Cancer Therapy: Preclinical

Clinical Cancer Research

In Vitro and *In Vivo* Antitumor Activity of a Novel Alkylating Agent, Melphalan-Flufenamide, against Multiple Myeloma Cells

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Abstract

Purpose: The alkylating agent melphalan prolongs survival in patients with multiple myeloma; however, it is associated with toxicities and development of drug-resistance. Here, we evaluated the efficacy of melphalan-flufenamide (mel-flufen), a novel dipeptide prodrug of melphalan in multiple myeloma.

Experimental Design: Multiple myeloma cell lines, primary patient cells, and the human multiple myeloma xenograft animal model were used to study the antitumor activity of mel-flufen.

Results: Low doses of mel-flufen trigger more rapid and higher intracellular concentrations of melphalan in multiple myeloma cells than are achievable by free melphalan. Cytotoxicity analysis showed significantly lower IC_{50} of mel-flufen than melphalan in multiple myeloma cells. Importantly, mel-flufen induces apoptosis even in melphalan- and bortezomib-resistant multiple myeloma cells. Mechanistic studies show that siRNA knockdown of aminopeptidase N, a key enzyme mediating intracellular conversion of mel-flufen to melphalan, attenuates anti–multiple myeloma activity of mel-flufen. Furthermore, mel-flufen–induced apoptosis was associated with: (i) activation of caspases and PARP cleavage; (ii) reactive oxygen species generation; (iii) mitochondrial dysfunction and release of cytochrome c; and (iv) induction of DNA damage. Moreover, mel-flufen inhibits multiple myeloma cell migration and tumor-associated angiogenesis. Human multiple myeloma xenograft studies showed a more potent inhibition of tumor growth in mice treated with mel-flufen than mice receiving equimolar doses of melphalan. Finally, combining mel-flufen with lenalidomide, bortezomib, or dexamethasone triggers synergistic anti–multiple myeloma activity.

Conclusion: Our preclinical study supports clinical evaluation of mel-flufen to enhance therapeutic potential of melphalan, overcome drug-resistance, and improve multiple myeloma patient outcome. *Clin Cancer Res; 19(11); 3019–31. ©2013 AACR.*

Introduction

Multiple myeloma remains incurable due to the development of a drug-resistant phenotype after prolonged therapy (1, 2). For many years, combined melphalan (mustard-L-phenylalanine) and prednisone has been a mainstay of multiple myeloma treatment in the nontransplant candidates. In transplant candidates, a treatment regimen comprising a high-dose melphalan (HDM) in conjunction with autologous stem cell transplantation (ASCT) has improved progression-free and overall survival in patients with multiple myeloma (3–5). More recent studies have combined melphalan and steroids with several novel agents such as bortezomib, thalidomide, or lenalidomide, as initial therapy of elderly newly diagnosed patients and have improved response extent and frequency, as well as prolonged progression free an overall survival (6–12). In a parallel fashion, integration of these novel therapies into the transplant paradigm as induction, consolidation, and maintenance has further improved outcome in this setting (13, 14). These studies exemplify the use of melphalan in the current multiple myeloma therapy, and provided impetus for the development of melphalan prodrug to increase tumor specificity, reduce toxicity, and prevent drug-resistance.

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Note: Supplementary data for this article are available at Clinical Cancer Research Online (http://clincancerres.aacrjournals.org/).

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doi: 10.1158/1078-0432.CCR-12-3752

Translational Relevance

The alkylating agent melphalan is actively used in multiple myeloma therapy; however, dose-limiting toxicities and development of resistance limits its use. Recent studies have focused on developing a prodrug to enhance the therapeutic potential of melphalan. Melphalan-flufenamide (mel-flufen) is an enzyme-activated prodrug of melphalan which allows for a more rapid and higher intracellular accumulation of melphalan in tumor cells than is achievable by direct exposure to equimolar doses of melphalan. Mel-flufen is undergoing evaluation in phase I/IIa clinical trials in solid tumors. Here, we used both *in vitro* and *in vivo* multiple myeloma xenograft models to show that mel-flufen is a more potent anti–multiple myeloma agent than melphalan, which can overcome conventional drug resistance. Moreover, the combination of mel-flufen with bortezomib, lenalidomide, or dexamethasone induces synergistic anti–multiple myeloma activity. Our preclinical data therefore provide the framework for clinical evaluation of mel-flufen, either alone or in combination, to improve patient outcome in multiple myeloma.

Pharmacologic screening of alkylating oligopeptides led to the identification of a novel melphalan-containing prodrug melphalan-flufenamide (mel-flufen; L-melphalanyl-*p*-L-fluoro phenylalanine ethyl ester), a molecular entity with a more potent antitumor activity than parental drug melphalan despite identical alkylating capacity (Fig. 1A; refs. 15–17). Mel-flufen is rapidly incorporated into the tumor cells, followed by intracellular hydrolysis, which in part is mediated by aminopeptidase N (ANPEP), an enzyme overexpressed in several tumor cell malignancies (18). Studies using solid tumor cell models showed that treatment with mel-flufen causes at least a 10-fold higher loading of melphalan, which explain its higher tumor cell cytotoxicity (15–17, 19). To date, the mel-flufen activity against multiple myeloma cells is undefined. In the present study, we examined the antitumor activity of mel-flufen in multiple myeloma cells using both *in vitro* and *in vivo* model systems. Our studies show that mel-flufen is more potent than melphalan and can overcome resistance not only to melphalan, but also to novel agents, providing the rationale for its clinical evaluation to improve patient outcome in multiple myeloma.

Materials and Methods

Cell culture and reagents

Multiple myeloma cell lines including MM.1S (dexamethasone-sensitive), MM.1R (dexamethasone-resistant), RPMI-8226, LR-5 (melphalan-resistant derivative of RPMI-8226), KMS-12BM, and INA-6 [interleukin (IL)-6 dependent] were cultured with RPMI-1640 medium supplemented with 10% FBS, 2 mmol/L L-glutamine, 100 U/mL penicillin, and 100 μg/mL streptomycin. ANBL-6-bortezomib–sensitive (ANBL-6.WT) and -resistant (ANBL-6.BR) were kindly provided by Dr. Robert Orlowski (MD Anderson Cancer Center, Houston, TX). Tumor cells from patients with multiple myeloma were purified (>95% purity) by $CD138^+$ selection using the Auto MACS magnetic cell sorter (Miltenyi Biotec Inc.). Informed consent was obtained from all patients in accordance with the Helsinki protocol. Peripheral blood mononuclear cells (PBMC) from healthy donors were maintained in culture medium, as earlier. Mel-flufen was obtained from Oncopeptides AB. Melphalan was purchased from Sigma Chemical Company and Apoteket AB (Alkeran; Apoteket AB); bortezomib and lenalidomide were purchased from Selleck Chemicals LLC; and dexamethasone was obtained from Calbiochem.

Measurement of intracellular concentrations of mel-flufen and melphalan

The intracellular concentration of melphalan in RPMI-8226 cells was assessed at various time points after treatment with freshly made solutions of mel-flufen or melphalan. For each treatment series, RPMI-8226 cells were resuspended at a concentration of 2.5×10^6 cells/mL in a total volume of 6 mL of complete prewarmed RPMI media, and 1 mL sample was removed at 0, 5, 15, 30, 60, or 120 minutes after addition of each drug. The 1 mL sample was added to 4 mL of precooled PBS and centrifuged for 5 minutes at 1,000 rpm; the resulting cell pellet was washed in 5 mL of precooled PBS and solubilized by adding 50 μL of ethanol/acetonitrile (1:1, v/v). The resulting precipitated cell debris was cleared by centrifugation at 10,000 rpm for 5 minutes and the supernatant was collected and frozen at −80°C until further analyses. The intracellular amount of mel-flufen or melphalan was measured in a aliquot of 25 μL of the sample, which was mixed with 75 μL of an internal standard solution consisting of 1 μg/mL of fluorescein diluted in 1:1 (acetonitrile:ethanol), centrifuged for 4 minutes at 3,700 rpm (Heraeus Biofuge 13). Supernatant was transferred to 200 μL high-performance liquid chromatography (HPLC) vials and then analyzed for mel-flufen or melphalan content by liquid chromatography/mass spectrometry (LC/MS; SIM of 498 Da for mel-flufen, 305 Da for melphalan, and 333 Da for the fluorescein standard). The above analyses were conducted at OncoTargeting AB. The mean ± SEM of peak area of mel-flufen and melphalan at each time point was calculated. The area under the curve for 0 to 120 minutes of melphalan [area under curve (AUC) 0–120 minutes] was determined for each treatment and is shown relative to AUC 0 to 120 minutes of 0.5 μmol/L of mel-flufen.

