

AD _____

Award Number: DAMD17-03-1-0078

TITLE: SDF-1, DC1/DC2, and Tumor Angiogenesis

PRINCIPAL INVESTIGATOR: Weiping Zou, M.D., Ph.D.

CONTRACTING ORGANIZATION: Tulane University
New Orleans, LA 70112

REPORT DATE: April 2006

TYPE OF REPORT: Final

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for Public Release;
Distribution Unlimited

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision unless so designated by other documentation.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 01-04-2006		2. REPORT TYPE Final		3. DATES COVERED (From - To) 10 MAR 2003 - 9 MAR 2006	
4. TITLE AND SUBTITLE SDF-1, DC1/DC2, and Tumor Angiogenesis				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER DAMD17-03-1-0078	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Weiping Zou, M.D., Ph.D. E-mail: wzou@tulane.edu				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Tulane University New Orleans, LA 70112				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Medical Research and Materiel Command Fort Detrick, Maryland 21702-5012				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Angiogenesis is essential for both primary and metastatic tumor growth. A number of molecules have been identified in this process. Early clinical trials with anti-angiogenic molecules, however, have not demonstrated significant benefits predicted from preclinical models. In the last 3 years, we have focused on human ovarian carcinomas and studied ovarian cancer associated dendritic cell subsets (DC1 and DC2) and chemokine SDF-1, and their contribution to tumor angiogenesis. We observed that the balance of DC subset distribution and functions in the tumor environment is relevant to tumor angiogenesis. Tumor DC2 induce tumor angiogenesis, whereas DC1 inhibit tumor angiogenesis. Ovarian tumors manipulate DC subpopulation distributions and functions by producing SDF-1 to favor tumor angiogenesis. Tumor VEGF and SDF-1 synergistically form a novel angiogenic pathway. Targeting this pathway may be applicable to development of antiangiogenesis therapies.					
15. SUBJECT TERMS Dendritic cells, SDF-1, angiogenesis, ovarian tumors					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 39	19a. NAME OF RESPONSIBLE PERSON USAMRMC
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (include area code)

Table of Contents

Cover.....	1
SF 298.....	2
Introduction.....	4
Body.....	5
Key Research Accomplishments.....	8
Reportable Outcomes.....	9
Conclusions.....	12
References.....	12
Appendices.....	15

INTRODUCTION:

Angiogenesis is essential for both primary and metastatic tumor growth. A number of molecules have been identified in this process. Early clinical trials with anti-angiogenic molecules, however, have not demonstrated significant benefits predicted from preclinical models (1-3). Previously in vitro identified angiogenic molecule b3 and b5 integrins have recently been shown no support in vivo angiogenesis (4, 5). Angiogenic molecule bFGF is found positively related to the prolonged survival of tumor patients (6). The reasons for these apparent discrepancies are that the extent of angiogenesis is determined by multiple factors. In tumor microenvironment, each individual tumor may display a different angiogenic phenotype (1, 2, 7, 8). Although endothelial cells and their released angiogenic molecules have extensively been studied, the potential angiogenic roles of tumor environmental immune cells, particularly tumor dendritic cells (DC) have not been defined. These immune cells may contribute to tumor development and progression by directly or/and synergistically inducing tumor angiogenesis with tumor cells.

Therefore, in the last 3 years, we have focused on human ovarian carcinomas and studied ovarian cancer associated dendritic cell subsets (DC1 and DC2) and chemokine SDF-1, and their contribution to tumor angiogenesis. As ovarian cancers have a poor prognosis, often associated with multifocal intraperitoneal dissemination. To examine events related to tumor angiogenesis in the tumor

microenvironment, we have studied ascites and tumor mass of patients with untreated ovarian carcinoma. Malignant ascites contains viable tumor cells, immune cells, soluble tumor antigens and soluble factors derived from tumor and immune cells (9-11). It is a relevant, highly accessible in vivo model for tumor microenvironment. We have tested our hypotheses in this 3 year study.

