Dose-Dense Chemotherapy Improves Mechanisms of Antitumor Immune Response

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Abstract

Dose-dense (DD) regimens of combination chemotherapy may produce superior clinical outcomes, but the basis for these effects is not completely clear. In this study, we assessed whether a DD combinatorial regimen of low-dose cisplatin and paclitaxel produces superior immune-mediated efficacy when compared with a maximum tolerated dose (MTD) regimen in treating platinum-resistant ovarian cancer as modeled in mice. Immune responses generated by the DD regimen were identified with regard to the immune cell subset responsible for the antitumor effects observed. The DD regimen was less toxic to the immune system, reduced immunosuppression by the tumor microenvironment, and triggered recruitment of macrophages and tumor-specific CD8\(_+\) T-cell responses to tumors [as determined by interleukin (IL)-2 and IFN-\(\gamma\) secretion]. In this model, we found that the DD regimen exerted greater therapeutic effects than the MTD regimen, justifying its further clinical investigation.

Fourteen patients with platinum-resistant relapse of ovarian cancer received DD chemotherapy consisting of weekly carboplatin (AUC2) and paclitaxel (60–80 mg/m\(^2\)) as the third- or fourth-line treatment. Serum was collected over the course of treatment, and serial IFN-\(\gamma\) and IL-2 levels were used to determine CD8\(_+\) T-cell activation. Of the four patients with disease control, three had serum levels of IL-2 and IFN-\(\gamma\) associated with cytotoxic CD8\(_+\) T-cell activity. The therapeutic effect of the DD chemotherapy relied on the preservation of the immune system and the treatment-mediated promotion of tumor-specific immunity, especially the antitumor CD8\(_+\) T-cell response. Because the DD regimen controlled drug-resistant disease through a novel immune mechanism, it may offer a fine strategy for salvage treatment.

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Introduction

Epithelial ovarian carcinoma (EOC) has the highest mortality rate among gynecologic malignancies, as it is typically asymptomatic and undiagnosed until the disease has progressed to advanced stages. Typical treatment for ovarian cancer is cytoreductive surgery when possible, followed by adjuvant chemotherapy. The introduction of modern platinum-based combination chemotherapy with paclitaxel has improved the 5-year survival rate of patients with advanced EOCs; however, long-term prognosis remains unfavorable. Disease relapse, acquired drug resistance, and short duration of progression-free survival are common and therefore, have motivated the search for better treatments.

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(5). Notably, evidence suggests that DD platinum-based combination therapy is a worthwhile option that can be safely extended, even for heavily treated patients with notoriously difficult drug-resistant disease (9). In theory, patients with platinum-resistant disease should be unresponsive to any platinum-based treatment; however, this supposition is contradicted by evidence. We speculate that platinum agent and paclitaxel given in a DD schedule at low dosages lead to the use of an immune-mediated tumor-killing pathway that is compromised when the drugs are given in the MTD regimen.

This study compares the efficacy and toxicity of platinum-based combination therapy administered in the DD and MTD regimen. We then determined whether antitumor effects involved the immune system. Because the experimental results from mouse models of platinum-resistant tumors suggested the DD regimen is superior and has immune-mediated efficacy, the treatment was examined in 14 patients with relapse of EOCs.

Materials and Methods

Mouse and cell lines

C57BL/6, (C57BL/6×C3/He) F1 mice, and athymic nude mice were purchased from BioLASCO. All animals were maintained under specific pathogen-free conditions. All procedures were conducted in accordance with approved protocols and recommendations for the proper care and use of laboratory animals. Mouse ovarian cancer cell lines, HM-1 (C57BL/6×C3/He F1 origin) and ID8, were used to establish the tumor model in syngeneic mice. ID8 was derived from the mouse ovarian cancer cell line, MOSEC (C57BL/6 origin), and carries the luciferase gene to enable in vivo imaging. The cells were cultured in MEM medium (Gibco-BRL) with 10% FBS (Hyclone), 100 U/mL penicillin (Gibco), and 100 pg/mL streptomycin (Sigma) under the condition of humidified atmosphere with 5% CO2/95% air at 37°C. Intraperitoneal tumor growth was monitored by in vivo imaging of tumor luminescence (indicating tumor load) by Xenogen IVIS 200 Imaging System.

