Expression of Interleukin-4 Receptor Alpha in Human Pleural Mesothelioma Is Associated with Poor Survival and Promotion of Tumor Inflammation

Bryan M. Burt¹, Andrew Bader¹, Daniel Winter¹, Scott J. Rodig², Raphael Bueno¹, and David J. Sugarbaker¹

Abstract

Purpose: The origin and pathogenesis of malignant pleural mesothelioma (MPM) are closely aligned with inflammation. MPM tumors express interleukin-4 receptor α (IL-4Rα), the principal subunit of the IL-4 receptor. We set out to determine the biologic function and clinical relevance of IL-4Rα in human MPM.

Experimental Design: Expression of IL-4Rα by human MPM tumors was determined by quantitative real-time PCR (n = 37) and immunohistochemistry (n = 52). Intracellular cytokine analysis of T-cell–derived IL-4 was carried out on matched tumor and blood samples from eight patients with MPM. Four human MPM cell lines were used to determine the direct effects of IL-4 on MPM tumor cells.

Results: High tumor mRNA expression of IL-4Rα was an independent predictor of poor survival in patients with epithelial MPM [HR, 3.13, 95% confidence interval (CI), 1.68–7.15; P = 0.0001]. Ninety-seven percent of epithelial MPM tumors and 95% of nonepithelial MPM tumors expressed IL-4Rα protein by immunohistochemistry, and strong IL-4Rα staining correlated with worse survival in patients with epithelial histology (P = 0.04). A greater percentage of tumor-infiltrating T cells produced IL-4 compared with matched blood T cells (21% ± 7% vs. 4% ± 2%, P = 0.0002). In response to IL-4, human MPM cells showed increased STAT-6 phosphorylation and increased production of IL-6, IL-8, and VEGF, without effect on proliferation or apoptosis.

Conclusions: Tumor expression of IL-4Rα is inversely correlated with survival in patients undergoing surgical resection for epithelial MPM. Tumor-infiltrating T cells in MPMs are polarized to produce IL-4 and may provide endogenous activation signals to MPM tumor cells in situ. The IL-4/IL-4 receptor axis is a potential therapeutic target in human MPM. Clin Cancer Res; 18(6); 1–10. ©2012 AACR.

Introduction

Malignant pleural mesothelioma (MPM) is an aggressive tumor that arises from the mesothelial lining of the pleura. It is a unique malignancy whose primary mode of spread is invasion of surrounding tissues and whose proclivity for distant metastases is low. MPM is a highly fatal tumor that is resilient to single modality treatment with surgery, chemotherapy, or radiation. With multimodality therapy in selected patients, median survival is 19 months (1). Approximately two-thirds of patients with MPM have epithelial histology. The remaining one third of patients have nonepithelial histology (sarcomatoid or biphasic), which are more aggressive tumors with significantly worse survival (2).

It recently has become evident that chronic inflammation may predispose individuals to develop cancer. Inflammation promotes the proliferation and survival of malignant cells, supports angiogenesis and metastasis, and subverts immune surveillance and responses to chemotherapy (3). MPM, in particular, is a cancer whose origin and pathogenesis are closely aligned with inflammation. Occupational exposure to asbestos is identified as the etiology of MPM in 80% of cases (4). Asbestos fibers are thought to initiate a carcinogenic inflammatory reaction marked by an influx of phagocytes into the tumor and the release of an array of proinflammatory cytokines, such as TNF-α, that promote malignant transformation of the mesothelium via NF-kB–dependent mechanisms (5). In human MPM tumors, ongoing inflammation is represented by massive leukocyte infiltrates of T lymphocytes and macrophages whose densities are correlated with survival (6, 7).

Interleukin-4 receptor α (IL-4Rα) is the major subunit of the IL-4 receptor. In addition to being present on immune cells such as B cells, T cells, and macrophages, IL-4Rα is expressed on a variety of cancer cell lines (8), and in situ on a number of solid human tumors including non–small cell...
Translational Relevance

Malignant pleural mesothelioma (MPM) is an aggressive tumor of the pleura that arises in a background of chronic inflammation. The overall survival of patients with MPM is poor despite multimodality treatment strategies that include surgery, chemotherapy, and radiation. In this study, we have identified interleukin-4 receptorα (IL-4Rα), the major subunit of the IL-4 receptor, as a biomarker with prognostic correlation in MPM. In patients undergoing resection for MPM, high tumor IL-4Rα expression was an independent predictor of decreased survival. Furthermore, freshly isolated T cells infiltrating human MPM tumors were polarized to produce IL-4, and IL-4 had direct biologic effects on MPM tumor cells that included promotion of STAT-6 phosphorylation and inflammatory cytokine production. Therefore, we believe that IL-4 endogenously produced in the tumor microenvironment may promote cancer inflammation and progression, and that interruption of the IL-4/IL-4 receptor axis may be a promising therapeutic target in human MPMs.