Cell viability, proliferation, and apoptosis assays

Cell viability was assessed by using colorimetric assay with MTT (Calbiochem), and cell proliferation analysis in coculture experiments with patient-derived bone marrow stromal cells (BMSC) was conducted using thymidine

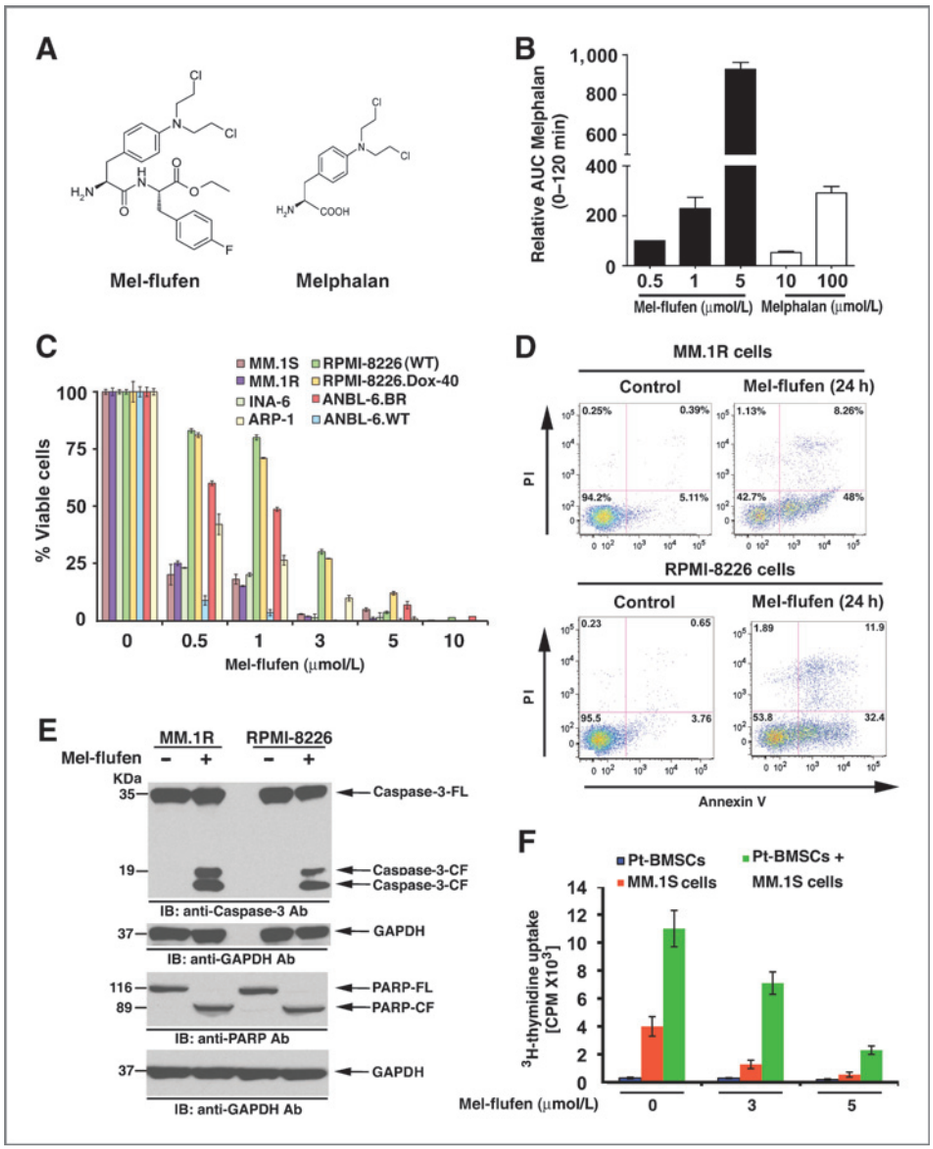


Figure 1. A, chemical structures of the melphalan-containing dipeptide mel-flufen and melphalan. B, RPMI-8226 cells were treated with indicated concentrations of either mel-flufen or melphalan; samples were harvested at 0, 5, 15, 30, 60, and 120 minutes, followed by analysis for intracellular accumulation of melphalan using LC/MS. The peak area of mel-flufen and melphalan was analyzed at each time point after normalization of signal intensity in each sample using the internal fluorescein standard. AUC 0 to 120 minutes was calculated from the individual samples. The values are given relative to AUC for Mel-flufen 0.5 μmol/L mean value. Data presented are mean ± SEM ($n = 3$). C, multiple myeloma cell lines were treated with indicated doses of mel-flufen for 24 hours, and cytotoxicity was assessed using MTT assay ($n = 3$; mean ± SD; $P < 0.005$ for all cell lines). D, MM.1R and RPMI-8226 cells were treated with mel-flufen (2 μmol/L) for 24 hours and analyzed for apoptosis by AnnexinV/PI staining assay ($n = 2$; mean ± SD; $P < 0.001$). E, MM.1R and RPMI-8226 multiple myeloma cells were treated with mel-flufen (1 and 3 μmol/L, respectively) for 24 hours; protein lysates were subjected to immunoblotting using indicated antibodies. F, MM.1S cells were treated with mel-flufen in the presence or absence of BMSCs for 24 hours, and DNA synthesis was measured by ^{3}H-TdR uptake (mean ± SD of triplicate cultures; $P < 0.002$ for all samples).

incorporation, as described previously (20). Apoptosis was quantified using Annexin V–FITC/propidium (PI) iodide apoptosis detection kit, as per manufacturer's instructions (BD Biosciences), followed by an analysis on FACS Calibur (BD Biosciences).

Aminopeptidase N activity assay

Enzymatic activity of ANPEP was measured with the substrate L-alanine-4-nitro-anilide (Sigma–Aldrich) as previously described (21).

Immunoblotting

Western blot analysis was conducted as previously described (22) using antibodies recognizing full length and cleaved forms of caspase-3, -7, -8, -9, and PARP (Cell signaling), as well as p53, γ-H2AX, ANPEP, and glyceraldehyde-3-phosphate dehydrogenase (GAPDH; Abcam).

Transient transfection assays

MM.1S cells were transiently transfected with genome control (scrambled) siRNA or siRNA against ANPEP (Smart pool siRNA; Dharmacon, Inc.) using Nucleofector Kit V, according to manufacturer's instructions (Amaxa Biosystems).

Human plasmacytoma xenograft model

All animal studies were approved by the Dana-Farber Cancer Institute (DFCI) Institutional Animal Care and Use Committee. The xenograft tumor model was conducted as previously described (23, 24). CB-17 severe combined immunodeficient (SCID) mice were subcutaneously inoculated with 6.0×10^6 MM.1S cells in 100 μL of serum-free RPMI-1640 medium, and then randomized to treatment groups when tumors reached approximately 100 mm^3. Mice were treated intravenously with vehicle, mel-flufen,

or melphalan with indicated concentrations and treatment duration times. Animals were euthanized when their tumors reached 2 cm^3.

In vitro migration and capillary-like tube structure formation assays

Transwell Insert Assays (Chemicon) were used to measure migration, and *in vitro* angiogenesis was assessed by Matrigel capillary-like tube structure formation assay, as previously described (25). For endothelial tube formation assay, human vascular endothelial cells (HUVEC) were obtained from Clonetics and maintained in endothelial cell growth medium-2 (EGM2 MV SingleQuots; Clonetics) containing 5% FBS.