Development of cisplatin-resistant cell line and cytotoxicity assay

Cisplatin-resistant cell lines (R HM-1) and (R ID8) were produced by culturing the cells with escalating doses of cisplatin (0.1–2 μg/mL of cisplatin within 2 months, maintained at 2 μg/mL). In vitro cytotoxicity was evaluated by MTT assay in accordance with protocol of the manufacturer (Sigma-Aldrich). The absorbance of each well was measured at 570/630 nm within a microplate reader. Each measurement was taken in triplicates and presented as mean ± SD.

Tumor treatment model and depletion of lymphocyte subpopulations

One million R HM-1 cells were inoculated subcutaneously in the left thigh of (C57BL/6×C3/He) F1 mice and athymic nude mice (day 0, 5 in each group). On day 4, mice began receiving paclitaxel and cisplatin intraperitoneally in either DD format (seven 3-day cycles of paclitaxel (5 mg/kg) plus cisplatin (3 mg/kg)) or MTD format [three 10-day cycles of paclitaxel (12 mg/kg) plus cisplatin (7 mg/kg)]. Other sets of mice were given the single-agent treatment either with paclitaxel (16 mg/kg in DD, 40 mg/kg in MTD) or cisplatin (10 mg/kg in DD, 25 mg/kg in MTD) at the same intervals. Chemotherapeutic drugs, paclitaxel (Taxol) and cisplatin (Platinex) were purchased from Bristol-Myers Squibb Company under the approval of the pharmaceutical committee in Mackay Memorial Hospital (Taipei, Taiwan). Control group mice were treated with PBS at 3-day intervals. R ID8 cells (5 × 10⁵) were intraperitoneally (i.p.) injected into C57BL/6 mice on days 0 and 5. On day 7, mice began treatment. Depletion of lymphocyte subpopulation was achieved through i.p. injection with 100 μg of rat monoclonal antibody GK1.5 (anti-CD4), 2.43 (anti-CD8), or PK136 (anti-NK1.1). Depletion was initiated 1 week before tumor challenge and continued every other day for the first week, followed by once per week after. Depletion was assessed 1 day after the fourth administration of antibodies by flow cytometric analysis of spleen cells stained with 2.43, GK1.5, or PK136 to confirm the depletion of CD8, CD4, or natural killer (NK) cells. Depletion was maintained by weekly antibody injections for the duration of the tumor growth follow-up.

Intracellular cytokine staining and flow cytometry analysis for immunohistoassay

After chemotherapy, cells were harvested from the peritoneal lavage of tumor-bearing mice. Analysis of tumor-infiltrating lymphocytes (TIL) was conducted on the R HM-1 tumors extracted from mice treated with DD, MTD, or control PBS. R HM-1 tumors were dissected, weighed, chopped into small pieces, and washed with HBSS. Tissues were incubated with a mixture of enzymes [collagenase type I (Gibco), collagenase type IV (Gibco), hyaluronidase (Sigma), and DNase I (Sigma)] in HBSS for 15 minutes at 37°C. After enzyme digestion, dissociated single cells were harvested and cultured in 24-well plates coated with monoclonal antibody OKT3 for 18 hours. For antigen stimulation, isolated cells (5 × 10⁶) from each group were harvested and cultured in vitro with 2 × 10⁵ live HM-1 or ID8 cells in culture medium containing IL-2 (100 U/mL) for 1 day. They were then cultured in medium added with 2 μg Golgistop (BD Pharmingen) for another 18 hours. Cells were then washed once in FACSBinding buffer and stained with allophycocyanin (APC)-conjugated monoclonal rat anti–mouse CD8a (1:100; eBioscience) for 20 minutes, and fixed using the Cytofix/Cytoperm kit in accordance to manufacturer's instructions (BD Pharmingen), followed by staining with fluorescein isothiocyanate (FITC)-conjugated rat anti–mouse IFN-γ (1:50; eBioscience) for 20 minutes. Flow cytometric analysis was conducted on a Becton Dickinson FACS can (BD FACSCalibur). Each group was measured in triplicate.