Materials and Methods

Patients, tissues, and cell lines

Patients. Human tumor, blood, and effusion were acquired from patients undergoing extrapleurectomy pneumonectomy (EPP) in accordance with Institutional Review Board policy and following informed consent. Required criteria for EPP include disease confined to the ipsilateral hemithorax and sufficient predicted postoperative pulmonary reserve. At our institution, EPP is more commonly carried out over pleurectomy/decoration for MPM and likely provides more complete resection, especially for patients with bulky disease. Patient cohorts for PCR and immunohistochemical experiments were based on previously published data sets constructed to represent institutional experience (15) and their clinicopathologic characteristics are shown in Supplementary Tables S1 and S2. For flow cytometry experiments, tissues were obtained from the operating room in patients undergoing cytoreductive surgery for biopsy-proven MPMs.

Tissues. The pathologic diagnosis of MPM was confirmed in all cases. For PCR experiments, tumor samples were snap frozen on the day of resection. For flow cytometry experiments, tumor and matched blood samples were obtained fresh and used on the day of surgery. Peripheral blood mononuclear cells were isolated by density centrifugation over Ficoll-Paque Plus (GE Healthcare). To isolate tumor-infiltrating mononuclear cells, tumor tissues were minced into fine fragments in cold Hank’s balanced salt solution (HBSS) and digested in RPMI [American Type Culture Collection (ATCC)] containing 10% fetal calf serum (FCS; Gibco), 1 mg/mL Collagenase D (Roche Diagnostic), and 100 μg/mL DNase (Qiagen) at 37°C for 3 hours. The tissue slurry was passed through 70 and 40 μm filters and washed with cold HBSS. The cells were then layered over a Ficoll-Paque density gradient and centrifuged at 1,000 × g for 20 minutes at which time the interface layer containing tumor mononuclear cells was harvested.

MPM cell lines. Four human MPM cell lines were maintained in RPMI media containing 10% FCS (Gibco). H2O52 cells (epithelial origin) were obtained from the ATCC. MS924 (epithelial) and MS428 cells (sarcomatoid) were kindly provided by Dr. Jonathan A. Fletcher, MD, Department of Pathology, Brigham & Women’s Hospital (Boston, MA). JMN cells (biphasic) were a gift from Dr. James Rheinwald (16).

Quantitative PCR

Quantitative PCR was carried out on MPM tumor tissues as previously described (17). Briefly, tumors were selected for portions with highest tumor density (>50% tumor cells per high-power field) and stored snap frozen. Total RNA (2 μg) was isolated using TRIzol reagent (Invitrogen Life Technologies) and reverse transcribed using Taq-Man Reverse Transcription reagents (Applied Biosystems). Quantitative real-time PCR (RT-PCR) was carried out using a SYBR-Green fluorometric-based detection system (Applied Biosystems) with a Stratagenex MX 3000P device. The primer sequences for IL-4Rα (synthesized by Invitrogen Life Technologies) used for RT-PCR were as follows: 5'-CTAGGAT-GACGTTGTCATCT-3' (forward) and 5'-GTGGCAGGAG- CATTGGTGTG-3' (reverse). PCR amplification of cDNA samples was carried out in triplicate using appropriate negative controls and the melting curves were in agreement with the expected amplified fragments. Ribosome 18S RNA was used as an internal control for normalization of data [5'-ATGGCGTTTCTTAGTGGTG-3' (forward) and 3'- CGCTGAGGCAGTCATGTAG-5' (reverse)].