Statistical analysis

Statistical significance of differences observed in drug-treated versus control cultures was determined by using the Student *t* test. The minimal level of significance was $P < 0.05$. Tumor volume and survival in mice was measured using the GraphPad PRISM (GraphPad Software/version 5). Isobologram analysis (26) was conducted using "CalcuSyn" software program (Biosoft). Combination index (CI) values of less than 1.0 indicate synergism and values more than 1.0 indicate antagonism.

Results and Discussion

Mel-flufen delivers high intracellular concentration of melphalan

RPMI-8226 multiple myeloma cells were treated with either mel-flufen (0.5, 1, or 5 μmol/L) or melphalan (10 or 100 μmol/L) and the intracellular content of mel-flufen or melphalan was measured using HPLC/MS. AUC 0 to 120 minutes was calculated from melphalan peak area curves in each sample and relative AUC is shown in Fig. 1B. Treatment of RPMI-8226 cells with mel-flufen led to high intracellular concentration of free melphalan as compared with cells exposed directly to melphalan (Fig. 1B). A high concentration was reached as early as after 15 minutes (data not shown). Importantly, treatment of RPMI-8226 cells with 5 μmol/L of mel-flufen load the cells with much more melphalan than can be achieved using even 100 μmol/L of melphalan (Fig. 1B). These data suggest that mel-flufen allows for a more rapid and higher intracellular accumulation of melphalan in multiple myeloma cells than is achievable by direct exposure to equimolar doses of melphalan. Our results using multiple myeloma cells are consistent with similar observation in other cancer cell lines (19). Previous studies showed that lipophilicity and an early intracellular hydrolysis of mel-flufen by peptidases inside the cells to release melphalan contributes to achieving rapid and high intracellular concentrations of melphalan (19, 27, 28). Earlier findings also showed that in tumor cells a limited exposure time, which simulate short half-life *in vivo*, proved more favorable for mel-flufen than for melphalan indicating a trapping mechanism through the enzymatic activation (29). Together, these results suggest that mel-flufen administration in patients with multiple myeloma is a more efficient therapeutic strategy for delivering higher concentrations of intracellular melphalan than by directly exposing cells to free melphalan.

Anti–multiple myeloma activity of mel-flufen *in vitro*

Human multiple myeloma cell lines (MM.1S, INA-6, RPMI-8226, MM.1R, Dox-40, ARP-1, and ANBL-6) were treated with various concentrations of mel-flufen for 24 hours, followed by assessment of cell viability using MTT assays. A significant concentration-dependent decrease in viability of all cell lines was observed in response to mel-flufen treatment (Fig. 1C). The cytotoxicity of mel-flufen was observed in multiple myeloma cell lines sensitive and resistant to conventional and novel therapies, as well as representing distinct cytogenetic profiles. For example, we examined isogenic cell lines dexamethasone-sensitive MM.1S and dexamethasone-resistant MM.1R with t(14;16) translocation and c-maf overexpression; RPMI-8266 with TP53, K-Ras, and EGF receptor (EGFR) mutations; and INA-6, an IL-6–dependent cell line with N-Ras activating mutation. The variable IC_{50} of mel-flufen observed against multiple myeloma cell lines may be attributed to their distinct genetic background and/or drug-resistance characteristics (30–33).

We next examined whether anti–multiple myeloma activity of mel-flufen is due to induction of apoptosis. Treatment of MM.1R or RPMI-8226 cells with mel-flufen triggered accumulation of cells in early (Annexin V^+/PI^-) and late-stage (Annexin V^+/PI^+) apoptosis (Fig. 1D). Moreover, mel-flufen–induced apoptosis was associated with: (i) activation of caspase-3, -7, -8, and -9, as well as PARP cleavage; (ii) reactive oxygen species (ROS) generation; and (iii) decrease in mitochondrial transmembrane potential ($\Delta\psi_m$) accompanied by release of cytochrome c (Fig. 1E and Supplementary Fig. S1A–S1D). Studies using pan-caspase inhibitor (Z-VAD-FMK) showed attenuation of mel-flufen–induced cytotoxicity in 3 multiple myeloma cell lines (Supplementary Fig. S1E). These findings suggest that mel-flufen triggers both mitochondria-dependent and—independent apoptotic signaling pathways.

Interaction and adhesion of multiple myeloma cells with BMSCs triggers cytokine secretion, which mediates paracrine growth of multiple myeloma cells, as well as confers cell adhesion–mediated drug resistance (CAM-DR; refs. 34, 35). To determine whether mel-flufen can overcome these protective effects, MM.1S cells were cultured with or without BMSCs in the presence or absence of various concentrations of mel-flufen. A significant inhibition of BMSCs-induced proliferation of MM.1S cells was observed in response to mel-flufen treatment (Fig. 1F). These data suggest that (i) mel-flufen not only directly targets multiple myeloma cells, but also can overcome the cytoprotective effects of the multiple myeloma-host bone marrow microenvironment.

The mechanism(s) of melphalan-resistance include decreased melphalan uptake, reduced induction of DNA cross-links, and/or increased repair of such DNA lesions, which otherwise are converted to DNA single