Peritoneal lavage and cytokine assays

The peritoneal cavity of experimental and control R ID8 tumor–bearing mice was lavaged with HBSS to obtain cells. The washout was passed through a 35-μm nylon mesh and collected. After red blood cell (RBC) lysis and repeated washes, cells were processed for in vitro culture and stimulation for further intracellular cytokine staining and flow cytometric
analysis as previously mentioned. In addition, CD8+ cells were isolated from pelleted cells using beads coated with CD8 antibody (MACs, MiltenyiBiotec). Isolated CD8+ cells were subjected to RNA extraction then quantitative real-time PCR (qRT-PCR) for the expression profiling of IFN-γ and IL-2. Human serum IFN-γ and IL-2 were quantified using multiplex bead-based assays (BD Cytometric Bead Array) and then analyzed by flow cytometry in accordance with manufacturer’s protocol. Blood samples from patients were obtained before treatment, 1 month after the initiation of treatment, and 2 months after the initiation of treatment. Patient enrollment was limited to those with platinum-resistant ovarian cancer recurrence who will receive weekly carboplatin (AUC 2) and paclitaxel (80 mg/m2) as the third- or fourth-line treatment.

**Macrophage inhibition**

Cisplatin-resistant (R HM-1) cells (1×10^6) were s.c. injected into female (C57BL/6 C3H/He) F1 mice on day 0 (5 in each group). On day 4, mice began DD regimen [seven 3-day cycles of paclitaxel (5 mg/kg) plus cisplatin (3 mg/kg)]. The control group mice were treated by PBS. Macrophage inhibitor, clodronate liposome (Encapsula NanoScience), and control liposome were i.p. administered since day 1 (1.5 mg/mice at 5-day intervals).

**Blood component analysis in mice receiving chemotherapy**

Female (C57BL/6 C3H/He) F1 mice were treated with different formats of chemotherapy. Blood from the tail vein was collected in heparinized tube. Component cells were separated by centrifugation (1,000 g, 5 minutes) and stained with antibodies: FITC-conjugated rat anti–mouse CD3 (AbD serotec, MCA 500F, 1:20), phycoerythrin (PE)-conjugated rat anti–mouse CD4 (BD,553730, 1:200), APC-conjugated rat anti–mouse CD8a (eBioscience, 17-0081, 1:100), PE-Cy7-conjugated rat anti–mouse NK.1 (eBioscience, 25-5941, 1:50), FITC-conjugated rat anti–mouse CD11b (eBioscience,12-0114, 1:100), PE-conjugated rat anti–mouse CD11c (eBioscience, 12-0114, 1:50), APC-conjugated rat anti–mouse F4/80 (eBioscience, 17-4801, 1:50), and APC-conjugated rat anti–mouse Gr-1 (eBioscience, 17-5931, 1:100). The hematologic components were analyzed by flow cytometry.

**Statistical analysis**

All data expressed as means ± SE are representative of at least 2 different experiments. Comparisons between individual data points were made using the Student t test or ANOVA.