Immunohistochemistry and tissue microarray

Immunostaining was carried out on a tissue microarray (TMA) of 58 resected MPM tumors as previously described (7). Each tumor was represented in duplicate or quadruplicate cores. Six patients were excluded because of damage to the tissue cores, resulting in a sample size of 52. In brief, the TMA slides were soaked in xylene, passed through graded alcohols, and then placed in distilled water. The slides were next treated with citrate buffer in a steam pressure cooker (Decloaking Chamber; BioCare Medical) and then washed in distilled water. All further steps were
carried out at room temperature in a hydrated chamber. To quench endogenous peroxidase activity, the slides were pretreated with peroxidase block (DAKO) for 5 minutes. A mouse monoclonal anti-human IL-4R antibody (H-4, SC-28361; Santa Cruz Biotechnology) was applied at 1:100 in DAKO diluent for 1 hour. Afterward, the slides were washed in 50 mmol/L Tris-Cl, pH 7.4, and detected with Mouse Envision kit (DAKO) as per manufacturer's instructions. After another washing step, immunoperoxidase staining was developed using a DAB chromogen (DAKO) and counterstained with hematoxylin. For image analysis, TMA slides stained with IL-4R were scanned at 200× magnification using an Aperio ScanScope XT workstation (Aperio Technology, Inc.). The images were visualized and annotated using ImageScope software (version 10.0.35.1800; Aperio Technology). For each core, 3 regions of interest (ROI) were selected by a pathologist (S.J. Rodig) based on areas containing predominantly tumor cells and thereby excluding the stromal compartment which harbors most of the immune infiltrate (Supplementary Fig. S1). Aperio software (positive pixel count v9 algorithm) was used to deconvolute the brown (positive staining for the antigen) and blue (hematoxylin stain) colorations. The percentage of the annotated area was scored by a software algorithm based upon a scale of pixel intensity ranging from 0 to 256, with 0 representing black and 256 representing white. Staining intensity thresholds were set as follows: strong (0–100), not strong (101–256). A representation of strong staining is shown in Supplementary Fig. S1B. Data were collected for each ROI and the results were averaged. Data from duplicate cores were similarly averaged.

Flow cytometry and intracellular cytokine detection

Flow cytometry was carried out on mononuclear cell suspensions and cancer cell lines with a LSR II cytometer (BD Biosciences) using the following monoclonal antibodies: CD4-FITC, CD45-PE-Cy5, CD8-PE-Cy7, CD3-Pacific Blue (all from BD Biosciences); and IL-4Rα-APC (R&D Systems). Matched immunoglobulin isotype antibodies and unstained cells were used as controls to set gates. Detection of intracellular IL-4 was carried out on blood and tumor mononuclear cell suspensions 4 hours after activation with 5 ng/mL phorbol 12-myristate 13-acetate (PMA; Sigma-Aldrich) and 1 μmol/L ionomycin (Sigma), in the presence of 10 μg/mL Brefeldin A (BD Biosciences). Surface staining was completed and then the cells were fixed and permeabilized. Intracellular IL-4 was assayed using an allophycocyanin (APC)-conjugated anti-IL-4 antibody (Intracellular Cytokine Detection kit; BD Biosciences). Flow cytometry data were analyzed with FlowJo software (TreeStar).

Cell-based assays

Five thousand cells were plated on 96-well cell culture plates in RPMI containing 10% FCS. Twenty-four hours later, recombinant human IL-4 (Invitrogen) was added at a concentration of 20 ng/mL. Cellular proliferation was measured at indicated time points using an MTT cell proliferation assay (ATCC), and apoptosis was assessed via measurement of caspase-3/7 activity with a luminescence-based assay (Promega). ELISA was used to assay the supernatant for cytokines IL-6, IL-8, and VEGF, 24 hours after the addition of IL-4. In-Cell ELISA assays were used to quantify changes in the concentration of STAT-6 and phosphorylated STAT-6, after 24 hours of culture in 20 ng/mL of IL-4. Final values were normalized to cell number using Janus Green reagent. To detect IL-4 in tumor tissues, snap-frozen MPM tumors were homogenized in buffer containing Iscove’s Medium (Gibco), 10% FCS, 0.5 mmol/L L-amino-n-capric acid (Sigma), and 0.05 mmol/L EDTA (Sigma). An ultrasensitive ELISA detection kit was used to detect IL-4 in the tissue homogenate. All ELISA kits were purchased from Invitrogen.