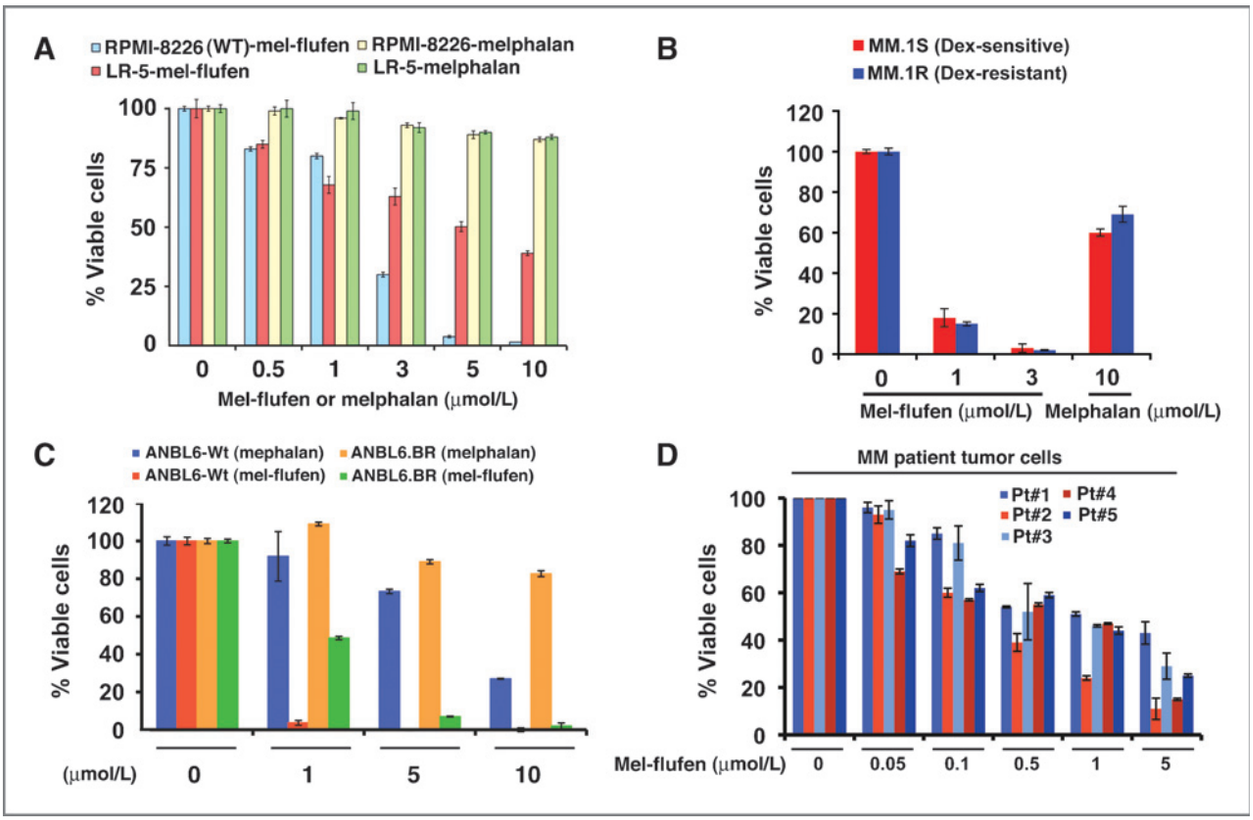


Figure 2. A, melphalan-sensitive RPMI-8226 [wild-type (WT)] and melphalan-resistant LR-5 cells were treated with indicated concentrations of mel-flufen for 24 hours, and cytotoxicity was assessed using MTT assay ($n = 3$; mean ± SD; $P < 0.005$). B, MM.1S and MM.1R cells were treated with mel-flufen or melphalan at the indicated concentrations for 24 hours, and cytotoxicity was measured by MTT assay ($n = 3$; mean ± SD; $P < 0.005$). C, bortezomib-sensitive ANBL6 (ANBL6.WT) and bortezomib-resistant ANBL6 (ANBL6.BR) multiple myeloma (MM) cells were treated with indicated concentrations of mel-flufen or melphalan, and cytotoxicity was measured using MTT assay ($n = 3$; mean ± SD; $P < 0.003$). D, purified patient multiple myeloma ($CD138^+$) cells were treated with mel-flufen at indicated doses for 24 hours, and cell viability was measured using Trypan blue assay (mean ± SD of triplicate cultures; $P < 0.001$ for all patient samples).

or double-strand breaks. Because mel-flufen exhibit a higher potency and rapid kinetics of action in tumor cells as compared with melphalan, we examined whether these attributes impart mel-flufen the ability to overcome melphalan-resistance. We used previously characterized (36) melphalan-sensitive RPMI-8226 and its melphalan-resistant derivative of RPMI-8226 (LR5) multiple myeloma cell lines. As seen in Fig. 2A, mel-flufen induces cytotoxicity even in melphalan-resistant LR5 cells, whereas melphalan alone does not significantly affect the viability of LR5 cells at tested concentrations. Higher concentrations of melphalan (100 μmol/L) showed similar resistance to melphalan in LR5 cells (data not shown). The mechanism(s) whereby mel-flufen overcomes melphalan-resistance remains to be examined; however, it is likely that mel-flufen induces a more potent and cumulative DNA damage and thereby can overcome the DNA cross-link repair capacity of multiple myeloma cells. Besides reduced DNA damage, melphalan resistance is also linked to other factors, such as increased glutathione-S-transferase activity, CAM-DR, mitochondrial alterations, or impaired caspase activation (36–39); and many of these mechanism(s) may likely be circumvented by achieving a sustained and higher intracellular concentrations of melphalan with mel-flufen.

We next examined the effects of mel-flufen in dexamethasone- or proteasome inhibitor-resistant multiple myeloma cells. We observed a significantly more potent anti–multiple myeloma activity of mel-flufen than melphalan when tested against dexamethasone-sensitive (MM.1S) and dexamethasone-resistant (MM.1R) cells (Fig. 2B). To determine whether mel-flufen can overcome bortezomib-resistance, we used bortezomib-sensitive (ANBL-6.WT) and bortezomib-resistant (ANBL-6.BR) multiple myeloma cell lines (40). Interestingly, we found that while ANBL-6.WT cells are sensitive to melphalan, ANBL6.BR cells were relatively resistant to melphalan. Importantly, mel-flufen decreases the viability in ANBL-6.BR cells (Fig. 2C), suggesting that it can overcome bortezomib resistance. Because the ANBL6.BR cells were derived after chronic exposure of ANBBL6.WT cells to low concentrations of bortezomib (acquired drug resistance), it is likely that, like LR5 (melphalan-resistant cells), ANBL6.BR cells have reduced DNA damage-associated signaling pathways. However, further studies in