Aim 1: To test our hypothesis that tumor SDF-1 induces in vivo angiogenesis

Aim 2: To test our hypothesis that tumor DC2 induces in vivo angiogenesis

Aim 3: To test our hypothesis that tumor DC1 induces in vivo angiogenesis

BODY:

Tumor derived SDF-1 and tumor angiogenesis: We show that human ovarian epithelial tumor cells express high levels of stromal derived factor-1 (SDF-1) (11) and release it into malignant ascites ($42,329 \pm 12,560$ pg/ml, n=6) (Figure 2 in article 1). Although SDF-1 does not contain the N-terminal Glu-Leu-Arg (ELR) motif with angiogenic function (12), mice lacking SDF-1 or CXCR4 have defective vascular system development (13, 14). We demonstrated that although SDF-1 in tumor ascites induced potent angiogenesis (Figure 1 in article 1), the pathological concentrations of SDF-1 have no angiogenic effects (Figure 3 in article 1). But high concentrations of SDF-1 directly induce angiogenesis in vivo. Strikingly, we

observed that pathological concentrations of SDF-1 and VEGF significantly and synergistically induced angiogenesis (Figure 3 in article 1). Migration, expansion and survival of vascular endothelial cells form the essential functional network of angiogenesis. We further provide a mechanistic basis for explaining the interaction between CXCL-12 and VEGF. We show that VEGF upregulates the receptor for CXCL-12, CXCR4 expression on vascular endothelial cells, and synergizes CXCL-12-mediated migration of vascular endothelial cells. Whereas CXCL-12 synergizes VEGF-mediated vascular endothelial cell expansion, and synergistically protects vascular endothelial cells from sera starvation-induced apoptosis with VEGF (Figure 4 in article 1). Altogether, these results demonstrated that tumor derived CXCL-12 and VEGF form a synergistic angiogenic axis in vivo. Interrupting this synergistic axis, rather than VEGF alone, will be a novel efficient anti-angiogenesis strategy to treat cancer.

In addition to our proposed studies, we further investigated the regulation of SDF-1 and VEGF pathway. We demonstrated that hypoxia stimulated tumor SDF-1 and VEGF expression (Figure 5 in article 1). Therefore, hypoxia serves as a triggering mechanism for fostering SDF-1 and VEGF synergistic angiogenesis.

Tumor DC1, DC2 and tumor angiogenesis: In our study of ovarian carcinoma patients, another important finding is the striking DC distribution: numerous DC2 (also referred as plasmacytoid dendritic cells), but no HLA-DR^{hi}CD11c⁺CD14⁻ myeloid dendritic cells (referred as DC1) (11) in malignant ascites. We have

demonstrated that tumor SDF-1 contributes to DC2 tumor migration and accumulation. Further, tumor DC2 may be detrimental to anti-tumor immunity (11). The significance of DC-system has been focused on tumor immunity. There are no reports regarding the DC system and tumor angiogenesis. We now showed that tumor DC2 induced a dose dependent in vivo angiogenesis (Figure 1 in article 2). Further, tumor DC2 derived TNF- α and IL-8 are basically for the in vivo angiogenic effects (Figure 2 in article 2). In support of this, tumor DC2 spontaneously produce high levels of angiogenic cytokines VEGF (1123 ± 235 pg/ml with no stimulation, 3124 ± 632 pg/ml with CD40L stimulation for 10^6 tumor DC2, n=5) and TNF- α (190 ± 89 pg/ml with no stimulation, 1033 ± 329 pg/ml with CD40L stimulation for 10^6 tumor DC2, n=5) (Figure 1 in article 2). Tumor DC2 produce undetectable IL-12 (< 20 pg/ml, n=6), induce little T cell IFN- γ (11, 15), and T cell IP-10 (< 80 pg/ml, n=5). IL-12, IFN- γ and IP-10 are potent angiogenic inhibitory cytokines. Thus, **tumor DC2 induce or/and support in vivo angiogenesis.**

