Effect of 17β-estradiol on tumor necrosis factor-α-induced cytotoxicity in the human peripheral T lymphocytes

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Abstract

We determined the effect of 17β-estradiol on tumor necrosis factor α (TNF-α)-induced cytotoxicity in human peripheral T lymphocytes (T cells) using lactate dehydrogenase assay. Treatment with 17β-estradiol (1–100 nM) for 24 h showed dose-dependent reduction of TNF-α-induced cytotoxicity in T cells. To further evaluate the mechanism of 17β-estradiol on TNF-α-induced cytotoxicity in T cells, we identified estrogen receptor (ER) protein in T cells using immunocytochemistry and used the pure ER antagonist ICI 172,780. ERα immunoreactivity was clearly observed in T cells. ERβ immunoreactivity was also detected in some T cells. ICI 172,780 (10⁻⁷ M) alone did not affect cytotoxicity in T cells, however, ICI 172,780 (10⁻⁷ M) completely abolished 17β-estradiol cytoprotective effects in T cells. TNF-α tended to increase nuclear factor κB (NF-κB) protein levels in nuclear extracts but it did not reach statistical significance by Western blotting. In contrast, NF-κB protein levels in nuclear extracts followed by TNF-α with 17β-estradiol treatment were significantly increased compared with NF-κB protein levels in untreated group. NF-κB blocker pyrrolidinedithiocarbamate (PDTC) (10⁻⁴ M) alone did not affect cytotoxicity in T cells. In contrast, PDTC (10⁻⁴ M) completely abolished 17β-estradiol cytoprotective effects in T cells. Caspase -3/-7 activity was significantly increased followed by TNF-α, and 17β-estradiol treatment significantly reduced the increment. The present studies suggest the protective effect of 17β-estradiol on TNF-α-induced cytotoxicity through ERs in T cells and that NF-κB activation and caspase suppression may be involved in the mechanism.

Journal of Endocrinology (2005) 184, 191–197

Introduction

It has become apparent over the past few decades that estrogens can affect cells of the immune system and may play a role in modulating lymphocyte development and function (Smithson et al. 1998, Grimaldi et al. 2002). It appears that premenopausal women are protected against atherogenesis compared with men, and it is this gender difference that initially led investigators to propose that estrogens may well be protective against cardiovascular disease (Bush 1990). Although favorable effects on lipid profiles have been thought to account for a significant portion of estrogen’s protective action, recent studies suggest that estrogens may have important actions at other steps in the atherogenic process (Nathan & Chaudhuri 1997). In vitro studies showed that the addition of estradiol to cultures of human lymphocytes causes a decrease in CD4⁺/CD8⁺ T-cell-subset ratios (Athreya et al. 1993), and enhances immunoglobulin secretion (Kanda & Tamaki 1999). However, the precise mechanism by which estrogens may be exerting this protective action remains unclear.

Survival and death in lymphoid cells are tightly regulated processes, and alteration of the delicate balance between the two can lead to a variety of autoimmune and inflammatory diseases (He & Ting 2002). Members of the tumor necrosis factor (TNF) superfamily are critical regulators of the balance between the two opposing processes, and binding to their cognate receptors can trigger signaling pathways leading to either survival or death (Locksley et al. 2001). Indeed, in the case of TNF receptor 1 (TNFR1), ligation of a single class of receptor can trigger either cell survival or apoptosis, depending on which signaling pathway predominates in the cell type examined. Upon binding of TNF-α to TNFR1, the death domain present in the cytoplasmic tail of the receptor is able to recruit and associate with two death-domain-containing signaling molecules known as TNFR1-associated death domain (TRADD) and receptor-interacting protein (RIP; Hsu et al. 1995, 1996a, 1996b). Both TRADD and RIP are required for signaling to nuclear factor κB (NF-κB), as well as the apoptosis pathway (Hsu H. et al. 1995, 1996b, Ting et al. 1996, Pimentel-Muinos & Seed 1999). It is at this juncture that the NF-κB and apoptotic signals are...
thought to bifurcate: TNF receptor-associated factor (TRAF) 2 recruitment leads to the activation of downstream kinases and NF-κB activation, whereas Fas-associated death domain (FADD) recruitment leads to the activation of caspase-8 and apoptosis (Hsu H. et al. 1996a, Liu et al. 1996). A recent report demonstrated that the enhancing role of estrogens on the immune/inflammatory response was exerted by activating the NF-κB complex (Cutolo et al. 2003).

