Dexamethasone enhances cell resistance to chemotherapy by increasing adhesion to extracellular matrix in human ovarian cancer cells

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Abstract

Glucocorticoids (GCs) are widely used as co-medication in the therapy of solid malignant tumors to relieve some of the side effects of chemotherapeutic drugs. However, recent studies have shown that GCs could render cancer cells more resistant to cytotoxic drug-induced apoptosis, but the mechanism is largely unknown. In the present study, we found that the treatment of human ovarian cancer cell lines HO-8910 and SKOV3 with synthetic GCs dexamethasone (Dex) significantly increased their adhesion to extracellular matrix (ECM) and their resistance to apoptosis induced by cytotoxic drugs cisplatin and paclitaxel. Dex also increased the protein levels of adhesion molecules integrins β1, α4, and α5 in HO-8910 cells. The neutralizing antibody against integrin β1 prevented Dex-induced adhesion and significantly abrogated the protective effect of Dex toward cytotoxic agents. We further found that transforming growth factor-β1 (TGF-β1) alone not only increased cell adhesion and cell survival of HO-8910 cells in the presence of cisplatin, but also had synergistic pro-adhesion and pro-survival effects with Dex. Moreover, TGF-β1-neutralizing antibody that could block TGF-β1-induced cell adhesion and apoptosis resistance markedly abrogated the synergistic pro-adhesion and pro-survival effects of Dex and TGF-β1. Finally, we further demonstrated that Dex could up-regulate the expression of TGF-β receptor type II and enhance the responsiveness of cells to TGF-β1. In conclusion, our results indicate that increased adhesion to ECM through the enhancement of integrin β1 signaling and TGF-β1 signaling plays an important role in chemoresistance induced by GCs in ovarian cancer cells.

Endocrine-Related Cancer (2010) 17 39–50

Introduction

Glucocorticoids (GCs) are being used in the treatment of childhood leukemia for several decades (Frei et al. 1965), and they have become one of the common drugs in almost all chemotherapy protocols for lymphoid malignancies due to their ability to induce apoptosis in the majority of hematological cells and efficiently kill lymphoid cells (Schmidt et al. 2004). Nowadays, GCs are also widely used as co-medication in cancer therapy of solid malignant tumors because of their effectiveness in the treatment of the malignant tumors or treatment-related edema, inflammation, pain, and electrolyte imbalance, as well as due to their ability to stimulate appetite, to prevent nausea, emesis, and toxic reactions caused by cytotoxic treatment (Rutz 2002, Rutz & Herr 2004). GCs are also given before, during, and after chemotherapy of solid malignant tumors to reduce acute toxicity, particularly hyperemesis, and to protect normal tissue, e.g. bone marrow progenitor cells, of cancer patients against the long-term effects of genotoxic drugs (Kriegler et al. 1994).
While GCs strongly induce apoptosis in the cells of the hematological lineage, they also support survival in several nonhematological tissues such as mammary gland, liver, lung, glioma, and subcutaneous adipocytes (Moran et al. 2000, Schorr & Furtth 2000, Mikosz et al. 2001, Zhang et al. 2001, Bailly-Maître et al. 2002, Webster et al. 2002). More recent data indicate that GCs can inhibit apoptosis induced by chemotherapy not only in established cancer cell lines and tumor xenografts, but also in the freshly isolated cells from surgical resections from tumors of various origins, including ovary, breast, prostate, pancreas, liver, colon, brain, cervix, bone, skin, and nervous system (Herr et al. 2003, Sui et al. 2006, Zhang et al. 2006a,b,c,d,e). In addition, the anti-chemotherapeutic effect of GCs can be seen in several anticancer drugs including cisplatin (Wolff et al. 1996, Gassler et al. 2005, Zhang et al. 2006a,b,d, 2007), paclitaxel (Wu et al. 2004, 2005, Sui et al. 2006), 5-fluorouracil (Zhang et al. 2006a, 2007), Adriamycin (Weller et al. 1997), actinomycin D (Wolff et al. 1996), doxorubicin (Wu et al. 2004), and gemcitabine (Gassler et al. 2005, Zhang et al. 2007). The GC-induced pro-survival effects should be of important clinical relevance when they interfere with the effect of chemotherapeutics. Recent studies suggest that GC-conferred cellular resistance to cancer therapy may occur through multiple mechanisms, for example, by enhancing DNA repair capacity, suppressing host anti-tumor immune responses, and blocking apoptosis (Rutz 2002, Herr et al. 2003, Rutz & Herr 2004). Some dexamethasone (Dex)-induced proteins, such as the inhibitors of apoptosis (cIAP-2, X-IAP, Bcl-XL, and Bcl-2), mitogen-activated protein kinase phosphatase-1, as well as GC-induced serum, and GC-inducible kinase-1 (SGK-1) may contribute to the prevention of chemotherapy-induced apoptosis by GCs (Webster et al. 2002, Herr et al. 2003, Wu et al. 2004, 2005, Runnebaum & Brüning 2005, Herr et al. 2007). However, the molecular mechanisms underlying the anti-apoptotic effect of GCs in epithelial cells are still largely unknown.