Statistical analysis

Statistical analysis was conducted using JMP statistical software (version 8.0; SAS Institute). Distributions were plotted to examine compliance with distributional assumptions. Nonparametric tests were used to compare dichotomous variables in univariate analyses. The Wilcoxon test was used to compare 2 groups of continuous variables and one-way ANOVA was used to compare 3 groups of continuous variables. Kaplan–Meier plots were used to illustrate the cumulative proportion surviving as a function of months since surgery, and differences in survival were tested for significance by the log-rank test. Cox proportional hazards regression was used to test the predictive capacity of IL-4Rα expression in univariate and multivariate models and to estimate 95% confidence intervals (CI) influencing survival. P values less than 0.05 were considered significant.

Results

Increased expression of the IL-4Rα message is predictive of poor survival in patients undergoing resection for epithelial MPM

Tumor expression of IL-4Rα was determined by RTPCR of MPM tumors from 37 patients undergoing EPP. Greater than median expression levels of IL-4Rα were associated with significantly worse survival for patients with epithelial (n = 22), but not nonepithelial MPM (n = 15; Fig. 1A). Univariate Cox proportional hazards modeling identified increased IL-4Rα expression as a predictor of worse survival in patients with epithelial MPM; when adjusted for age, gender, and stage, IL-4Rα expression was retained as an independent predictor of survival (Table 1). Interestingly, a slightly higher level of IL-4Rα expression was found in nonepithelial tumors than in epithelial tumors (Fig. 1B). The expression level of IL-4Rα did not correlate with pathologic stage in the epithelial group but could not be assessed in the nonepithelial group owing to the high distribution of stage III tumors in these patients (Fig. 1C).
Increased expression of the IL-4Rα protein is predictive of poor survival in patients undergoing resection for epithelial MPM

To confirm the expression of IL-4Rα on tumor cells from human MPM tumor specimens, we carried out flow cytometry on the CD45-negative cell fraction of tumor mononuclear cell suspensions, where high frequencies of IL-4Rα-positive cells were found (Fig. 2A). To determine the degree of expression of the IL-4Rα protein on epithelial and nonepithelial MPM, and if expression of the IL-4Rα protein was associated with survival in MPM, we stained our TMA of tumors from 52 patients with an anti-IL-4Rα antibody (Fig. 2B). IL-4Rα staining was present on the tumors of 31 of 32 patients with epithelial tumors (97%) and 19 of 20 patients with nonepithelial tumors (95%). Although a small, scattered fraction of cells in the stromal compartment of the tumor stained positive for IL-4Rα, the great majority of IL-4Rα staining was found on the tumor cells themselves. Similar to the RT-PCR data, strong IL-4Rα staining was associated with worse overall survival following EPP in patients with epithelial MPM (Fig. 2C). A greater fraction of epithelial tumors showed strong staining for the IL-4Rα protein than nonepithelial tumors (27% ± 4% vs. 10% ± 2%, Fig. 2D), and strong IL-4Rα staining was not associated with pathologic stage (Fig. 2E). Because IL-4Rα is expressed on tumor-infiltrating macrophages in human MPM (7), we compared IL-4Rα and CD68 staining on epithelial and nonepithelial mesothelioma tumors (Supplementary Fig. S1). While IL-4Rα strongly stained the tumor cell compartment, there was less marked staining in the tumor stroma. Conversely, CD68 staining was predominantly found on stromal cells.

Tumor-infiltrating T cells in human MPM are polarized to produce IL-4

Because T lymphocytes are a chief source of IL-4 in tumors, we carried out intracellular cytokine analyses to determine whether tumor-infiltrating T cells in MPM were a potential source of endogenous IL-4. Mononuclear cells were freshly isolated from matched tumor and blood samples from 8 patients undergoing EPP for MPM (epithelial, n = 4; nonepithelial, n = 4). We found that high frequencies of tumor-infiltrating CD3 T cells produced IL-4 after stimulation (21% ± 7%) when compared with matched blood