In order to investigate the effect of estrogens on TNF-α-induced cytotoxicity in human peripheral T lymphocytes (T cells), we first determined the effect of 17β-estradiol on TNF-α-induced cytotoxicity in T cells using lactate dehydrogenase (LDH) assay. Next, estrogen receptor (ER) protein in T cells was identified using immunocytochemistry and we investigated the involvement of ER for 17β-estradiol activity on TNF-α-induced cytotoxicity in T cells. Third, NF-κB protein levels after TNF-α with 17β-estradiol treatment were examined and we used a NF-κB blocker, pyrrolidinedithiocarbamate (PDTC) to evaluate whether the NF-κB cascade was involved in the intracellular mechanism of 17β-estradiol on TNF-α-induced cytotoxicity in T cells. Finally, caspase-3/-7 activity was investigated after TNF-α with 17β-estradiol treatment.

Materials and Methods

Cell preparation

Peripheral blood mononuclear cells (PBMCs) were prepared from heparinized venous blood samples from healthy women (28.2 ± 1.1 years; n=6) by density-gradient centrifugation with Ficoll-Paque and washed three times with PBS. For isolation of T cells, PBMCs were cultured in plastic dishes for 1 h at 37°C with 5% CO₂ and non-adherent cells were collected. The purity of CD3-positive cells was about 95% as determined by flow cytometry. The obtained cells were cultured in RPMI 1640 supplemented with 10% heat-inactivated fetal bovine serum and 1% penicillin (100 U/ml)/streptomycin (100 mg/ml).

TNF-α and 17β-estradiol treatment

T cells were plated on 96-well plates (10 x 10³ cells/well; Beckton Dickinson Laboratories, Franklin Lakes, NJ, USA) for cytotoxicity studies. 2 days later, the media in 96-well plates were washed and replaced with fresh RPMI 1640 media without fetal bovine serum. Various doses of water-soluble 17β-estradiol (Sigma Chemical Co.) with TNF-α (10 nM; Dainippon Pharmaceutical Co., Osaka, Japan) were added in the media 24 h prior to the LDH assay. TNF-α concentration (10 nM) was determined as described in a previous paper (Manna et al. 2000). In some experiments, 17β-estradiol/TNF-α were added to the culture 24 h prior to the LDH assay with pure ER antagonist ICI 172,780 (Tocris Cookson, Bristol, UK) or the NF-κB blocker PDTC (Sigma Chemical Co.).

LDH assay

Cytotoxicity was assessed as a function of LDH release in 96-well plates after 24 h 17β-estradiol/TNF-α treatment. Prior to each assay, the cells were lysed with 1% Triton X-100 in culture media for 10 min at 37°C to obtain a representative maximal LDH release for that particular culture as the positive control with 100% toxicity. Cellular supernatant (50 µl) were removed from each well and transferred to another 96-well plate to determine LDH release of the culture. 50 µl reconstituted substrate mix (Promega) was added to each well for 10 min and measured on a microplate reader at 490 nm. Total LDH released by culture (i.e. 100% toxicity) in all plates tested had an absorbance in the range of 1.0–1.5 at 490 nm. The spontaneous release of LDH in untreated cells (without estradiol and TNF-α, i.e. low control) was significantly higher than that of culture media alone. As a consequence, the percentage of cytotoxicity was determined using the following formula (Bursztajn et al. 2000):

\[
\text{Cytotoxicity} = \frac{(\text{experimental value} - \text{low control})}{(\text{positive control} - \text{low control}) \times 100}
\]

Immunocytochemistry

T lymphocytes (5 x 10³ cells/well) were plated on two-well culture slides (Asahi Technoglass Corp., Tokyo, Japan). The cells were fixed with 4% paraformaldehyde in PBS, pH 7.4, for 10 min at room temperature. The cells were permeabilized with 0.1% Triton X-100, 0.01% sodium azide and 1% BSA in PBS and blocked with 10% goat serum in PBS for 15 min. The cells were incubated overnight at 4°C with the following antibodies; anti-CD3 (Calbiochem-Novabiochem Corp., San Diego, CA, USA), anti-CD14 (Zymed Laboratories, San Francisco, CA), anti-ERα (mouse monoclonal IgG1, 1:200; Stress-Gen Biotechnologies, Victoria, Canada), anti-ERβ (rabbit polyclonal IgG, 1:200; Affinity BioReagents, Golden, CO, USA), anti-type I TNF-α receptor (Santa Cruz Biotechnology, Santa Cruz, CA, USA) and anti-NF-κB (p65; Santa Cruz Biotechnology). For detection of primary antibodies, secondary antibodies (Dako A/S, Glostrup, Denmark) were used at a dilution of 1:200. Negative controls for each experimental condition consisted of appropriate dilutions of secondary antibodies alone. The coverslips mounted with Eukitt medium (O. Kindler, Freiburg, Germany) were examined under an Olympus microscope and digitized using the appropriate software (Lumina Vision, Mitani-Corp., Fukui, Japan).