In our previous work, we found that Dex could dramatically prolong the detachment time of the cells digested with trypsin in human ovarian cancer cell line HO-8910, suggesting that Dex may be able to increase the cell adhesion ability to extracellular matrix (ECM). Since cell adhesion to ECM is pivotal for the survival and growth of most of the solid cancer cells derived from epithelium (Rozzo et al. 1997, Pinkse et al. 2004), we hypothesized that the increase in cell resistance to cytotoxic therapy-induced apoptosis by Dex may be due to its promotion effect in cell adhesion to ECM. Therefore, in the present study, we investigated the effect of Dex on cell adhesion to ECM of two human ovarian cancer cell lines, HO-8910 and SKOV3, and examined the relationship between Dex’s effect of enhancing adhesion and Dex-induced cell resistance to chemotherapeutic agents. We further explored the mechanism of Dex’s action and mainly focused on the adhesion molecular integrin β1 subfamily, as well as on the transforming growth factor-β1 (TGF-β1) signaling. Our results provide new evidence that Dex’s role in pro-adhesion through the enhancement of integrin β1 signaling and TGF-β1 signaling is one of the basic mechanisms responsible for Dex-induced apoptotic resistance against chemotherapy in ovarian cancer cells.

Materials and methods

Cell culture

Human ovarian cancer cell line HO-8910 was described previously (Chen et al. 2006). Human ovarian cancer cell line SKOV3 was cultured in RPMI-1640 (Invitrogen) supplemented with 10% fetal bovine serum, 100 U/ml penicillin, and 100 µg/ml streptomycin (Huashun Technology, Inc., Shanghai, China) at 5% CO₂ and at 37 °C.

Semi-quantitative reverse transcription-PCR

Total RNA was extracted with the TRIzol reagent (Invitrogen). After reverse transcription (RT), the cDNA products were amplified by PCR at an annealing temperature of 58 °C (integrin β1) or 55 °C (TGF-β receptor type II (TβR-II), glyceraldehyde-3-phosphate dehydrogenase (GAPDH)). The amplifying cycles and templates were 24 cycles and 75 ng cDNA for integrin β1, 24 cycles and 40 ng cDNA for TβR-II, and 20 cycles and 20 ng cDNA for GAPDH according to the results of optimization. The primers were sense 5'-GCACGTTCCAGAAGTCGTT-3' and antisense 5'-AGATATGGCAACTCCCAGTGTT-3' for TβR-II (467 bp; Li et al. 2006), sense 5'-ACAGCTCTCCTCTGTCG-3' and antisense 5'-CAGTTGTCTAGCCACTCT-3' for integrin β1 (157 bp; Kappert et al. 2000), and sense 5'-TTCATGGCACTCACTATG-3' and antisense 5'-GTGGCAGTGATGGCATGGAC-3' for GAPDH (443 bp). PCR products were separated on 2% agarose gels and visualized by ethidium bromide staining.
Western blotting