**Results**

**DD chemotherapy was more effective in controlling platinum-resistant HM-1 tumor**

Tumor-bearing mice treated by DD regimen received 7 cycles (3-day intervals) of paclitaxel (5 mg/kg) and cisplatin (3 mg/kg). Mice treated by MTD regimen received 3 courses (10-day interval) of higher dosages of paclitaxel (12 mg/kg) and cisplatin (7 mg/kg) by i.p. injection. The control group received PBS. MTD chemotherapy did not significantly reduce the size of R HM-1 tumor, unlike DD chemotherapy (P=0.017, control vs. DD; Fig. 1A). The R HM-1 tumor was chemosensitive when low-dose cisplatin and paclitaxel were administered by DD protocol. DD efficacy was also better than MTD, even using treatment with single-agent cisplatin or paclitaxel (P=0.0003, DD vs. MTD cisplatin; P=0.002, DD vs. MTD paclitaxel;
Supplementary Fig. S1). This suggests the therapeutic effect is not dose-dependent and might involve another mechanism that we theorize to be immunologic.

**Therapeutic effect of DD chemotherapy against platinum-resistant tumor is immune-dependent**

DD chemotherapy did not produce the same therapeutic effect in immunodeficient tumor-bearing mice (Fig. 1B). The immune profile (CD8⁺, CD4⁺, NK, CD11b⁺, CD11c⁺, and F4/80⁺ cells) of mice following treatment showed that the MTD regimen was toxic to all the immune cells of interest, whereas DD regimen preserved CD8⁺, CD4⁺, and CD11b⁺ cells with minimal reduction of NK, CD11c⁺, and F4/80⁺ cell count (P < 0.0001, P < 0.001, and P < 0.001, respectively; Fig. 2A).

**DD chemotherapy preferentially decreased myeloid-derived suppressor cells**

DD chemotherapy significantly reduced the number of myeloid-derived suppressor cells (MDSC) found in tumor-bearing mice, whereas the same phenomenon was not observed in the control and MTD groups (P < 0.0001, DD vs. control; P < 0.001, DD vs. MTD; Fig. 2B). Selective cytotoxicity toward immunosuppressive MDSCs is important for overcoming cancer immune tolerance, as MDSCs mediate T-cell anergy and promote the development of regulatory T (Treg) cells that inhibit effective antitumor immune response (10, 11). Other treatments found to preferentially reduce MDSCs have also documented a corresponding boost in the response of T cells and number of TILs with associated therapeutic response (12–14).

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**Figure 2.** MTD chemotherapy caused significant myelosuppression, whereas DD chemotherapy preserved the major immune cells and decreased MDSCs. A, female (C57BL/6 C3H/He) F1 mice (without tumor) were treated with different formats of chemotherapy. MTD chemotherapy–treated mice were severely depleted of CD8⁺, CD4⁺, NK, CD11b⁺, CD11c⁺, and F4/80 cells. Conversely, DD chemotherapy preserved the numbers of CD8⁺, CD4⁺, and CD11b⁺ cells.

The suppression of NK, CD11c⁺, and F4/80 cells by DD chemotherapy is much less than that by MTD chemotherapy (***, P < 0.0001; **, P < 0.001; and *, P < 0.005, respectively). B, female (C57BL/6 C3H/He) F1 mice (with or without R HM-1 tumor) were treated with different formats of chemotherapy. In tumor-free mice, the different treatments did not significantly change the numbers of MDSCs. In R HM-1 tumor–bearing mice, DD chemotherapy drastically reduced the number of MDSCs in comparison to the control and MTD groups (**, P < 0.0001, control vs. DD; **, P < 0.001, DD vs. MTD; C, DD and MTD regimen similarly reduced the number of Treg cells in tumor-bearing mice (percentage of CD4⁺CD25⁺ cells, P = 0.048, control vs. DD). #, P < 0.05.