Table 1. Association of IL-4Rα message with survival in MPM

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<th>Variable</th>
<th>Nonadjusted</th>
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<tr>
<td></td>
<td>HR (95% CI)</td>
<td>P</td>
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<tr>
<td>All (n = 37)</td>
<td>1.78 (1.32–2.47)</td>
<td>&lt;0.0001</td>
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<tr>
<td>Epithelial (n = 22)</td>
<td>2.97 (1.70–6.02)</td>
<td>&lt;0.0001</td>
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<tr>
<td>Nonepithelial (n = 15)</td>
<td>0.91 (0.50–1.66)</td>
<td>0.8</td>
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aAdjusted for age, gender, and stage.
CD3 T cells from the same patients (4% ± 2%; Fig. 3A and B), suggesting that T cells within MPM tumors are skewed to produce IL-4. Although both CD4 and CD8 tumor-infiltrating T cells produced IL-4 (Fig. 3C), CD8 T cells were the major T-cell subset responsible for IL-4 production within the tumor, representing 63% ± 12% of tumor CD3⁺IL-4⁺ T cells, and CD4 T cells were the major T-cell subset responsible for IL-4 production in the blood, representing 56% ± 14% of blood CD3⁺IL-4⁺ T cells (Fig. 3D). This difference was due mainly to a greater number of CD8 than CD4 T cells

Figure 3. Tumor-infiltrating T cells in human MPM are polarized to produce IL-4. Mononuclear cells were freshly isolated from matched blood and tumor specimens from patients undergoing surgical resection of MPM. Intracellular IL-4 production was determined in CD3 T cells by intracellular cytokine analysis after 4 hours of nonspecific stimulation with PMA and ionomycin. A, flow cytometric dot plots from one representative patient. B, summary data of matched tumor and blood CD3⁺IL-4⁺ cells from 8 patients. C, representative contour plot of intratumoral CD4 and CD8 T-cell subsets and intracellular IL-4 production. D, CD4 and CD8 subset composition of CD3⁺IL-4⁺ T cells (n = 5). E, the percentage of CD4 and CD8 T cells that stain positive for IL-4 (n = 5). IL-4 concentrations (F) and IL-13 concentrations (G) in tumor (n = 8), effusion (n = 8), and serum (n = 10) of patients with MPM was determined by ultrasensitive ELISA. Values represent pg/mg of tissue and pg/mL of effusion and serum.
within the tumor, as a similar number of CD8 and CD4 T cells in each compartment stained positive for IL-4 (Fig. 3E). Similar numbers of IL-4+ tumor-infiltrating T cells were found in epithelial and nonepithelial tumors (not shown).

To further characterize the phenotype of tumor-infiltrating T cells in human MPMs, we assayed for T-cell production of IFN-γ and IL-10. Interestingly, we found that tumor-infiltrating T cells in human MPM were significant producers of IFN-γ in response to PMA/ionomycin when compared with matched circulating T cells (Supplementary Fig. S2A, 47% ± 4% tumor, 20% ± 12% blood, \( P = 0.02 \)). A small frequency of both tumor-infiltrating T cells and matched circulating T cells produced IL-10 in response to PMA/ionomycin stimulation (Supplemental Fig. S2B, 5% ± 1% tumor, 3% ± 1% blood, \( P = 0.2 \)). To determine whether the ligands for the IL-4 receptor are present in MPM tumors, we used ELISA to detect IL-4 and IL-13 concentrations within the tumor tissue. Low levels of IL-4 were measured in tumor tissues (\( n = 8 \)), whereas IL-4 was undetectable in the serum (\( n = 10 \)) and effusion (\( n = 8 \)) of patients with MPM (Fig. 3F). IL-13 was present in all compartments, with higher levels found in tumors and effusions than in serum (Fig. 3G).

STAT-6 signaling is activated in human MPM cancer cells in response to IL-4

Because human MPM tumor cells express high in situ levels of IL-4Rα and tumor-infiltrating T cells in MPM are skewed toward an IL-4–producing phenotype, we asked whether IL-4 had a biologic effect on MPM tumor cells. To investigate the function of IL-4Rα on human MPM cancer cells, we studied 4 human MPM cell lines. We first confirmed that each of these cell lines showed cell surface expression of IL-4Rα using flow cytometry (Fig. 4A). We then cultured MPM tumor cells in the presence of IL-4 to determine whether IL-4 caused activation of STAT-6 signaling. Culture with IL-4 increased the levels of phosphorylated STAT-6 in each of the 4 MPM cell lines by 29% to 46%, suggesting that the IL-4Rα receptor complex on MPM tumor cells is functional (Fig. 4B).