Total cell lysates were prepared with 1 × SDS lysis buffer containing 0.1 mM β-mercaptoethanol, and 2 μg/ml of each of the protease inhibitors leupeptin, aprotinin, and pepstatin. After electrophoresis, the protein was transferred to a nitrocellulose membrane, blocked with 5% nonfat milk, and probed overnight with primary antibodies against integrin β1 (Upstate, Lake Placid, NY, USA, 1/500), integrins α4 and α5 (Chemicon, Temecula, CA, USA, 1/500), TβR-II (Santa Cruz Biotechnology, Santa Cruz, CA, USA, 1/500), cleaved caspase-3 (Asp175) (Cell Signaling, Boston, MA, USA, 1/500), and β-actin (Sigma, 1/10 000). The blots were then washed, exposed to HRP-conjugated secondary antibodies (Rockland Immunochemicals, Gilbertsville, PA, USA, 1/5000) for 2 h, and finally detected by ECL chemiluminescence (Pierce, Rockford, IL, USA).

Transient transfection and luciferase assay

Twenty-four hours before transfection, HO-8910 cells were plated in triplicate into a 24-well plate at a density of 5 × 10^4 cells/well. Cells were transiently transfected with 1 μg/well of p3TP-Luc-driven luciferase reporter plasmid (kindly provided by Dr J Massagué) using Lipofectamine plus transfection reagent (Invitrogen Life Technologies). In order to normalize the transfection efficiency, pRL-TK-Renilla-luc (30 ng/well, Promega) was co-transfected into the cells. Cells were grown for 12 h and then treated with 10^{-7} M Dex (Sigma–Aldrich Chemicals) and/or 10 ng/ml TGF-β1 (Peprotech, Rocky Hill, NJ, USA) for 24 h. The luciferase activities were determined using the dual luciferase assay system. Values were normalized by renilla luciferase, and are presented as fold induction over control.

Analysis of viability

Cells were seeded at 2 × 10^3 cells/well in 96-well culture plates in triplicate, and cultured in RPMI-1640 containing 5% charcoal–dextran-stripped CBS. Cisplatin (Sigma–Aldrich Chemicals), paclitaxel (a gift from Prof. Zhu Minghua, Department of Pathology, Shanghai Hospital, Second Military Medical University), and/or Dex were added and refreshed for every other 24 h. For the blockade assay, 10–20 μg/ml integrin β1 antibody, 10 μg/ml TGF-β1 antibody, or control IgG was also added to the medium. At the indicated time, the viable cells were determined by 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay as described above (Chen et al. 2006).

Measurement of apoptosis

Cells were cultured in appropriate media containing 5% CBS with each agent for the indicated time. Cells were trypsinized and stained with FITC-conjugated annexin V and propidium iodide (BD Biosciences, Heidelberg, Germany) according to the manufacturer’s instructions. The apoptotic cells were analyzed by flow cytometric analysis.

Cell adhesion assay

Cell adhesion ability to ECM was determined by cell adhesion assay (Chen et al. 2004). Cells were incubated in the medium containing the agents for the indicated time and were then digested and counted. Cells, 8 × 10^4, were seeded into 96-well plates precoated with 10 μg/ml fibronectin (FN; Calbiochem, Darmstadt, Germany) and incubated at 37 °C for 1 h. The plates were gently washed thrice with PBS to remove the unattached cells. The remaining cells in the 96-well plates were determined by MTT assay.

For the blockade experiment, the 96-well plates were precoated with 10 μg/ml FN for 1 h, followed by 1% BSA for 45 min at 37 °C. Resuspended cells, 2 × 10^4, were incubated with 10–20 μg/ml integrin β1 antibody, 10 μg/ml TGF-β1 antibody, or control IgG for another 45 min at 37 °C before seeding into wells to detect the cell adhesion ability with the same procedure as described above.

Statistical analysis

Data are expressed as mean ± S.D. of at least three determinations. Statistical significance between experimental groups was analyzed by ANOVA, and the significance level was set at P < 0.05.