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Ideally, cancer treatment should also be able to interfere with Treg function or quantity. The primary function of Treg is to maintain peripheral tolerance by suppressing self-reactive T cells that have escaped the primary lymph node; however, the prevention of autoimmunity also contributes to cancer immune tolerance (15). In mouse tumor models, the reduction of Treg cells with low-dose cyclophosphamide was able to recover the antitumor effects induced by immunotherapy (16–18). While the present study did not find DD regimen to be more effective than MTD regimen at reducing the percentage of CD4⁺CD25⁺ Treg cells (P = 0.85; Fig. 2C), both regimens led to the decline of Treg count (P = 0.048, control vs. DD; Fig. 2C). From this, we believe cisplatin and paclitaxel to have an intrinsic, dose-independent drug effect that is selectively cytotoxic to Treg cells.

**Therapeutic effect of DD chemotherapy is associated with tumor macrophage recruitment**

DD chemotherapy increased the recruitment of F4/80⁺ macrophages into the tumor. Representative flow cytometric data of tumor-bearing mice treated with DD regimen showed greater numbers of intratumoral F4/80⁺ cells than mice treated with MTD regimen (P < 0.001, control vs. DD, control vs. MTD; Fig. 3A).

The association of tumor macrophage recruitment with antitumor effect was investigated with the administration of macrophage inhibitor, clodronate liposome. The tumor growth curve showed that clodronate liposome partially abolished the antitumor effect of DD chemotherapy, whereas the same was not observed in the control group that only received the vehicle (liposome: P = 0.01, clodronate liposome vs. liposome only; Fig. 3B). We believe the recruitment of macrophages to the tumor is a component of treatment efficacy.

**DD chemotherapy promotes tumor-specific CD8⁺ T lymphocytes responsible for therapeutic effect against platinum-resistant tumor**

To delineate the effector cell types responsible for the antitumor effect of a treatment, selective depletion of lymphocyte subpopulations was achieved by injecting monoclonal antibodies against CD8, CD4, or NK1.1 in R HM-1 tumor-bearing mice. Tumor growth curve indicated the antitumor effect of DD regimen was most dependent on CD8⁺ T cells.
DD therapeutic effect on drug-resistant tumor is immune dependent and mediated by CD8+ effector cells. A, the use of neutralizing antibodies for depletion of lymphocyte subpopulations revealed that CD8+ T cells are essential for tumor eradication. R HM-1 cells (1 × 106) were injected s.c. into female (C57BL/6, C3H/He) F1 mice (5 in each group, day 0). Neutralizing antibodies were given i.p. (100 μg/mice/d initiated on D1, given every other day for 2 weeks, then 200 μg/mice/d every week). On day 4, mice began DD format chemotherapy. Control group mice were treated with PBS. Tumor growth curve shows that antitumor effect was abolished when CD8+ cells were depleted by anti-CD8 antibody (**, P < 0.001, anti-CD8 vs. rat IgG), whereas the anti-CD4 and anti-NK antibodies did not affect tumor growth. B, in the absence of CD8+ T lymphocytes, MTD shows moderately more therapeutic effect than DD. R HM-1 cells (1 × 106) were injected s.c. into female (C57BL/6, C3H/He) F1 mice (5 in each group, day 0). Neutralizing antibodies were given i.p. (100 μg/mice/d initiated on D1, given every other day for 2 weeks, then 200 μg/mice/d every week). Lymphocyte depletion assay failed to identify a specific population of effectors cells that is associated with antitumor effects of MTD chemotherapy for R HM-1 tumor. C, in tumor-bearing mice, DD chemotherapy elicited antitumor CD8+ IFN-γ− T lymphotic reaction. Mice bearing R HM-1 tumor were treated with different formats of chemotherapies. After treatment, spleens were obtained, and the single-cell splenocyte suspension was prepared by tissue dissociation and enzyme digestion. Cells were then stained with anti–mouse CD8 and anti–mouse IFN-γ antibodies before getting analyzed by flow cytometry. Representative flow cytometric data show that CD8+ IFN-γ− cells were found in greater numbers in the mice receiving DD chemotherapy (**, P < 0.001, DD vs. control and MTD). D, representative flow cytometric data show that more tumor-infiltrating CD8+ IFN-γ− T lymphocytes were also induced in mice treated by DD (**, P < 0.001, DD vs. control and MTD).