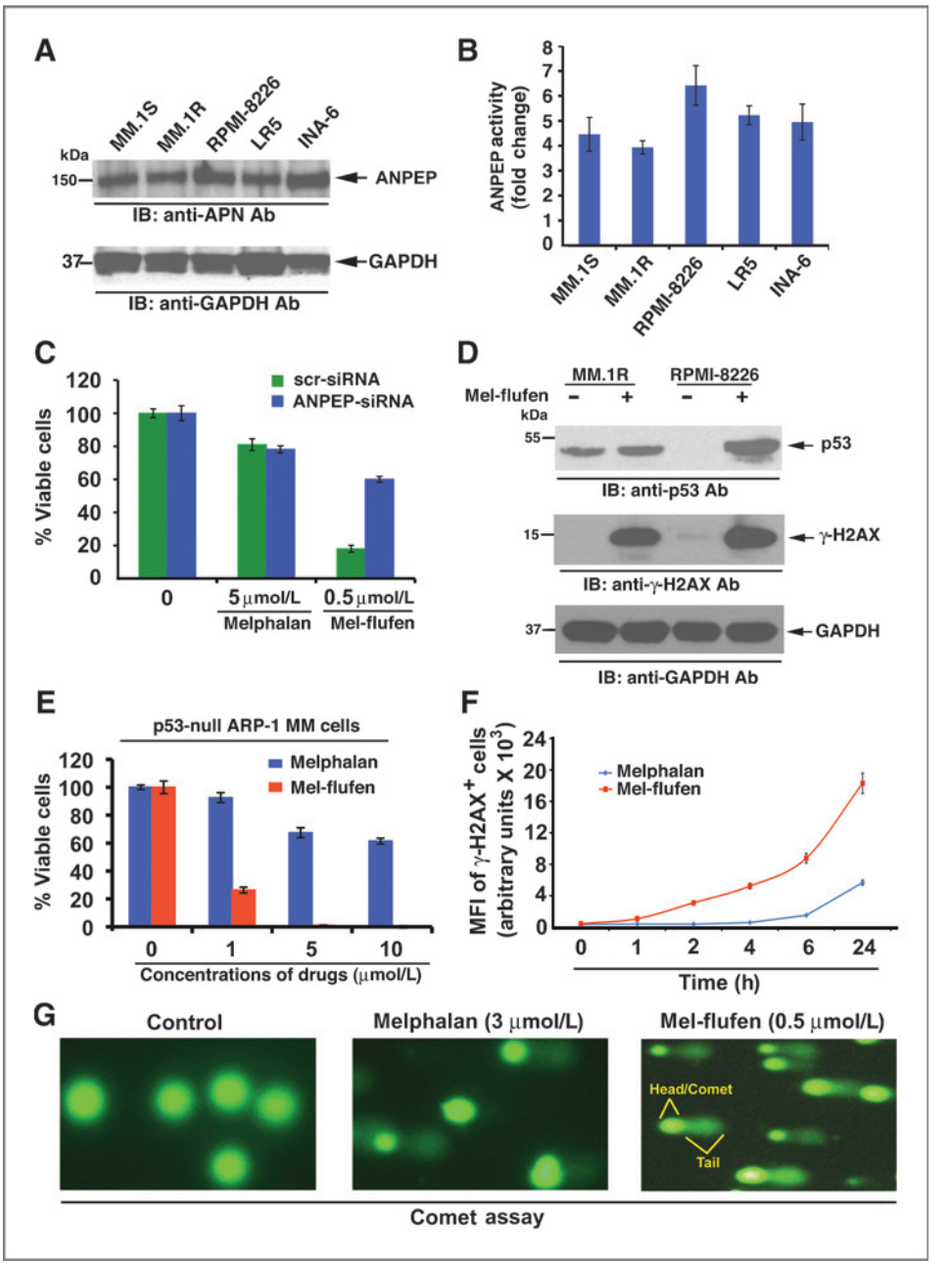


Figure 3. A, total protein lysates from MM.1S, MM.1R, RPMI-8226, LR-5, and INA6 cells were subjected to immunoblot analysis using anti-ANPEP, or anti-GAPDH antibodies (Ab). B, bar graph shows the baseline ANPEP activity in various multiple myeloma (MM) cell lines. C, MM.1S cells were transfected with scr-siRNA or ANPEP-siRNA; 24 hours after transfection, cells were treated with indicated concentrations of melphalan or mel-flufen for 24 hours, followed by analysis of viability ($n = 3$; mean ± SD; $P < 0.001$ in scr- versus ANPEP siRNA-transfected cells in response to mel-flufen). Percentage cell viability was normalized (as 100%) for scr- or ANPEP-siRNA controls, respectively. D, MM.1R and RPMI-8226 multiple myeloma cells were treated with mel-flufen (2 μmol/L for MM.1R and 5 μmol/L for RPMI-8226 cells) for 24 hours; protein lysates were prepared and subjected to immunoblotting using indicated antibodies. E, p53-null ARP-1 multiple myeloma cells were treated with indicated concentrations of either mel-flufen or melphalan for 24 hours, and cytotoxicity was assessed using MTT assay ($n = 3$; mean ± SD; $P < 0.001$). F, MM.1S cells were treated with mel-flufen (1 μmol/L) or melphalan (1 μmol/L) for 1, 2, 6, and 24 hours; cells were then washed and stained with Alexa Fluor 647–conjugated anti-H2AX antibody, followed by quantification of γ-H2AX–positive cells using flow cytometry ($n = 3$; mean ± SD; $P < 0.005$). MFI, mean fluorescence intensity. G, MM.1S cells were treated with melphalan (3 μmol/L) or mel-flufen (0.5 μmol/L) for 4 hours, harvested, and subjected to alkaline comet assay. For each slide, images were randomly captured by fluorescence microscopy and representative images from 3 independent experiments are shown.

ANBL6.BR cells are needed to delineate the mechanism(s) whereby mel-flufen overcomes bortezomib-resistance, as well as mechanism(s) conferring cross-resistance to melphalan and bortezomib. Nevertheless, our data show that mel-flufen, but not melphalan, overcomes bortezomib-resistance.

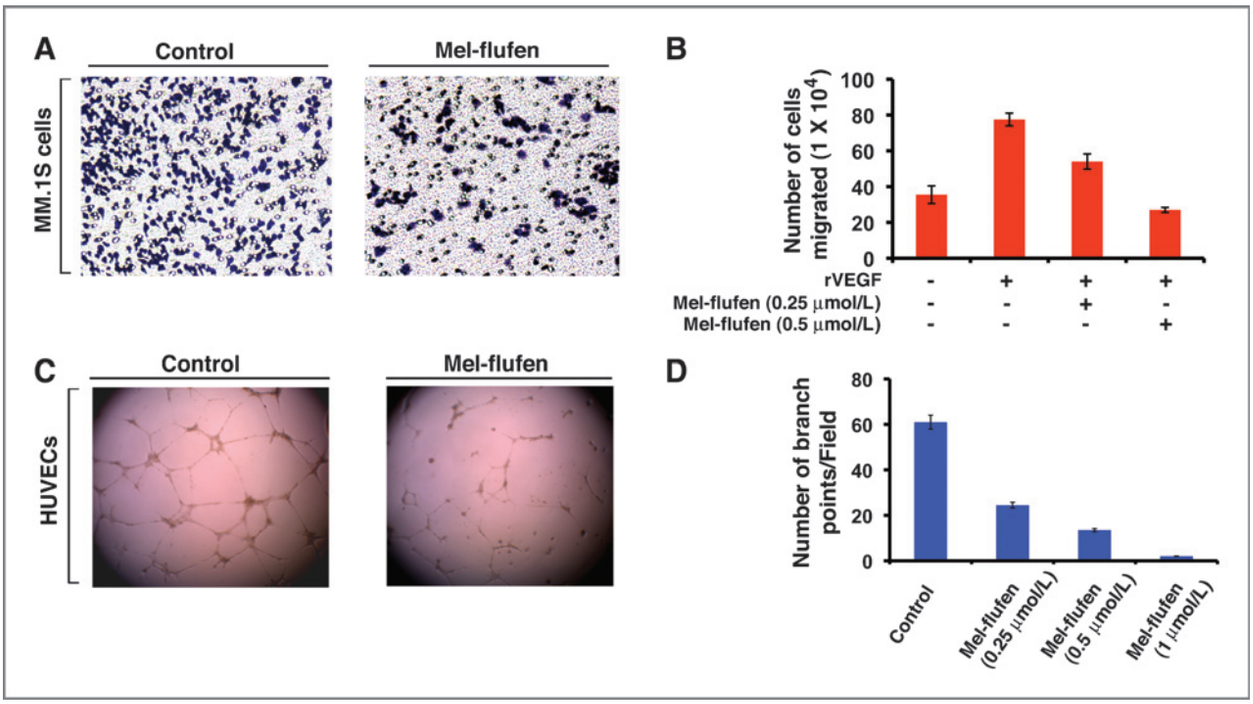


Figure 4. A, Transwell insert assay: MM.1S cells were pretreated with mel-flufen (0.5 μmol/L) for 12 hours; cells (>90% viable). Cells were then washed and incubated in serum-free medium for 2 hours (cell viability >90%) and thereafter plated on a fibronectin-coated polycarbonate membrane in the top chamber of Transwell inserts, and exposed for 4 hours to serum-containing medium in the bottom chamber. Cells migrating to the bottom face of the membrane were fixed with 90% ethanol and stained with crystal violet (magnification: ×10/0.25 numerical aperture oil). A total of 3 randomly selected fields was examined for cells that had migrated from top to bottom chambers. Image is representative of 3 experiments with similar results. B, cells were plated as in A, and the effect of mel-flufen on migration was assessed in the presence or absence of rVEGF (1 μg). The bar graph represents quantification of migrated cells. C, HUVECs were cultured in the presence or absence of mel-flufen (1 μmol/L) for 16 hours, and then assessed for *in vitro* angiogenesis using Matrigel capillary-like tube structure formation assays (magnification: ×4/0.10 NA oil; media: EBM-2). Image is representative of 2 experiments with similar results. *In vitro* angiogenesis is evidenced by capillary tube branch formation (dark brown; $n = 3$; mean ± SD; $P < 0.005$). D, HUVECs were cultured in the presence or absence of indicated concentrations of mel-flufen for 16 hours, followed by assessment of *in vitro* angiogenesis as in C. The bar graph represents quantification of capillary-like tube structure formation by vehicle alone and mel-flufen–treated cells. Branch points in several random view fields per well were counted; values were averaged; and statistically significant differences were measured using Student *t* test ($n = 2$; mean ± SD; $P = 0.03$ for control vs. mel-flufen–treated cells).

We next determined whether mel-flufen similarly affects purified patient multiple myeloma cells. Tumor cells from 5 patients with multiple myeloma, including those relapsing after multiple prior therapies including bortezomib, lenalidomide, and dexamethasone, were treated with mel-flufen. Patients were considered refractory to specific therapy when disease progressed on therapy or relapsed within 2 months of stopping therapy. A significant dose-dependent decrease in viability of all patient multiple myeloma cells was noted after mel-flufen treatment (Fig. 2D). These data show that mel-flufen induces cytotoxicity in tumor cells obtained from patient whose multiple myeloma is resistant to bortezomib, dexamethasone, or lenalidomide therapies. Importantly, mel-flufen at the IC_{50} for multiple myeloma cells does not significantly affect the viability of normal PBMCs (data not shown), suggesting specific anti–multiple myeloma activity and a favorable therapeutic index for mel-flufen.