Immunoblotting

The nuclear extracts (Dudek et al. 2001) for NF-κB from control (medium only) or treated cells (TNF-α or 17β-estradiol/TNF-α) were prepared by centrifugation (15 000 g) of the nuclear pellets and were stored at −80°C until the time of use. Nuclear extracts (60 µg protein) from control (medium only) or treated cultures (TNF-α or 17β-estradiol/TNF-α) were analyzed by 10% polyacrylamide gel electrophoresis (SDS-PAGE) followed by transfer onto 0.2-µm nitrocellulose membranes (Schleicher & Schuell). The membranes were incubated with 5% milk in PBS for 20 min at room temperature and then incubated overnight with anti-ER (mouse monoclonal IgG1) or anti-CD3 (mouse monoclonal IgG1). The membranes were then washed and incubated with anti-mouse or anti-rabbit IgG antibody conjugated with horseradish peroxidase (Amersham, Arlington Heights, IL). The membranes were then washed and incubated with an ECL detection kit (Amersham). Western blots were scanned using a scanner with the appropriate software (Quantity One, Bio-Rad). Band density was measured using the appropriate software.
estradiol/TNF-α; 10 µg protein) were mixed in electrophoresis sample buffer and were boiled for 5 min and electrophoresed by SDS/PAGE using 10% linear gel. After electrophoresis, separated proteins were transferred to polyvinylidine difluoride (PVDF) membranes followed by blocking with 5% skimmed milk for 60 min at room temperature. The membrane was incubated with anti-NF-κB at a final concentration of 1:200 in 1 × TBS solution (0·15 M NaCl/20 mM Tris–HCl, pH 7·6) overnight at 4 °C. Subsequently, the membranes were washed for 5 min, incubated with biotinylated F (ab′)2 fragment of rabbit anti-mouse or swine anti-rabbit immunoglobulin as secondary antibodies (Dako A/S) for 30 min at room temperature, and then washed again. The membranes were incubated with streptavidin–horseradish peroxidase conjugate (Gibco BRL, Life Technologies) for 20 min at room temperature and washed in TTBS (TBS+Tween-20) for 5 min and TBS for 10 min. The bands were visualized by an enhanced chemiluminescence (ECL) detection reagents (Amersham) and quantitated using a computer-assisted image analyzer (Kodak 1D Image Analysis Software, Scientific Imaging Systems, New Haven, CT, USA).

Measurement of caspase-3/-7 activity

Caspase-3/-7 activity was measured by Apo-ONE homogenous caspase-3/-7 assay (Promega) according to the manufacturer’s instructions. In brief, 100 µl Apo-ONE caspase-3/-7 reagent was added to each well of a black 96-well plate containing 100 µl blank, control cells (medium only) or treated cells (TNF-α or estradiol/TNF-α) in culture. The contents of wells were gently mixed using a plate shaker at 300 r.p.m. from 30 s. The fluorescence of each well was measured at an excitation wavelength of 485 nm and an emission wavelength of 530 nm.

Data analysis

Data were analyzed by ANOVA followed by Fisher’s protected least-squares difference test.

Results

Effect of 17β-estradiol on TNF-α-induced cytotoxicity in T cells

TNF-α treatment (10 nM) revealed 10–30% cytotoxicity in T cells. 17β-estradiol treatment (1–100 nM) showed dose-dependent decreases of TNF-α-induced cytotoxicity in T cells (Fig. 1). In contrast, 17β-estradiol treatment (1000 nM) did not affect TNF-α-induced cytotoxicity in T cells (Fig. 1).

Identification of ERα and ERβ in T lymphocytes using immunocytochemistry

ERα and ERβ immunoreactivity were clearly observed in T cells by immunocytochemistry. ERα and/or ERβ immunoreactivity were colocalized with some CD3-positive cells (Fig. 2A). ERβ immunoreactivity was colocalized with some ERα-positive cells (Fig. 2B). The percentages of ERα, ERβ, ERα/ERβ and no ERα/no ERβ-positive cells are shown in Table 1. In addition, type 1 TNF-α receptor immunoreactivity was observed in T cells using immunocytochemistry (data not shown).