DD regimen results were validated in another intraperitoneal ovarian tumor model

We conducted the same experiments in the ID8 tumor model. ID8 is another aggressive mouse ovarian cancer cell line that is derived from the MOSEC cell line (19). In this platinum-resistant tumor model, DD regimen was again more effective than MTD regimen (P = 0.022, DD vs. MTD; Supplementary Fig. S2). Akin to the R HM-1 tumor model experiments, DD regimen induced the recruitment of CD14+/F4/80+ macrophages into the peritoneal cavity of ID8 tumor–bearing mice (P < 0.001, control vs. DD; P < 0.01, DD vs. MTD; Fig. 5A). DD treatment of tumor-naïve mice had no macrophage recruitment to the abdominal cavity (Fig. 5B). Flow cytometric analysis found a high proportion of activated IFN-γ−-secreting macrophages following DD

(P < 0.001, anti-CD8 vs. rat IgG; Fig. 4A), whereas the antitumor effect of MTD regimen did not seem to be associated with any of the monitored immune cells (Fig. 4B). Subsequently, we found DD chemotherapy-induced tumor-specific immune responses. Flow cytometric analysis of the splenocytes identified CD8+ IFN-γ+ T cells in mice that received DD treatment (P < 0.001, DD vs. control and MTD; Fig. 4C). Moreover, the percentage of tumor-infiltrating CD8+ IFN-γ+ T cells was highest in mice treated with DD chemotherapy than in those treated with MTD or control (P < 0.001, DD vs. control and MTD). The R HM-1 tumor model experiments have shown that DD regimen with cisplatin and paclitaxel promotes tumor macrophage recruitment, reduces immunosuppression of the tumor microenvironment, and elicits tumor-specific antitumor CD8+ T-cell responses.
tumor-bearing mice, DD chemotherapy elicited CD8+ TILs inside the peritoneal cavity of tumor-bearing mice. A, in this i.p. tumor model, DD chemotherapy elicited and recruited largest number of CD14-F4/80+ macrophages inside the peritoneal cavity of R ID8 tumor-bearing mice (**, P < 0.001, control vs. DD; *, P < 0.01, DD vs. MTD). B, the proportion of macrophage did not change in tumor-naïve mice regardless of chemotherapy. C, flow cytometric analysis indicated more activated macrophages, as determined by IFN-γ secretion, after DD chemotherapy. Following treatment, cells from the peritoneal lavage of R ID8 tumor-bearing mice were cultured in medium with protein transporter inhibitor BD GolgiPlug. Cells were stained with anti–mouse IFN-γ FITC antibodies before analysis by flow cytometry. Representative data show the number of F4/80+ IFN-γ+ cells increased in mice receiving DD chemotherapy but not in the mice receiving MTD and PBS (control; 8.16% in DD vs. 2.11% in MTD and 2.31% in control, both; *P < 0.001). D, in ID8 tumor-bearing mice, DD chemotherapy elicited CD8+ IFN-γ+ TILs. Mice bearing R ID8 tumor were treated with different formats of chemotherapies. After treatment, peritoneal cells were obtained by lavage and prepared for single-cell suspension. Cells were then stained with anti–mouse CD8 and anti–mouse IFN-γ antibodies before getting analyzed by flow cytometry. Representative flow cytometric data show that peritoneal CD8+ IFN-γ+ cells were found in greater numbers within the tumors of mice receiving DD chemotherapy (**, P < 0.001, control vs. DD and DD vs. MTD). E, CD8+ T cells from peritoneal lavage in mice treated with different formats of chemotherapies were isolated and examined for the expression of IFN-γ and IL-2 by QPCR. A significant enhancement in the expressions of IFN-γ and IL-2 was noted in the peritoneal CD8+ cells in DD group mice (IFN-γ; *, P < 0.01, control vs. DD, DD vs. MTD, IL-2; **, P < 0.01, control vs. DD; #, P = 0.034, DD vs. MTD).

