years shows that exposure to analogics can generate negative endocrine and reproductive effects during fetal life (6). Nonetheless, no in-depth studies have analyzed the effect of mild analogics 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 disruption 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 analogics 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 used 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.


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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 $10^{-9}$ 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 (LHCR), 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 ($\beta = -0.451; P = 0.01$) (Fig. 4B). Accordingly, a dose of $10^{-4}$ M repressed gene expression of AMH and INHBB by $\sim35\%$ (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
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 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. *$P \leq 0.05$, **$P \leq 0.01$.

**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 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. A Mann–Whitney U test was performed. (C) Number of apoptotic germ cells. Values are means ± SEM of caspase+ cells in three independent experiments from different donors. (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. **$P \leq 0.01$. 

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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 hypogonadal 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 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^{-5} 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.

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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 analog 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 male, 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, kidney inpeptic 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 2 wk after an 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 (KBodan A/S), which were refilled every week. To verify compliance, ibuprofen levels in the blood were determined by HPLC at every blood-sampling time point (see below). Additionally, to monitor liver and kidney function, blood samples were analyzed for creatine, C-reactive protein, alkaline phosphates, and total cholesterol during the study. No subjects reported any adverse signs of taking the medication, nor did any blood parameters indicate or suggest adverse effects.

**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 h, 2, 4, 7, and 30 d. 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, 17β-estradiol, AMH, inhibin B, and SHBG, as previously described in Aksglaede et al. (63), and ibuprofen 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 explant culture system (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 Biomedine; authorization no. PP09-015), 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-mm³ 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 neutral buffered 4% 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 tests 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 tests explants produced an average of 0.29 ± 0.06 ng INSL3 per milliliter of explant after 24 h of culture and 0.41 ± 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 tests explants produced an average of 570.43 ± 78.50 ng inhibin B per milliliter of explant after 24 h of culture and 529.44 ± 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 (Immunotech).

RNA was extracted from testes with the NucleoSpin RNA II kit (Machery-Nagel) according to the manufacturer's instructions and then was precipitated. Each total RNA sample (250 ng) was reverse transcribed with the Script cDNA Synthesis Kit (Bio-Rad). Quantitative PCR was performed on 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, 15-s annealing, and 20-s 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 (SPE) with C18 cartridges, reagents, and solvents from Solvent Documentation Synthesis. Standard reference steroids were from Sigma. For the external standards, we used Steraloids. The steroids were either synthesized in the laboratory for screening or prepared by isotopic dilution. Samples were spiked with 400 pg of internal standards (etiocholanolone-d₅, 17a-testosterone-d₃, dihydrotestosterone-d₃, 19-androstenedione-d₃, progesterone-d₉, 17a-methyltestosterone-d₃, and 17β-estradiol-d₃). Samples were applied to a C18 SPE column (2 g stationary phase) previously conditioned with 10 mL methanol and 10 mL water. The column was washed with water (5 mL) and then with cyclohexane (5 mL), and the steroids were eluted with methanol (10 mL). The extracts were dried (N2, 45°C), and 400 pg of external standard (norgestrel) was added. Derivation 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 rxi vivo experiments using human adult testis explants were conducted in accordance with OECD guidelines and the declaration of Helsinki. Testes were collected after exposure to ibuprofen, abiraterone, and PGD2 (Sigma-Aldrich). Toxicity was evaluated with the Alamar Blue assay (Sigma-Aldrich). Deuterated steroids analogs were obtained for analysis from CDN Isotopes and Toronto
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