Mechanism(s) mediating mel-flufen activity

Earlier studies established that (i) ANPEP (also known as CD13) plays a key role in catalyzing the release of free melphalan from mel-flufen, and (ii) hydrolysis of the peptide bond in mel-flufen by ANPEPs is a prerequisite for mel-flufen–induced cytotoxicity (19). Of note, the activity and/or the expression of ANPEP is elevated in many cancer types, and is associated with various characteristics of malignant phenotype including cell proliferation, cytokine secretion, tumor invasion, and angiogenesis (18). These studies suggest ANPEP as a viable therapeutic target in cancer (18). As seen in Fig. 3A and B, both ANPEP expression and activity are constitutively elevated in multiple myeloma cells. Importantly, transfection of ANPEP siRNA, but not negative-control (scrambled) siRNA, significantly inhibited mel-flufen–induced apoptosis in MM.1S cells, whereas no marked difference in melphalan-induced cytotoxicity was evident (Fig. 3C). The residual mel-flufen cytotoxic activity in ANPEP-siRNA–tranfected cells may be attributed to limitations of RNA interference strategy, which usually results in incomplete gene loss. Another possibility is that mel-flufen or its intermediate metabolite in multiple myeloma cells is substrate of other aminopeptidases, as reported in solid tumor cells (19). Nevertheless, our data provide the evidence that mel-flufen–triggered apoptosis

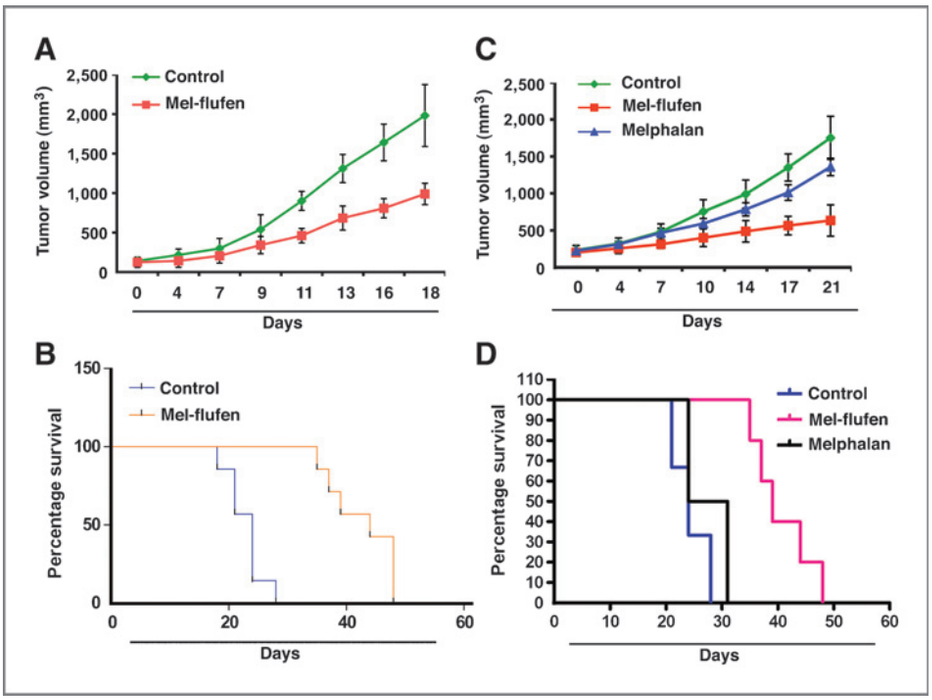


Figure 5. A, average and SD of tumor volume (mm^3) is shown from mice ($n = 5$/group) versus time (days) when tumor was measured. MM.1S cells (5×10^6 cells/mouse) were implanted in the rear flank of female mice (6 weeks of age). Tumor-bearing mice were randomized to treatment groups and treated intravenously with vehicle or mel-flufen (3 mg/kg) on a twice-weekly schedule for 2 weeks (mean tumor volume ± SD). A significant delay in tumor growth in mel-flufen–treated mice was noted compared with vehicle-treated control mice ($P = 0.008$). Bars indicate mean ± SD. B, Kaplan–Meier survival plot shows significant increase survival of mice receiving mel-flufen versus vehicle-alone–treated mice [$P = 0.0002$; log-rank (Mantel–Cox) test]; median survival was 24 days in vehicle-treated mice versus 44 days in mel-flufen–treated mice (CI, 95%). C, MM.1S cells (5×10^6 cells/mouse) were implanted in the rear flank of female mice, as in A. Tumor-bearing mice were randomized to treatment groups and treated intravenously with vehicle (6 mice/group), mel-flufen (2 mg/kg; 6 mice/group), or equimolar dose of melphalan (2 mice/group) on a twice weekly schedule for 3 weeks (mean tumor volume ± SD). More potent anti–multiple myeloma activity of mel-flufen was noted compared with either vehicle- or melphalan-treatment. Bars indicate mean ± SD. D, Kaplan–Meier survival plot shows significant ($P < 0.05$) increase in survival of mice receiving mel-flufen as compared with vehicle- or melphalan-treated mice.

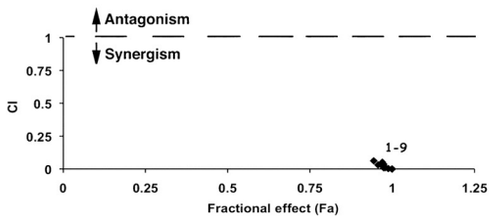
in multiple myeloma cells is facilitated, at least in part, u ANPEP.

Previous studies have shown that melphalan triggers DNA-damage response/repair signaling, associated with activation of p53 (41). We therefore next examined whether mel-flufen–induced apoptosis in multiple myeloma cells correlates with induction of similar signaling cascades. Examination of mel-flufen–treated multiple myeloma cells showed a robust increase in p53 (Fig. 3D, top) in RPMI-8226 cells, albeit to a lesser extent in MM.1R cells. Interestingly, our data (Fig. 1C) show that mel-flufen trigger cytotoxicity even in p53-null ARP-1 multiple myeloma cells, suggesting that functional p53 may not be obligatory for efficient induction of mel-flufen–induced apoptosis. Nevertheless, given the established role of p53 in melphalan response, we conducted a side-by-side comparison of melphalan and mel-flufen activity using p53-null ARP-1 cells. As expected, we found

Figure 6. Combination of low doses of mel-flufen and lenalidomide, bortezomib, or dexamethasone trigger synergistic anti–multiple myeloma activity. A, MM.1S cells were treated for 24 hours with mel-flufen, lenalidomide, or mel-flufen plus lenalidomide, and then assessed for viability using MTT assays. Isobologram analysis shows the synergistic cytotoxic effect of mel-flufen and lenalidomide. The graph (right) is derived from the values given in the table (left). The numbers 1 to 9 in graph represent combinations shown in the table. CI < 1 indicates synergy. B, MM.1S cells were treated for 24 hours with mel-flufen, bortezomib, or mel-flufen plus bortezomib, and then assessed for viability using MTT assays. Isobologram analysis shows the synergistic cytotoxic effect of mel-flufen and bortezomib. The graph (right) is derived from the values given in the table (left). C, MM.1S cells were treated for 24 hours with mel-flufen, dexamethasone, or mel-flufen plus dexamethasone, and then assessed for viability using MTT assays. Isobologram analysis shows the synergistic cytotoxic effect of mel-flufen and dexamethasone. The graph (right) is derived from the values given in the table (left). D, melphalan-resistant LR-5 cells were treated for 24 hours with mel-flufen, lenalidomide, or mel-flufen plus lenalidomide, and then assessed for viability using MTT assays. Isobologram analysis shows the synergistic cytotoxic effect of mel-flufen and lenalidomide. The graph (right) is derived from the values given in the table (left). E, melphalan-resistant LR-5 cells were treated for 24 hours with mel-flufen, bortezomib, or mel-flufen plus bortezomib, and then assessed for viability using MTT assays. Isobologram analysis shows the synergistic cytotoxic effect of mel-flufen and bortezomib. The graph (right) is derived from the values given in the table (left). F, melphalan-resistant LR-5 cells were treated for 24 hours with mel-flufen, dexamethasone, or mel-flufen plus dexamethasone, and then assessed for viability using MTT assays. Isobologram analysis shows the synergistic cytotoxic effect of mel-flufen and dexamethasone. The graph (right) is derived from the values given in the table (left).