Figure 5. DD chemotherapy elicited the greatest number of IFN-γ-secreting CD14-F4/80+ macrophage and subsequent CD8+ IFN-γ+ TILs inside the peritoneal cavity of tumor-bearing mice. A, in this i.p. tumor model, DD chemotherapy elicited and recruited largest number of CD14-F4/80+ macrophages inside the peritoneal cavity of R ID8 tumor–bearing mice (**, P < 0.001, control vs. DD; *, P < 0.01, DD vs. MTD), B, the proportion of macrophage did not change in tumor-naïve mice regardless of chemotherapy. C, flow cytometric analysis indicated more activated macrophages, as determined by IFN-γ secretion, after DD chemotherapy. Following treatment, cells from the peritoneal lavage of R ID8 tumor–bearing mice were cultured in medium with protein transporter inhibitor BD GolgiPlug. Cells were stained with anti–mouse IFN-γ FITC antibodies before analysis by flow cytometry. Representative data show the number of F4/80+ IFN-γ+ cells increased in mice receiving DD chemotherapy but not in the mice receiving MTD and PBS (control; 8.16% in DD vs. 2.11% in MTD and 2.31% in control, both; **, P < 0.001). D, in ID8 tumor–bearing mice, DD chemotherapy elicited CD8+ IFN-γ+ TILs. Mice bearing R ID8 tumor were treated with different formats of chemotherapies. After treatment, peritoneal cells were obtained by lavage and prepared for single-cell suspension. Cells were then stained with anti–mouse CD8 and anti–mouse IFN-γ antibodies before getting analyzed by flow cytometry. Representative flow cytometric data show that peritoneal CD8+ IFN-γ+ cells were found in greater numbers within the tumors of mice receiving DD chemotherapy (**, P < 0.001, control vs. DD and DD vs. MTD). E, CD8+ T cells from peritoneal lavage in mice treated with different formats of chemotherapies were isolated and examined for the expression of IFN-γ and IL-2 by QPCR. A significant enhancement in the expressions of IFN-γ and IL-2 was noted in the peritoneal CD8+ cells in DD group mice (IFN-γ; *, P < 0.01, control vs. DD, DD vs. MTD, IL-2; **, P < 0.01, control vs. DD; #, P = 0.034, DD vs. MTD).

treatment, whereas MTD chemotherapy and PBS (control) did not produce the same results (8.16% vs. 2.11% and 2.31%, both P < 0.0001; Fig. 5C). Higher numbers of activated CD8+ T cells were purified from the peritoneal lavage of mice given DD chemotherapy (P < 0.001, control vs. DD and DD vs. MTD; Fig. 5D). Following DD treatment, CD8+ T cell from the peritoneal lavage of tumor-bearing mice again had higher levels of IFN-γ and IL-2 (IFN-γ; P < 0.01, control vs. DD, DD vs. MTD; IL-2, P < 0.01, control vs. DD, P = 0.034, DD vs. MTD; Fig. 5E). The expression of IFN-γ and IL-2 is known to accompany the activation of cytotoxic T cells. DD chemotherapy is more effective than MTD chemotherapy in the treatment of multiple tumor models.

Change in cytokine profile was correlated with the therapeutic effects of DD chemotherapy in ovarian cancer patients