Results

Dex increases cell viability by the inhibition of chemotherapeutic drug-induced apoptosis in ovarian cancer cells HO-8910 and SKOV3

We first investigated the effects of cisplatin or paclitaxel alone or plus Dex on the survival of HO-8910 cells. As shown in Fig. 1A, cisplatin could significantly decrease the survival cell number in a dose-dependent manner. Co-treatment of cells with Dex and different doses of cisplatin significantly increased the survival cell number. Dex, 10^{-7} M, increased the survival cell number by 53.8% (P < 0.01) in the presence of 2 μg/ml cisplatin, a dose commonly used in the clinic. A similar protective effect of Dex was also seen when cells were treated with paclitaxel,
another chemotherapeutic drug (Fig. 1C). These findings were confirmed in SKOV3, a different human ovarian cancer cell line (Fig. 1B and D).

Since $10^{-7}$ M Dex alone led to a slight inhibition of cell growth by about 20% (Fig. 1A), the increase in survival cell number when cells were co-treated with Dex and cisplatin or paclitaxel (C and D) as indicated in the absence or presence of $10^{-7}$ M Dex for 4 days, and then the viability was monitored. Values plotted are mean $\pm$ S.E.M. $^*P<0.05$, $^**P<0.01$ versus corresponding dose of cytotoxic drugs. (E and F) Dex protects cell apoptosis against cisplatin in HO-8910 cells. HO-8910 cells were cultured in a medium containing ethanol or 2 $\mu$g/ml cisplatin in the absence or presence of $10^{-7}$ M Dex for 48 h. Apoptosis was analyzed by staining the cells with annexin–FITC and by FACS analysis (E). The expression of cleaved caspase-3 was determined by western blotting (F). Relative densitometric units of cleaved caspase-3/$\beta$-actin are shown in the upper panel, with the density of the control bands set at 1.0. Experiments were performed thrice with similar results. Values plotted are mean $\pm$ S.E.M. $^#P<0.05$ versus control, $^*P<0.05$, $^**P<0.01$ versus cisplatin.

**Figure 1** Dex protects cell survival in response to cytotoxic drugs in human ovarian cancer cells HO-8910 and SKOV3. (A–D) The detection of cell survival by MTT assay. HO-8910 (A and C) and SKOV3 (B and D) cells were cultured in a medium containing ethanol or various doses of cisplatin (A and B) or paclitaxel (C and D) as indicated in the absence or presence of $10^{-7}$ M Dex for 4 days, and then viability was monitored. Values plotted are mean $\pm$ S.E.M. $^*P<0.05$, $^**P<0.01$ versus corresponding dose of cytotoxic drugs. (E and F) Dex protects cell apoptosis against cisplatin in HO-8910 cells. HO-8910 cells were cultured in a medium containing ethanol or 2 $\mu$g/ml cisplatin in the absence or presence of $10^{-7}$ M Dex for 48 h. Apoptosis was analyzed by staining the cells with annexin–FITC and by FACS analysis (E). The expression of cleaved caspase-3 was determined by western blotting (F). Relative densitometric units of cleaved caspase-3/$\beta$-actin are shown in the upper panel, with the density of the control bands set at 1.0. Experiments were performed thrice with similar results. Values plotted are mean $\pm$ S.E.M. $^#P<0.05$ versus control, $^*P<0.05$, $^**P<0.01$ versus cisplatin.

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Dex increases cell adhesion ability of ovarian cancer cells in the absence or presence of cisplatin

Our preliminary studies found that HO-8910 cells treated with Dex were more resistant to trypsin digestion than cells treated with a vehicle control. The detachment time of the cells treated with or without 10^{-7} M Dex for 24 h followed by digestion with 0.25% trypsin was 16 ± 3.5 and 4 ± 0.5 min respectively. This phenomenon was also observed in SKOV3 cells, suggesting that the cell adhesion to ECM may be strengthened by Dex. We further investigated the effect of Dex on cell adhesion ability. As shown in Fig. 2A and B, Dex could significantly increase the cell adhesion ability to FN-coated culture plates in a time- and dose-dependent manner in both HO-8910 and SKOV3 cells. In addition to the increased cell adhesion ability, Dex treatment also induced a fibroblast-like change in cell morphology (data not shown).