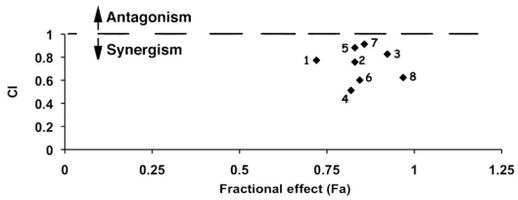
A **MM.1S cells**

Combination dosage number	Mel-flufen (μmol/L)	Fraction affected	Lenalidomide (μmol/L)	Fraction affected	Fa (Combination)	CI
1	0.25	0.8	1	0.24	0.96	0.031
2	0.25	0.8	3	0.28	0.97	0.009
3	0.25	0.8	5	0.34	0.94	0.062
4	0.5	0.87	1	0.24	0.97	0.01
5	0.5	0.87	3	0.28	0.98	0.003
6	0.5	0.87	5	0.34	0.96	0.037
7	1	0.90	1	0.24	0.99	0.003
8	1	0.90	3	0.28	0.99	0.002
9	1	0.90	5	0.34	0.97	0.051



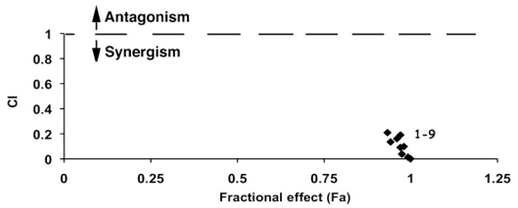
B **MM.1S cells**

Combination dosage number	Mel-flufen (μmol/L)	Fraction affected	Bortezomib (nmol/L)	Fraction affected	Fa (Combination)	CI
1	0.20	0.65	0.83	0.02	0.72	0.774
2	0.20	0.65	2.5	0.7	0.83	0.758
3	0.20	0.65	4.16	0.81	0.92	0.827
4	0.41	0.73	0.83	0.02	0.81	0.512
5	0.41	0.73	2.5	0.7	0.83	0.883
6	0.83	0.77	0.83	0.02	0.84	0.602
7	0.83	0.77	2.5	0.7	0.85	0.913
8	0.83	0.77	4.16	0.81	0.96	0.624



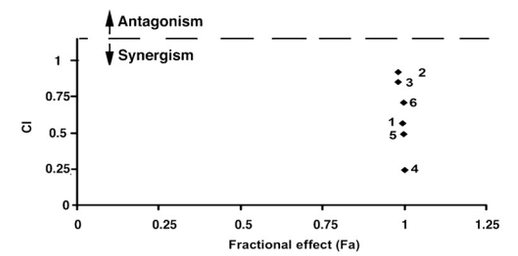
C **MM.1S cells**

Combination dosage number	Mel-flufen (μmol/L)	Fraction affected	Dexamethasone (nmol/L)	Fraction affected	Fa (Combination)	CI
1	0.25	0.8	10	0.3	0.94	0.135
2	0.25	0.8	30	0.48	0.97	0.038
3	0.25	0.8	50	0.59	0.93	0.209
4	0.5	0.87	10	0.3	0.97	0.091
5	0.5	0.87	30	0.48	0.99	0.013
6	0.5	0.87	50	0.59	0.96	0.161
7	1	0.90	10	0.3	0.99	0.001
8	1	0.90	30	0.48	0.98	0.098
9	1	0.90	50	0.59	0.97	0.19



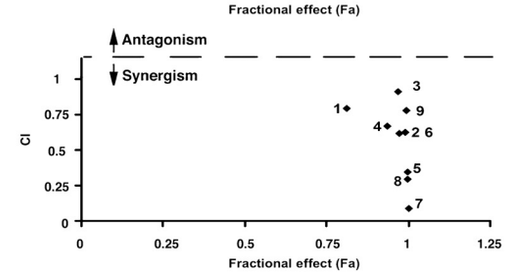
D **Melphalan-resistant LR5 cells**

Combination dosage number	Mel-flufen (μmol/L)	Fraction affected	Lenalidomide (μmol/L)	Fraction affected	Fa (Combination)	CI
1	6	0.55	5	0.0001	0.99	0.56
2	6	0.55	10	0.001	0.98	0.85
3	6	0.55	15	0.01	0.98	0.92
4	8	0.60	5	0.0001	0.99	0.24
5	8	0.60	10	0.001	0.99	0.48
6	8	0.60	15	0.01	0.99	0.70



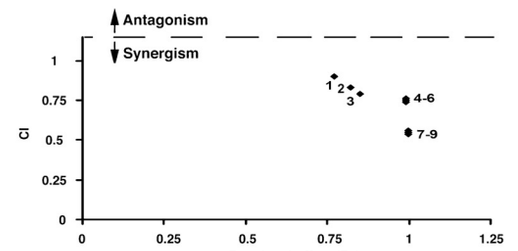
E **Melphalan-resistant LR5 cells**

Combination dosage number	Mel-flufen (μmol/L)	Fraction affected	Bortezomib (nmol/L)	Fraction affected	Fa (Combination)	CI
1	1	0.13	10	0.34	0.81	0.795
2	1	0.13	20	0.88	0.97	0.618
3	1	0.13	30	0.91	0.96	0.914
4	2	0.25	10	0.34	0.93	0.668
5	2	0.25	20	0.88	0.99	0.345
6	2	0.25	30	0.91	0.99	0.629
7	5	0.50	10	0.34	0.99	0.091
8	5	0.50	20	0.88	0.99	0.297
9	5	0.50	30	0.91	0.99	0.78



F **Melphalan-resistant LR5 cells**

Combination dosage number	Mel-flufen (μmol/L)	Fraction affected	Dexamethasone (μmol/L)	Fraction affected	Fa (Combination)	CI
1	3	0.35	10	0.2	0.77	0.90
2	3	0.35	15	0.21	0.82	0.83
3	3	0.35	20	0.22	0.85	0.79
4	6	0.55	10	0.2	0.99	0.74
5	6	0.55	15	0.21	0.99	0.75
6	6	0.55	20	0.22	0.99	0.76
7	8	0.60	10	0.2	0.99	0.54
8	8	0.60	15	0.21	0.99	0.55
9	8	0.60	20	0.22	0.99	0.55



that high concentrations of melphalan (5–10 μmol/L) are required to achieve 30% to 40% cell death; importantly, mel-flufen (0.5 μmol/L) at the concentrations 10-fold lower than melphalan (5 μmol/L) is able to trigger significant cytotoxicity in p53-null ARP-1 multiple myeloma cells (Fig. 3E). These data suggest that although mel-flufen increases p53 levels (Fig. 3D), its cytotoxic activity in multiple myeloma cells is not dependent on p53. Our findings have important clinical implications, as 10% to 15% of patients with multiple myeloma have p53 mutations/deletions at presentation, which confer drug resistance, and majority of patients acquire this abnormality with disease progression; a therapeutic approach using mel-flufen would allow for potent anti–multiple myeloma activity even in this patient population.

An early event in the response of mammalian cells to DNA double-strand breaks is the phosphorylation of histone H2AX (γ-H2AX) at the sites in proximity to DNA breaks (42). A robust induction of γ-H2AX was observed in mel-flufen–treated MM.1R and RPMI-8226 cells (Fig. 3D, middle), suggesting that mel-flufen–induced DNA cross-links were indeed converted to DNA double-strand breaks. We next compared the potency of mel-flufen and melphalan in inducing DNA double-strand breaks. MM.1S cells were treated with mel-flufen (1 μmol/L) or melphalan (1 μmol/L) for 1, 2, 6, and 24 hours; cells were then washed and stained with Alexa Fluor 647–conjugated anti-H2AX (pS139) antibody, followed by quantification of γ-H2AX–positive cells using flow cytometry. Results show an early and potent induction of DNA double-strand breaks in mel-flufen- versus melphalan-treated MM.1S cells (Fig. 3F).