Human MPM cancer cells respond to IL-4 via production of inflammatory and angiogenic cytokines

IL-4 is a pleiotropic cytokine that has been shown to have varied and sometimes opposing effects on tumors that include both increasing and decreasing the proliferation and survival of malignant cells (18). To determine whether IL-4 could provide a direct survival benefit to human MPM cells, we cultured MPM tumor cells in the presence of IL-4 and found no change in proliferation or apoptosis (Fig. 5A and B). To determine whether IL-4 had proinflammatory or anti-inflammatory effects on MPM tumor cells, we assayed cell culture supernatants for production of various cytokines including IL-6, IL-8, and VEGF. Addition of IL-4 resulted in statistically significant increases in production of the inflammatory cytokine IL-6 on each of the 4 MPM cell lines (Fig. 5C). MS924 and JMN cells similarly increased production of the inflammatory cytokine IL-8, whereas no change in IL-8 production was seen in H2052 or MS428 MPM cells. Culture in IL-4 resulted in increased production of the angiogenic cytokine, VEGF, in H2052, MS924, and JMN cells. Although all MPM cell lines made significant quantities of TGF-β, no increase in production was found in response to IL-4, and no MPM cell lines made significant quantities of TNF-α, macrophage colony-stimulating factor, or monocyte chemotactic protein 1 (MCP-1) while resting or in response to IL-4 stimulation (not shown).

**Discussion**

IL-4Rα is the major subunit of the IL-4 receptor and a primary IL-4–binding protein. After binding of IL-4 and receptor complex formation, intracellular signaling ensues through phosphorylation of STAT-6 (19, 20). IL-4Rα is expressed on a number of cancer cell lines derived from nonhematologic human malignancies that include pancreatic adenocarcinoma, renal cell carcinoma, melanoma, ovarian carcinoma, Kaposi sarcoma, glioblastoma, colon carcinoma, gastric carcinoma, breast carcinoma, lung carcinoma, and head and neck cancers (8, 21). Moreover, elevated expression of IL-4Rα has been found on several human tumors in situ. For example, IL-4Rα has been detected in 66% to 79% of non–small cell lung cancer tumors (9), 60% of ovarian carcinomas (10), 77% of head and neck cancers (11), and is also present on pancreatic, breast, bladder, and prostate carcinomas (12).

In addition to its expression on tumor cells, IL-4Rα is detected on circulating and tumor-infiltrating myeloid immune cells with immunosuppressive properties in cancer-bearing hosts. IL-4Rα is a marker of the recently...
described myeloid-derived suppressor cells in tumor-bearing mice and also identifies a fraction of circulating mononuclear and polymorphonuclear cells with T-cell suppressive function in patients with melanoma and colon cancer (22, 23). In human MPM, we have found that IL-4Ra is highly expressed on a population of tumor-infiltrating macrophages that displays an immunoregulatory phenotype (7). Given the high expression of IL-4Ra on multiple human cancers and the tumor-promoting effects of IL-4 on human cancer cells (18), it is likely that IL-4Ra plays a role in tumor progression in humans. For example, IL-4Ra competent murine tumors exhibit increased tumor growth when compared with tumors from IL-4Ra–deficient counterparts (24). Herein, we show that patients with epithelial MPM whose tumors show high IL-4Ra expression have a significant survival disadvantage after surgical resection. The reason for this difference between epithelial and nonepithelial MPM is not exactly clear; however, nonepithelial MPM is a particularly aggressive tumor and the immune response to epithelial and nonepithelial MPM is distinct (7). It should be noted that our PCR data represent IL-4Ra expression of the entire tumor mass (tumor cells and stromal cells that include macrophages), whereas our immunohistochemical experiments were designed to focus on tumor cell expression of IL-4Ra. To our knowledge, this is the first study to equate tumor expression of IL-4Ra with survival indices in patients with cancer.

The distinction of Th1 and Th2 immune responses has important implications for patients with cancer. Antitumor immune responses are sustained principally by tumor-infiltrating lymphocytes consisting primarily of T cells. While Th1 responses typically signify the production of IL-2 and IFN-γ with activation of cytotoxic T-cell responses, Th2 responses generally represent a cytokine profile including IL-4, IL-5, IL-6, and IL-13 (25), of which IL-4 is the prototypic Th2 cytokine. IL-4 has differential effects on immunity that could be advantageous to tumor growth. These include inhibition of Th1 cell differentiation and cellular immunity, abrogation of CD8 T-cell cytotoxicity, accumulation of Th2 cytokines, and facilitation of Th2 CD4 T-cell development (26, 27). Most clinical studies support the finding of an abnormal Th1 to Th2 ratio in patients with various cancers.
and it has been shown that the nature of the immune response (Th1 vs. Th2) can affect outcome in patients with cancer. Specifically, high serum and tumor IL-4 levels, and high frequencies of IL-4-secreting T cells are elevated in patients with cancer and parallel worse prognosis (28–30). Our data show that the natural immune reaction to human MPM involves tumor-infiltrating T cells skewed toward an IL-4-producing phenotype.