Based on the above-mentioned data, we proposed that Dex-enhanced adhesion to ECM may be involved in its protecting the cells from apoptosis induced by chemotherapeutic drugs. To test this hypothesis, we investigated the effect of cisplatin on cell adhesion in the absence or presence of Dex. As shown in Fig. 2C, in the absence of Dex, the treatment of cells with cisplatin for 24 h dramatically decreased the adhesive cell number by 51% (P < 0.05) as compared with that of the control. However, when cells were treated with both cisplatin and increasing concentrations of Dex, the adhesive cell number gradually increased. There was a twofold increase in the adhesive cells at 10^{-7} M Dex compared to the cells treated with cisplatin alone.

Dex up-regulates protein expressions of integrins α4β1 and α5β1 in HO-8910 cells

As one of the receptors of ECM proteins, adhesion molecular integrin β1 subfamily plays a crucial role in regulating cell adhesion to ECM (Hynes 1992). All members of integrin β1 subfamily are heterodimers formed by one common integrin β1 subunit and different kinds of α subunits (Hynes 1992). We investigated the effect of Dex on the expression of integrin β1 as well as on the two kinds of α subunit, α4 and α5, which are the primary receptors of FN in HO-8910 cells. As shown in Fig. 3, though Dex could not change the expression of integrin β1 at the mRNA level (data not shown), it could induce the expression of integrins β1, α4, and α5 at the protein levels in a time- and dose-dependent manner.

Figure 2 Dex enhances cell attachment to fibronectin and antagonizes the impairment of cisplatin on cell adhesion. Cells were pretreated with 0–1 μM Dex for 24 h (A) or with 10^{-7} M Dex for 0–48 h (B), or treated with ethanol, 2 μg/ml cisplatin, or 2 μg/ml cisplatin combined with 1–10^{-7} M Dex for 24 h (C). Cells, 8 × 10^4, were seeded into a 96-well plate coated with 10 μg/ml fibronectin. Sixty minutes later, cells were washed thrice with PBS, and the number of the remaining cells that were attached was determined by MTT assay. Data are summarized from three independent sets of experiments. *P < 0.05 and **P < 0.01 versus control in A and B. *P < 0.05, **P < 0.01 in C.
Blocking of integrin β1-mediated cell adhesion attenuates the protective effect of Dex on chemotherapeutic drug-induced apoptosis in HO-8910 cells

In an effort to elucidate the role of Dex-induced expression of integrin β1 in the protection of cells against chemotherapeutic agents, we further examined the influence of the integrin β1-blocking antibody on the cell adhesion and cell survival. As shown in Fig. 4A, preincubation of the cells with integrin β1-blocking antibody significantly blocked Dex-induced cell adhesion in a dose-dependent manner. As compared with Dex plus IgG group, addition of 10 and 20 μg/ml integrin β1-blocking antibody reduced the number of cells attached by 25% (P < 0.05) and 67.3% (P < 0.01) respectively. Meanwhile, the cell survival protective effect of Dex was also decreased when the cells were treated with Dex combined with integrin β1-blocking antibody. As shown in Fig. 4B, 20 μg/ml integrin β1-blocking antibody could reduce the protective effect of Dex from cisplatin by 61.5% (P < 0.05). A similar but stronger reduction in the protective effect of Dex could be seen when paclitaxel was used in the experiments (Fig. 4C). These results indicate that the enhancement of cell adhesion to ECM, which is mainly mediated by integrin β1 subfamily, plays an important role in GCs protecting cells against chemotherapeutic agents in HO-8910 cells.

Dex and TGF-β1 have a synergistic effect on enhancing cell adhesion and resistance to cisplatin in HO-8910 cells

TGF-β1 is the most important growth factor that facilitates cell adhesion to ECM by increasing matrix production and accumulation, as well as by enhancing the expression of cell adhesion molecules (Dawes et al. 2007). Considering that ovarian epithelial cells can secrete TGF-β1 (Peng 2003), we therefore tested whether TGF-β1-signaling pathway is involved in Dex’s role in pro-adhesion and pro-survival.