Effect of the ER antagonist ICI 172,780 on 17β-estradiol with TNF-α in T cells

ER antagonist, ICI 172,780 (100 nM) alone did not affect cytotoxicity in T cells (data not shown). 17β-estradiol treatment (100 nM) significantly decreased TNF-α-induced cytotoxicity in T cells. In contrast, ICI 172,780 (100 nM) completely abolished 17β-estradiol cytoprotective effects in T cells (Fig. 2C).

Effect of 17β-estradiol with TNF-α on NF-κB protein levels from the nuclear extracts in T cells

In order to evaluate the modulation of NF-κB protein followed by TNF-α/17β-estradiol treatment, we examined...
NF-κB protein levels in the nuclear extracts using Western blotting. TNF-α tended to increase NF-κB protein levels in the nuclear extracts but it did not reach statistical significance. In contrast, NF-κB protein levels followed by TNF-α with 17β-estradiol treatment were significantly increased compared with NF-κB protein levels in untreated group (Fig. 3).

**Effect of NF-κB blocker PDTC on 17β-estradiol with TNF-α in T cells**

NF-κB blocker PDTC (10^{-4} M) alone did not affect cytotoxicity in T cells (data not shown). 17β-estradiol treatment (100 nM) again clearly decreased TNF-α-induced cytotoxicity in T cells. In contrast, PDTC (10^{-4} M) completely abolished 17β-estradiol cytoprotective effects in T cells (Fig. 4).

**Effect of 17β-estradiol with TNF-α on caspase-3/-7 activity in T cells**

We examined the regulation of caspase-3/-7 activity after TNF-α/17β-estradiol treatment in T cells. TNF-α significantly increased caspase-3/-7 activity. 17β-estradiol treatment significantly reduced TNF-α-induced caspase-3/-7 activity (Fig. 5).

**Discussion**

Regulation of apoptosis is considered an important mechanism for controlling the number of monocytes

<table>
<thead>
<tr>
<th>Immunoreactivity</th>
<th>% of immunopositive cells</th>
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<tr>
<td>ERα only</td>
<td>76.3 ± 9.6</td>
</tr>
<tr>
<td>ERβ only</td>
<td>1.0 ± 0.58</td>
</tr>
<tr>
<td>ERα and ERβ</td>
<td>8.7 ± 3.2</td>
</tr>
<tr>
<td>No ERα and no ERβ</td>
<td>14.0 ± 6.1</td>
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![Table 1 Percentages of each cell type. The separate counts were performed three times on 300 cells and data represent means ± s.d.](https://www.endocrinology-journals.org)

**Figure 2** Identification of ERα and ERβ in T cells using immunocytochemistry. (A) CD3- and ERα-positive cells are indicated by double arrows. In contrast, cells stained only for CD3 are shown by a single arrow. (B) Both ERα- and ERβ-positive cells are indicated by double arrows. T cells stained only for ERα are shown by single arrows. Note, the number of ERα-positive cells was greater than that of ERβ-positive cells. (C) Effect of ER antagonist, ICI 172,780 (ICI) on 17β-estradiol (E2)/TNF-α treatment in T cells. Data represent means ± S.E.M. (n=6). * denotes significant alterations at P<0.05 when compared with the group treated with TNF-α without 17β-estradiol, as determined by one-way ANOVA followed by Fisher’s protected least-squares difference test.
available and therefore the intensity of the physiological response to infection or wound healing. Failure in the control of programmed cell death may become particularly relevant in pathological conditions such as tumor growth, and autoimmune and chronic inflammatory disorders, where apoptosis has been identified as a key factor in disease progression or remission (van der Loosdrecht et al. 1993, Mountz et al. 1994, Deshpande et al. 1997, Thatte & Dahanukar 1997). It has recently been reported that estradiol treatment resulted in a dose-dependent, receptor-mediated inhibition of TNF-α-induced endothelial cell apoptosis, providing another mechanism that may account for the atheroprotective effect of estrogens (Spyridopoulos et al. 1997).