The direct effects of IL-4 on tumor cells are varied and sometimes opposing. In human colon cancer cell lines, treatment with IL-4 results in dose-dependent increases in cellular proliferation (31), and IL-4 is an autocrine growth factor made by pancreatic cancer cells (21). IL-4 protects human prostate, breast, and cancer cell lines from chemotherapy and death receptor–induced apoptosis through upregulation of antiapoptotic proteins cFLIP/FLAME-1 and Bcl-xl (12). Similar results are seen in murine in vivo tumor models where IL-4 increases tumor growth, reduces apoptosis, and promotes metastases (24, 32). Conversely, IL-4 is required for the development of effective antitumor immunity (33). For instance, IL-4 can have a direct inhibitory effect on proliferation of human cancer cells (34, 35), and IL-4 can be a potent antitumor agent in animal models (36, 37). It has been suggested that the differential positive and negative effects of IL-4 on tumor development may be explained by the source of IL-4, with exogenously delivered IL-4 exerting tumor-suppressing effects and endogenously produced IL-4 exerting tumor-promoting effects (18).

Our data show that IL-4 did not have a direct effect on MPM tumor cell line proliferation or apoptosis. Activation of human MPM cells with IL-4 resulted in upregulation of STAT-6 phosphorylation and an increase in production of inflammatory and angiogenic cytokines including IL-6, IL-8, and VEGF. Each of these cytokines has been shown to be produced by MPM cell lines where they act as potent autocrine growth factors and are each detected at significant levels in the effusions of patients with MPMs (38–42). IL-6 is a multifunctional, proinflammatory cytokine involved in acute phase inflammatory responses and additionally stimulates VEGF production by MPM cells (43). It has been suggested that IL-6 may be responsible for the systemic manifestations of MPM that include fever, cachexia, and thrombocytosis (44). IL-8 is a member of the C-X-C chemokine family and has direct growth-potentiating and angiogenic effects on tumors. VEGF is a powerful mitogen for the vascular endothelium, and in patients with MPM, elevated serum levels of VEGF correlate with advanced disease stage and worse survival (45). It is reasonable to surmise that each of these factors has tumor-promoting effects in the tumor microenvironment.

Taken together, the high expression of IL-4Rα on human tumor cells, its association with protumor function, and its correlation with survival reported here make it a promising therapeutic target. Puri’s group has targeted tumor IL-4Rα with a chimeric protein consisting of a circularly permuted IL-4 molecule that is fused to a truncated form of Pseudomonas exotoxin. This agent has been shown to have potent cytotoxic activity in vitro against numerous IL-4Rα expressing cell lines and in vivo in xenograft models of various human cancers including MPM (8, 14, 46, 47). Ultimately, this molecule has been brought to clinical trials and has shown encouraging results in patients with glioblastoma (48).

In summary, MPM is a malignancy whose origin and development are deeply rooted in inflammation. We have found that IL-4Rα is highly expressed in situ by tumor cells in human MPM tumors, tumor expression of IL-4Rα is predictive of survival in patients undergoing cytoreductive surgery for epithelial MPM, and that MPM tumor cells respond to IL-4 via upregulation of STAT-6 signaling and inflammatory cytokine production. We hypothesize that IL-4 endogenously produced by MPM tumor-infiltrating T cells provides stimulus to the IL-4 receptor on MPM tumor cells in vivo and promotes inflammatory and angiogenic signals that stimulate tumorigenesis. Taken together, it seems that mesothelioma tumors with high IL-4Rα expression are clinically more aggressive cancers that have worse outcome after surgical resection. These data have important implications for future research and clinical applications. IL-4Rα is a potentially useful marker of prognosis in patients undergoing surgical resection and possibly also for patients undergoing definitive chemotherapy; however, this requires further investigation. Moreover, the IL-4/IL-4Rα axis represents a promising target for directed therapy in man, with potential application for IL-4 and IL-4 receptor blocking agents and IL-4Rα–specific cytotoxins.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

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