As shown in Fig. 5A, the adhesion ability of cells treated with 10⁻⁷ M Dex, 10 ng/ml TGF-β1 alone, and both the agents for 24 h was 1.89-fold (P < 0.01), 1.4-fold (P < 0.05), and 2.64-fold (P < 0.01) respectively compared to that of the control cells, indicating that TGF-β1 not only increased adhesion of HO-8910 cells alone, but also had a synergistic pro-adhesion effect with Dex. Moreover, 10 μg/ml TGF-β1-neutralizing antibody that could significantly block the pro-adhesion effect of TGF-β1 markedly inhibited the synergistic effect of Dex and TGF-β1 on cell adhesion. A similar synergistic pro-survival effect was
also observed when cells were co-treated with Dex and TGF-β1 in the presence of cisplatin. And such a synergistic effect was also markedly abrogated by TGF-β1-neutralizing antibody (Fig. 5B). These results indicate that TGF-β1-signaling pathway is involved in Dex-induced cell adhesion to ECM as well as in the cell resistance to cisplatin in HO-8910 cells.

Dex enhances the responsiveness of HO-8910 cells to TGF-β1 by increasing the expression of TβR-II

The synergistic effect of Dex and TGF-β1 on cell adhesion as well as on the cell resistance to cisplatin in HO-8910 cells suggests that there is a positive crosstalk between GC- and TGF-β1-signaling pathways. Therefore, we examined the effect of Dex on the expression of TGF-β1 and its two types of receptors (TβR-I and TβR-II). The results demonstrated that the expressions of TGF-β1 and TβR-I remain unaffected (data not shown), but TβR-II expression in HO-8910 cells was significantly up-regulated by 10⁻⁷ M Dex at both mRNA and protein levels (Fig. 5C).

It is well known that the binding of TGF-β1 to constitutively active TβR-II leads to the recruitment and interaction of TβR-I, which phosphorylates downstream Smad proteins that activate target genes in the nucleus. We then examined the response of cells to TGF-β1 signaling by transient transfection of cells with p3TP-luc, a TGF-β1-responsive reporter gene. As shown in Fig. 5D, TGF-β1, Dex, and TGF-β1 plus Dex induced a 2-fold (P < 0.01), 1.5-fold (P < 0.05), and 2.8-fold (P < 0.01) increase in luciferase activity respectively. These results indicate that Dex may enhance the responsiveness of cells to TGF-β1 by up-regulating the expression of TβR-II.

Discussion

Recently, more and more data from preclinical studies, and to some extent from clinical studies, have strongly recommended a GC-conferred resistance to cancer therapy in the majority of malignant solid tumors – irrespective of tumor origin and the nature of specific anticancer drugs (Wolff et al. 1996, Weller et al. 1997, Webster et al. 2002, Herr et al. 2003, Wu et al. 2004, 2005, Gassler et al. 2005, Runnebaum & Brüning 2005, Sui et al. 2006, Zhang et al. 2006a,b,c,d,e, 2007). In this study, we have demonstrated that Dex could protect human ovarian

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**Figure 4** Dex-enhanced cell attachment and cell survival are partially reversed by integrin β1-blocking antibody. (A) Cells were cultured in a medium in the absence or presence of 10⁻⁷ M Dex for 24 h and were digested and counted. Cells, 2 × 10⁴, were incubated with IgG, 10 µg/ml, or 20 µg/ml integrin β1-blocking antibody for 45 min, and then seeded into a 96-well plate coated with 10 µg/ml FN. Sixty minutes later, the cell adhesion ability was assayed. (B and C) Cells, 2 × 10³, were cultured in a medium containing chemotherapeutic drugs, and chemotherapeutic drugs plus 10⁻⁷ M Dex, combined with either integrin β1-blocking antibody or IgG for 4 days, and cell survival was detected by MTT assay. Data are representative of three independent sets of experiments. *P < 0.05, **P < 0.01.
cancer cell lines HO-8910 and SKOV3 from apoptosis induced by chemotherapeutic drugs, including cisplatin and paclitaxel, as well as adriamycin and actinomycin D (data not shown).

These findings indicate that the use of GCs as co-medication in the therapy of ovarian carcinomas and other solid tumors may result in the desensitization to chemotherapy, ultimately leading to faster tumor growth. Therefore, GCs should be administered carefully in routine chemotherapy in cancer patients.