Tumor DC1 and tumor angiogenesis: On the other hand, although there are no substantial amount of DC1 in malignant ascites, we have demonstrated that malignant ascites monocytes/macrophages can be in vitro differentiated into functional DC1 (16). These DC1 produce potent IL-12 ($1,830 \pm 250$ pg/ml, n=4), induce strong T cell IFN- γ ($5,274 \pm 432$ pg/ml) and IP-10 ($1,860 \pm 182$ pg/ml, n=4). Thus, tumor DC1 produce or induce a large amount of anti-angiogenic cytokines (IL-12, IFN- γ , IP-10). We further tested the in vivo angiogenic activity.

We showed that tumor DC1 suppressed angiogenesis in a dose dependent manner (Figure 2 in article 2). Whereas blocking experiments revealed that tumor DC1 derived IL-12 is crucial for DC1-mediated angiogenesis suppression (Figure 2 in article 2). Our data indicate that **tumor DC1 suppress tumor angiogenesis by producing or inducing anti-angiogenic cytokines.**

Summary: The balance of DC subset distribution and functions in the tumor environment is relevant to tumor angiogenesis. Tumor DC2 induce tumor angiogenesis, whereas DC1 inhibit tumor angiogenesis. Ovarian tumors manipulate DC subpopulation distributions and functions by producing SDF-1 to favor tumor angiogenesis. **Tumor VEGF and SDF-1 synergistically form a novel angiogenic pathway.** Targeting this pathway may be applicable to development of anti-angiogenesis therapies.

KEY RESEARCH ACCOMPLISHMENTS

Tumor derived SDF-1 and VEGF synergistically induced angiogenesis.

SDF-1 and VEGF synergistically regulate CXCR4 expression.

Hypoxia regulates tumor derived SDF-1 and VEGF production.

Tumor associated PDC induced angiogenesis in vivo.

Tumor associated PDC IL-8 and TNF- α are the critical angiogenesis factors

Tumor associated MDC suppressed angiogenesis in vivo

Tumor associated MDC derived IL-12 is critical for suppressing angiogenesis in vivo.

REPORTABLE OUTCOMES

Published manuscripts

Two original articles and one Nature review article were directly related to this proposal and directly supported by this grant. These 3 articles are enclosed. Several original and review articles are indirectly related to this work and we cite these articles here, but not providing the full articles.

Zou W. Regulatory T cells, tumor immunity and immunotherapy. **Nature Review (Immunology)** in press.

Wei S, Kryczek I, **Zou W.** Regulatory T cell compartmentalization and trafficking, in press.

Kryczek I, Wei S, Zou L, Zhu G, Mottram P, Chen L, **Zou W**. Induction of B7-H4 on Antigen Presenting Cells through Interleukin 10: Novel Suppressive Mode for Regulatory T Cells, **in press**.

Kryczek I, Zou L, Rodriguez P, Wei S, Zhu G, Mottram P, Ochoa A, L Chen L, **Zou W**. B7-H4 expression identifies a novel suppressive macrophage population in human ovarian carcinoma, **in press**.

Wei S, Kryczek I, Cheng P, Mottram P, Alvarez X, Zou L, Emilie D, Lackner A, **Zou W**. Plasmacytoid dendritic cells induce CD8⁺ regulatory T cells in human ovarian cancers. **Cancer Res, 2005, 65, 5020-5026**.

Zou W. Immunosuppressive networks in the tumor environment and their therapeutic relevance. **Nature Review (Cancer), 2005, 5:263-274**.

Kryczek I, Cheng P, Mottram P, Alvarez X, Moons L, Evdemon-Hogan M, Wei S, Zou L, Machelon V, Emilie D, Lackner A, Curiel TJ, Carmeliet P, **Zou W**. CXCL-12 and VEGF synergistically induce neoangiogenesis in human ovarian cancers. **Cancer Res, 2005, 65, 465-472**.