The DD regimen results were validated in patients with relapse of platinum-resistant ovarian cancer. Following Institutional Review Board (IRB) approval (Protocol number: 09MMHIS095), 14 patients were recruited and treated by DD regimen with weekly carboplatin (AUC 2) and paclitaxel...
Patients who responded to DD chemotherapy had higher serum levels of IFN-γ and IL-2. Fourteen patients with platinum-resistant recurrence of ovarian cancer received DD chemotherapy with weekly carboplatin (AUC 2) plus paclitaxel (80 mg/m²) as their third or fourth line of treatment. Their serum levels of IFN-γ were measured before treatment (PreDD), 1 month after (DD1), and 2 months after (DD2) the start of DD chemotherapy. Of the four patients whose disease was controlled, 3 had higher serum levels of IFN-γ and IL-2 (red), whereas patients with no response had low or undetectable levels of IFN-γ or IL-2 (black; DD2 for IFN-γ, **P < 0.001, responsive vs. unresponsive; DD1 and DD2 for IL-2, *P < 0.001, responsive vs. unresponsive). The drug-induced immunogenic apoptosis of human ovarian cancer cells produce unique signals that promote dendritic cell maturation, enhance cross-presentation of tumor antigens, and enable T-cell priming that lead to tumor-specific CD8⁺ T cells to accompany IFN-γ and IL-2 elevation. We tested and confirmed higher serum levels of these cytokines in 3 of 4 patients whose disease was controlled. While the statistical power of the patient study is challenged by the small sample size, the results are promising enough that the regimen should be investigated in a larger clinical study. We believe that disease control in patients is related to the antitumor immunity that is produced as a consequence of DD treatment. The results of the present study suggest that antitumor effect of DD regimen is potentiated by tumor-specific immune response, and ergo, is more effective against drug-resistant disease. Furthermore, the gentler nature of low-dose dose dense regimen makes it ideal for maintenance therapy following the initial marrow-depriving MTD treatment.

**Discussion**

Phase I trials of new chemotherapeutic drugs typically focus on the identification of the MTD due to the assumption that it leads to the greatest antitumor cytotoxicity and effectiveness. Consequently, studies have neglected to investigate the possible advantages of low-dose chemotherapy. The data of the present study strongly imply that DD administration of low-dose platinum agent and paclitaxel spares the immune system from major toxicity and modifies the tumor microenvironment in favor of immunogenic tumor cell death, which results in the generation of antitumor immunity. This treatment modality leads to tumor macrophage recruitment, production of tumor-specific CD8⁺ T cells, and the selective reduction of immunosuppressive MDSCs and Treg cells of the tumor microenvironment. These immunologic changes are associated with the therapeutic response in tumor-bearing mice. It has been theorized that the combined effort of chemotherapy and host immunity results in the best management of persistent malignancies (20). The probability for success may depend on whether or not the drug-induced tumor cell death triggers the mechanisms that promote the development of tumor-specific immune response (21, 22).

The drug-induced immunogenic apoptosis of human ovarian cancer cells produce unique signals that promote dendritic cell maturation, enhance cross-presentation of tumor antigens, and enable T-cell priming that lead to tumor-specific CD8⁺ T cells to accompany IFN-γ and IL-2 elevation. We tested and confirmed higher serum levels of these cytokines in 3 of 4 patients whose disease was controlled. While the statistical power of the patient study is challenged by the small sample size, the results are promising enough that the regimen should be investigated in a larger clinical study. We believe that disease control in patients is related to the antitumor immunity that is produced as a consequence of DD treatment. The results of the present study suggest that antitumor effect of DD regimen is potentiated by tumor-specific immune response, and ergo, is more effective against drug-resistant disease. Furthermore, the gentler nature of low-dose dose dense regimen makes it ideal for maintenance therapy following the initial marrow-depriving MTD treatment.

**Disclosure of Potential Conflicts of Interest**

No potential conflicts of interest were disclosed.

**Authors’ Contributions**

- **Conception and design:** C.-L. Chang, C.-F. Hung
- **Development of methodology:** C.-L. Chang, C.-F. Hung
- **Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.):** C.-L. Chang, Y.-T. Hsu, C.-C. Wu, Y.-Z. Lai, C.-F. Hung
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Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): C. Wang, Y.-C. Yang, C.-F. Hung
Study supervision: Y.-C. Yang, C.-F. Hung

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