The protection of normal tissue by GCs may be good for patients, but the protection of cancer cells may impair the effect of chemotherapy. Thus, it is understandable that the appeal for reevaluating the administration of GCs in the management of solid cancer patients has emerged recently. After performing an overall statistical analysis of a large screening study, Zhang et al. (2007) also suggested the replacement of GCs by nonsteroidal anti-emetic agents, which do not induce therapy resistance.

**Figure 5** Dex enhances cell adhesion and survival responses to TGF-β1 in HO-8910 cells. (A) Dex enhances cell adhesion ability induced by TGF-β1. HO-8910 cells were treated with the indicated agents for 24 h, and the cell adhesion ability was assayed. (B) Dex enhances TGF-β1-induced cell apoptosis resistance to cisplatin. Cells were incubated with the indicated agents for 4 days, and the survival cell number was determined with MTT assay. (C) Dex increases the expression of TβRII mRNA and protein in HO-8910 cells. Cells were treated with 10^{-7} M Dex for different times, and TβRII mRNA and protein levels were determined by semi-quantitative RT-PCR and western blotting respectively. Relative densitometric units of TβRII/GAPDH and TβRII/β-actin are shown in the upper panel, with the density of the control bands set at 1.0. The blots represent one of the three independent experiments. (D) Dex enhances the luciferase activity induced by TGF-β1. Cells were transfected with the reporter plasmid p3TP-Luc, and were then incubated with agents as indicated. Sixteen hours later, cells were harvested and assayed for luciferase activity. All the results shown above are representative of three independent experiments. *P<0.05, **P<0.01 versus control (or cisplatin), *P<0.05.
In addition to chemotherapy resistance, we also noticed that Dex alone led to an inhibition of cell growth in HO-8910 and SKOV3. Similar results were also reported in several other solid tumor cells such as glioblastoma cells and osteosarcoma cells (Mattern et al. 2007). The effects of GCs may reflect their important role in maintaining the homeostasis of cell number. They inhibit the proliferation of cells under physiological conditions; however, they enhance cell survival under the pressure of cytotoxic drugs and other harmful stimuli. Moreover, it is known that cell cycle arrest may reduce the sensitivity of cells to the chemotherapeutic drugs. So, Dex-induced cell growth inhibition and cell cycle arrest in G1 may also be one of the mechanisms of its anti-apoptotic effect on cancer therapy. Mattern et al. (2007) held a similar opinion that the inhibition of cell growth by inducing cell cycle arrest may be crucially involved in switching the balance of several interacting pathways to survival upon treatment with GCs.

For anchorage-dependent monolayer culture, attachment of cells to ECM is one of the prerequisites for cell survival, growth, and differentiation. As reported, Dex increased cell adhesion ability in lung fibroblasts (Brener et al. 2001) and lens epithelial cells (Sawhney 2002), but decreased it in amnion epithelial cells (Guller et al. 1995a) and placental cells (Guller et al. 1995b), indicating that Dex plays a role in regulating cell adhesion to ECM in a cell-specific manner. Our study adds new data that Dex significantly promotes the adhesion of human ovarian cancer cells HO-8910 and SKOV3 to ECM, and demonstrates for the first time that the enhancement of adhesion by Dex is associated with its effect of promoting cell viability to chemotherapy.