Kryczek I, Frydman N, Gaudin F, Krzysiek R, Fanchin R, Emilie D, Chouaib S, **Zou W**, Machelon V. The chemokine SDF-1/CXCL12 contributes to T lymphocyte recruitment in human pre-ovulatory follicles and coordinates with lymphocytes to increase granulosa cell survival and embryo quality. **Am J Reprod Immunol**, 2005, **54(5):270-83**.

Curiel, T.J., G. Coukos, L. Zou, X. Alvarez, P. Cheng, P. Mottram, M. Evdemon-Hogan, J.R. Conejo-Garcia, L. Zhang, M. Burow, Y. Zhu, S. Wei, I. Kryczek, B. Daniel, A. Gordon, L. Myers, A. Lackner, M.L. Disis, K.L. Knutson, L. Chen, and **W. Zou**. Specific recruitment of regulatory T cells in ovarian carcinoma fosters immune privilege and predicts reduced survival. **Nat Med** 2004,**10:942-949**.

Zou L, Barnett B, Safah H, LaRussa VF, Evdemon-Hogan M, Mottram P, Wei S, David O, Curiel TJ, **Zou W**. Bone marrow is a reservoir for CD4⁺CD25⁺ regulatory T cells that traffick through CXCL12/CXCR4 signals. **Cancer Res** 2004, **64**, **8451-8455**.

Curiel J, Cheng P, Mottram P, Alvarez X, Kryczek I, Moons L, Evdemon-Hogan M, Wei S, Zou L Hoyle G, Lackner A, Carmeliet P, **Zou W**. Dendritic cell subsets differentially regulate angiogenesis in human ovarian cancer. **Cancer Res** 2004, **64**, **5535-5538**.

Curiel TJ, Wei S, Dong H, Alvarez X, Cheng P, Mottram P, Krzysiek R, Knuston K, Daniel B, Zimmermann MC, David O, Burow M, Gordon A, Dhurandhar N, Myers L, Berggren R, Hemminki A, Alvarez RD, Emilie D, Curiel DT, Chen L, **Zou W**. Blockade of B7-H1 Improves Myeloid Dendritic Cell-Mediated Anti-Tumor Immunity. **Nat Med** 2003, **9:562-567**.

CONCLUSIONS

In summary, our data demonstrate a novel role for SDF-1 and VEGF in human cancer. Tumor derived SDF-1 and VEGF synergistically induce tumor angiogenesis. This is a previously unappreciated angiogenesis pathway. Blocking SDF-1 and VEGF, rather than VEGF alone may be a novel strategy to block tumor neoangiogenesis. Further, we show that dendritic cell balance in tumor environment is crucial for promoting tumor angiogenesis. Tumor DC1 suppress and tumor DC2 enhance tumor angiogenesis.

REFERENCES:

1. Ellis LM, Liu W, Ahmad SA, et al. Overview of angiogenesis: Biologic implications for antiangiogenic therapy. *Semin Oncol* 2001;28:94-104.