To confirm the differential induction of DNA damage by mel-flufen and melphalan, we next conducted alkaline comet assay. The comet assay is a single cell gel electrophoresis assay and uses the principle that damaged DNA migrates, forming a "tail," whereas undamaged DNA with intact supercoiled structure, does not migrate, forming the head of the comet. The intensity and length of the comet tail is proportional to extent of DNA damage. Results showed that even low concentrations of mel-flufen (0.5 μmol/L) are able to trigger more potent and greater DNA damage than is observed in cells treated with higher concentrations (3 μmol/L) of melphalan (Fig. 3G and Supplementary Fig. S2). Together, these results suggest that mel-flufen is more efficient inducer of DNA damage than melphalan.

Overall, our mechanistic studies shows that (i) mel-flufen–induced cytotoxicity is facilitated via ANPEP; (ii) mel-flufen triggers DNA damage associated with induction of γ-H2AX and p53; (iii), although p53 is upregulated in response to mel-flufen treatment, the cytotoxic activity of mel-flufen is not dependent on p53, suggesting that there may be a p53-independent component to mel-flufen–induced cytotoxicity; and (iv) mel-flufen–induced apoptosis is associated with activation of caspases and PARP cleavage. Of note, DNA damage response signaling is linked to activation of p53/caspases signaling axis (43), suggesting a potential cross-talk between these pathways during mel-flufen–induced apoptosis. It is possible that mel-flufen, such as melphalan, triggers pleiotropic signaling pathways; however, due to the rapid intracellular accumulation characteristics of mel-flufen compared with melphalan, the kinetics of alterations in apoptotic response signaling may vary and this issue remains to be defined.

Effect of mel-flufen on migration of multiple myeloma cells and angiogenesis

Multiple myeloma cell growth is associated with angiogenesis (44, 45). As noted earlier, ANPEP expression/activity is associated with malignant phenotype, including angiogenesis (46); and importantly, mel-flufen is ANPEP-activated prodrug of melphalan. We examined the effect of mel-flufen on multiple myeloma cell migration and angiogenesis using Transwell insert systems and *in vitro* tubule formation assays. VEGF is elevated in the multiple myeloma bone marrow microenvironment, and prior studies showed that VEGF triggers growth, migration, and angiogenesis in multiple myeloma (44, 45, 47). We first examined whether mel-flufen affects VEGF-induced multiple myeloma cell migration. VEGF alone markedly increases MM.1S cell migration; conversely, mel-flufen inhibits VEGF-dependent multiple myeloma cell migration, evidenced by a decrease in the number of crystal violet–stained cells (Fig. 4A and B). These cells were more than 95% viable before and after conducting the migration assay, excluding the possibility that drug-induced inhibition of migration is due to cell death. Additional experiments show that melphalan also inhibits tumor-associated angiogenesis and multiple myeloma cell migration, albeit at much higher concentrations than mel-flufen (data not shown). These findings are consistent with more potent and robust accumulation of intracellular melphalan upon mel-flufen treatment. These results suggest that mel-flufen may negatively regulate homing of multiple myeloma cells to the bone marrow.

We next used *in vitro* capillary-like tube structure formation assays to examine the antiangiogenic activity of mel-flufen. Angiogenesis was measured *in vitro* using Matrigel capillary-like tube structure formation assays in which HUVECs plated onto Matrigel differentiate and form capillary-like tube structures similar to *in vivo* neovascularization. This assay therefore provides evidence for antiangiogenic effects of drugs. HUVECs were seeded in 96-well culture plates precoated with Matrigel; treated with vehicle [dimethyl sulfoxide (DMSO)], mel-flufen for 16 hours; and then examined for tube formation using an inverted microscope. As seen in Fig. 4C and D, tubule formation was markedly decreased in the mel-flufen–treated cells versus vehicle control. HUVEC cell viability was assessed using Trypan blue exclusion assay, and less than 5% cell death was observed with mel-flufen treatment. Our results are consistent with earlier *in vivo* data showing that mel-flufen decreases the number of blood vessel formation in SH-SY5Y xenograft model (17). Taken together, our findings suggest that mel-flufen

blocks multiple myeloma cell migration and inhibit tumor-associated angiogenesis.

Anti–multiple myeloma activity of mel-flufen in xenograft mouse model

Having shown that mel-flufen induces apoptosis in multiple myeloma cells *in vitro*, we next examined the *in vivo* efficacy of mel-flufen using a human plasmacytoma MM.1S xenograft mouse model (23). Treatment of tumor-bearing mice with mel-flufen intravenously significantly inhibited multiple myeloma tumor growth ($P = 0.001$) and prolonged survival ($P < 0.001$) of these mice (Fig. 5A and B, respectively). Equimolar doses of melphalan also reduced tumor progression (Fig. 5C), albeit to a lesser extent than mel-flufen. Moreover, mel-flufen–treated mice survived for a longer time than mice receiving equimolar doses of melphalan ($P < 0.01$; CI, 95%; Fig. 5D). These *in vivo* data confirm our *in vitro* findings showing more potent anti–multiple myeloma activity and tumor cell selectivity of mel-flufen versus melphalan.

Combined treatment with mel-flufen and lenalidomide, bortezomib, or dexamethasone induces synergistic anti–multiple myeloma activity

We next examined whether mel-flufen can be combined with other drugs to enhance cytotoxicity and overcome melphalan-resistance. MM.1S cells were first treated with both mel-flufen and lenalidomide simultaneously across a range of concentrations for 24 hours, and then analyzed for viability using MTT assay. An analysis of synergistic anti–multiple myeloma activity using the Chou and Talalay method (26) showed that the combination of low concentrations of mel-flufen and lenalidomide triggered synergistic anti–multiple myeloma activity, with a CI < 1.0 (Fig. 6A, graph and table). We next examined whether mel-flufen adds to the anti–multiple myeloma activity of proteasome inhibitor bortezomib and conventional anti–multiple myeloma agent dexamethasone. As with lenalidomide, the combination of mel-flufen with bortezomib or dexamethasone triggered synergistic anti–multiple myeloma activity, evidenced by a significant decrease in viability of MM.1S cells (Fig. 6B and C, graphs and tables). Importantly, a similar synergism was observed between mel-flufen and lenalidomide, bortezomib, or dexamethasone in melphalan-resistant LR5 multiple myeloma cells (Fig. 6D–F, graphs and tables). Although definitive evidence of decreased toxicity of combination therapy awaits results of clinical trials, the synergy observed *in vitro* may allow for use of lower doses and decreased toxicity.

Collectively, our preclinical studies therefore show potent *in vitro* and *in vivo* anti–multiple myeloma activity of mel-flufen at doses that are well tolerated in human multiple myeloma xenograft mouse models. These findings provide the framework for clinical trials of mel-flufen both as a single agent and together with lenalidomide, bortezomib, or dexamethasone to increase response, overcome drug resistance, reduce side effects, and improve patient outcome in multiple myeloma.

Disclosure of Potential Conflicts of Interest

D. Chauhan is a consultant to Oncopeptide AB. K. Viktorsson is employed as Head of Preclinical Research at Oncopeptides AB. R. Lewensohn has ownership interest (including patents) in Oncopeptides AB. No potential conflicts of interest were disclosed by the other authors.

Disclaimer

The Editor-in-Chief of Clinical Cancer Research (K.C. Anderson) is an author of this article. In keeping with the AACR's Editorial Policy, the article was peer reviewed and a member of the AACR's Publications Committee rendered the decision about acceptability.

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Development of methodology: D. Chauhan, R. Lewensohn
Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): K. Viktorsson
Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): D. Chauhan, A. Ray, K. Viktorsson, N. Munshi, P. Richardson, R. Lewensohn, K.C. Anderson
Writing, review, and/or revision of the manuscript: D. Chauhan, K. Viktorsson, J. Spira, C. Paba-Prada, N. Munshi, P. Richardson, R. Lewensohn, K.C. Anderson
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Study supervision: D. Chauhan, R. Lewensohn

Grant Support

This investigation was supported by NIH grants P50100707 and CA078378 (to D. Chauhan and K.C. Anderson); Swedish Cancer Society, Swedish Research Council and Stockholm Cancer Society (to K. Viktorsson and R. Lewensohn).

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Received December 5, 2012; revised February 23, 2013; accepted April 1, 2013; published OnlineFirst April 12, 2013.

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