It is well known that adhesion molecule integrin β1 subfamily plays a crucial role in regulating cell adhesion to ECM proteins, such as collagen, FN, and laminin (Hynes 1992, Rozzo et al. 1997, Jin & Varner 2004). It has been reported that Dex shows cell typespecific regulation on the expression of integrin β1. For example, the expressions of integrin β1 mRNA and protein were reduced in human skin fibroblast (Zoppi et al. 1998) and human cytotrophoblast (Ryu et al. 1999), while they were induced in human gastric carcinoma cells (Murakami et al. 1998) by Dex. But there is no information about how Dex affects the expression of integrin β1 in ovarian cancer cells. Our further experiment demonstrated that the expressions of integrin β1 as well as of the two kinds of α subunits, α4 and α5, were up-regulated by Dex at the protein level in human ovarian cancer HO-8910 cells. And the regulation of Dex on integrin β1 seems to occur at the post-transcriptional level since this regulation was not seen at the mRNA level (data not shown). Moreover, we demonstrated that the blocking of cell adhesion to ECM with neutralizing antibody of integrin β1 significantly attenuated the protection of Dex from chemotherapy in HO-8910 cells, indicating that cell adhesion to ECM mediated by integrin β1 adhesion molecule is responsible for the effect of Dex against chemotherapeutic agents. However, it should be pointed out that the neutralizing antibody of integrin β1 could not completely block the Dex-induced cell adhesion to ECM, suggesting that other adhesion molecules besides integrin β1 and/or other mechanisms may also be involved in the action of Dex. Our recent results indicate that Dex could enhance cell adhesion by increasing the expression of some ECM components, such as collagen I and hyaluronic acid, in HO-8910 cells (unpublished data). This finding is in line with the latest report that the enhanced ECM deposition may play a direct role in primary chemoresistance in ovarian carcinoma (Etemadmoghadam et al. 2009).

Several studies have reported that there is a synergistic effect between GC- and TGF-β1-signaling pathways to regulate a variety of physiological and pathologic processes, such as modulating cell differentiation in osteoclast (Takuma et al. 2003) or cell growth in U937 cells (Kanatani et al. 1996). Since TGF-β1 is the most important growth factor that facilitates cell adhesion to ECM by increasing matrix production and accumulation, and ovarian epithelial cells can secrete TGF-β1 (Peng 2003), we therefore hypothesized that TGF-β1-signaling pathway may be involved in Dex’s role in pro-adhesion and pro-survival. The results of this experiment showed that TGF-β1 alone has the pro-adhesion and pro-survival effects, although the effects are weaker than those of Dex, and the combination of Dex and TGF-β1 showed the obvious synergistic effect on cell adhesion as well as on cell resistance to cisplatin. Furthermore, the neutralizing antibody of TGF-β1 not only could significantly block the pro-adhesion and pro-survival effects of TGF-β1 itself, but could also obviously inhibit the synergistic effect of Dex and TGF-β1. These results suggested that there is a positive crosstalk between GC- and TGF-β1-signaling pathways. Our previous studies found that Dex induced the expression of TβR-II and enhanced growth-inhibitory effect of TGF-β1 on androgen-independent human prostate cancer PC-3 cells (Li et al. 2006). In this experiment, we also found that Dex up-regulated TβR-II expression, but did not affect the expression of TGF-β1 and TβR-I. We indeed demonstrated subsequently that Dex could enhance the responsiveness
of HO-8910 cells to TGF-β1 by a TGF-β1-responsive reporter gene assay. Therefore, the induction of TβR-II expression by Dex may be an explanation for the Dex-enhanced TGF-β1-induced cell adhesion to ECM and cell resistance to cisplatin in HO-8910 cells. Since we only observed the effect of Dex on TGF-β1 signaling in this study, whether TGF-β1 signaling can enhance the effect of Dex in turn is unclear now and it is worthy of further study.

In summary, using human cancer cell line, which is commonly used in the elucidation of the mechanisms responsible for the biological activity, we provide new evidence that Dex’s role in pro-adhesion to ECM is one of the basic mechanisms of Dex-induced apoptotic resistance against chemotherapy. The pro-adhesion action of Dex is achieved at least by enhancing the protein levels of members of integrin β1 subfamily and TGF-β1-signaling pathway. It will be of considerable interest to know whether this effect of GC is involved in its cell protection against apoptosis induced by other harmful stimuli, such as hypoxia and ischemia. Furthermore, our studies are performed on human ovarian cancer cell line, and whether the conclusions could be applied to cancer cells from other epithelial origins is unknown. Additional experiments will be required to extend our conclusions.

Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of this research.

Funding

This work was supported by a grant from the National Natural Science Foundation of China (No. 30470671).

Acknowledgements

We thank Dr Joan Massagué for kindly providing us with the p3TP-Luc construct and Dr Yi-Li Yang for critical read.

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