In the present study, TNF-α treatment (10 nM) showed 10–30% cytotoxicity in T cells. 17β-estradiol treatment (1–100 nM) dose dependently decreased TNF-α-induced cytotoxicity in T cells. These observations are in agreement with the report that treatment with estradiol or progesterone increased survival and prevented apoptosis induced by TNF-α in both undifferentiated and macrophage–like phorbol 12-myristate 13-acetate-differentiated U937 cells, as assessed by Trypan Blue-exclusion cell counting, thymidine incorporation and annexin V labeling, followed by flow cytometry and DNA fragmentation studies (Vegeto et al. 1999). Estrogens modulate target–cell activity by binding to specific intracellular receptors, which are hormone-regulated transcription factors (Katzenellenbogen et al. 1996, Kuiper et al. 1996). ER effects have been focused on the ERα identified and cloned several years ago (Green et al. 1986, Greene et al. 1986).

Recently, a second ER, designated ERβ, has been described and shown to share common structural and
functional characteristics with ERα (Kuiper et al. 1996, Mosselman et al. 1996). In the present study, ERα and ERβ protein were detected in T cells using immuno-cytochemistry. These observations are in agreement with the report that PBMCs and lymphocytes contain ERs (Carbone et al. 1986, Tubiana et al. 1986, Weusten et al. 1986). During menopause there is a significant decrease in the percentage of ER-positive monocytes, and an increase in blood monocyte number, which declines following estrogen-replacement therapy to values of the young (Ben-Hur et al. 1995). The pure ER antagonist ICI 172,780 completely abolished 17β-estradiol cytotoxic effects in T cells, further supporting the importance of ER for 17β-estradiol activity on TNF-α-induced cytotoxicity. However, additional studies including cell-surface ER are required to investigate the functional nature of ER for cell protection.

TNF-α-induced signaling is believed to diverge; TRAF2/RIP recruitment leads to activation of downstream kinases in the NF-κB and c-Jun N-terminal kinase (JNK) pathways, leading to survival, while FADD recruitment leads to apoptosis (Hsu et al. 1996a). It is possible that the presence of RIP within the TNFR1 signaling complex could have either prevented or decreased the recruitment of FADD and caspase-8 by competing for binding to TRADD (Harper et al. 2003, Hsu H. et al. 1996b). In unstimulated cells, NF-κB is found in cytoplasm and is bound to the inhibitory IκB-α and IκB-β, which prevent it from entering the nucleus (Baldwin 1996). The entry of NF-κB from the cytoplasm to the nucleus is regulated by IκB, whose induction and binding to NF-κB prevents the translocation of NF-κB into the nucleus, where it binds to specific regions in the promoter regions of target genes (Scheinman et al. 1995, Barnes & Karin 1997). A recent study showed that PDTC inhibits TNF-α signaling into apoptosis by blocking cytoplasmic NF-κB translocation to the nucleus and both TNF-α and PDTC alone cause apoptosis and reduce cell growth, but their combined effects are additive in reducing cell growth of DU-145 and ALVA-101 human prostate cancer cells (Gunawardena et al. 2002). In the present study, TNF-α with 17β-estradiol increased NF-κB protein levels in nuclear extracts and PDTC completely abolished 17β-estradiol cytoprotective effects in T cells. These results are keeping with the observation by Cutolo et al. (2003) that the enhancing role of estrogens on the immune/inflammatory response was exerted by activating the NF-κB complex. In addition, 17β-estradiol significantly reduced TNF-α-induced caspase-3/-7 activity in T cells. These observations are in agreement with the report that estrone antagonized not only the N-methyl-D-aspartate (NMDA)-induced caspase-3-like activity, but also NMDA-mediated LDH release in hippocampal neurons (Kajta et al. 2004). Furthermore, a recent report demonstrated that preincubation with 17β-estradiol completely prevented both TNF-related apoptosis-inducing ligand (TRAIL)-induced DR4 and DR5 upregulation and apoptosis (Cantarella et al. 2004), further supporting that 17β-estradiol suppressed TNF-α-induced apoptosis signaling pathway. Taken together, the reduced cytotoxicity could be a functional consequence of increased NF-κB and decreased caspase activity by the estrogen.

Although further studies including functional assays of NF-κB are needed to assess cellular responses to estrogens in T cells, the present studies provide an experimental basis for understanding the protective effect of 17β-estradiol during inflammation and apoptosis.

Funding

The authors declare that there is no conflict of interest that would prejudice the impartiality of this scientific work.

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Received 19 July 2004
Accepted 30 September 2004

Made available online as an Accepted Preprint 6 October 2004