2. Ellis LM, Liu W, Fan F, et al. Role of angiogenesis inhibitors in cancer treatment. *Oncology (Huntingt)* 2001;15:39-46.
3. Jung YD, Ahmad SA, Akagi Y, et al. Role of the tumor microenvironment in mediating response to anti- angiogenic therapy. *Cancer Metastasis Rev* 2000;19:147-57.
4. Reynolds LE, Wyder L, Lively JC, et al. Enhanced pathological angiogenesis in mice lacking beta3 integrin or beta3 and beta5 integrins. *Nat Med* 2002;8:27-34.
5. Carmeliet P. Integrin indecision. *Nat Med* 2002;8:14-6.
6. Obermair A, Speiser P, Reisenberger K, et al. Influence of intratumoral basic fibroblast growth factor concentration on survival in ovarian cancer patients. *Cancer Lett* 1998;130:69-76.
7. Yu JL, Rak JW, Carmeliet P, et al. Heterogeneous vascular dependence of tumor cell populations. *Am J Pathol* 2001;158:1325-34.
8. Carmeliet P and Jain RK. Angiogenesis in cancer and other diseases. *Nature* 2000;407:249-57.
9. Beatty P, Hanisch FG, Stolz DB, et al. Biochemical characterization of the soluble form of tumor antigen MUC1 isolated from sera and ascites fluid of breast and pancreatic cancer patients. *Clin Cancer Res* 2001;7:781s-7s.
10. Rabinowich H, Suminami Y, Reichert TE, et al. Expression of cytokine genes or proteins and signaling molecules in lymphocytes associated with human ovarian carcinoma. *Int J Cancer* 1996;68:276-84.

11. Zou W, Machelon V, Coulomb-L'Hermin A, et al. Stromal-derived factor-1 in human tumors recruits and alters the function of plasmacytoid precursor dendritic cells. *Nat Med* 2001;7:1339-46.
12. Strieter RM, Polverini PJ, Kunkel SL, et al. The functional role of the ELR motif in CXC chemokine-mediated angiogenesis. *J Biol Chem* 1995;270:27348-57.
13. Tachibana K, Hirota S, Iizasa H, et al. The chemokine receptor CXCR4 is essential for vascularization of the gastrointestinal tract. *Nature* 1998;393:591-4.
14. Nagasawa T, Hirota S, Tachibana K, et al. Defects of B-cell lymphopoiesis and bone-marrow myelopoiesis in mice lacking the CXC chemokine PBSF/SDF-1. *Nature* 1996;382:635-8.
15. Rissoan MC, Soumelis V, Kadowaki N, et al. Reciprocal control of T helper cell and dendritic cell differentiation. *Science* 1999;283:1183-6.
16. Zou W, Borvak J, Marches F, et al. Macrophage-derived dendritic cells have strong Th1-polarizing potential mediated by beta-chemokines rather than IL-12. *J Immunol* 2000;165:4388-96.

Contact:

Weiping Zou, MD, PhD
Associate Professor of Medicine, Immunology and Molecular Biology
Section of Hematology & Medical Oncology
Tulane University School of Medicine
1430 Tulane Ave. SL-78
New Orleans, LA 70112
Office: 504-988-6057
Fax: 504-988-5516
Email: wzou@tulane.edu

APPENDICES

Included PDF for 3 original journal articles

CXCL12 and Vascular Endothelial Growth Factor Synergistically Induce Neoangiogenesis in Human Ovarian Cancers

Ilona Kryczek,^{1,2} Andrzej Lange,² Peter Mottram,¹ Xavier Alvarez,¹ Pui Cheng,¹ Melina Hogan,¹ Lieve Moons,³ Shuang Wei,¹ Linhua Zou,¹ Véronique Machelon,⁴ Dominique Emilie,⁴ Margarita Terrassa,¹ Andrew Lackner,¹ Tyler J. Curiel,¹ Peter Carmeliet,³ and Weiping Zou¹

¹Tulane University Health Science Center, New Orleans, Louisiana; ²Institute of Immunology and Experimental Therapy, Polish Academy of Sciences, Wrocław, Poland; ³Center for Transgene Technology and Gene Therapy, Flanders Interuniversity Institute for Biotechnology, Leuven, Belgium; and ⁴Institut Paris-Sud Sur Les Cytokines, Institut National de la Santé et de la Recherche Médicale, Clamart, France

Abstract

Ovarian carcinomas have a poor prognosis, often associated with multifocal i.p. dissemination accompanied by intense neovascularization. To examine tumor angiogenesis in the tumor microenvironment, we studied malignant ascites and tumors of patients with untreated ovarian carcinoma. We observed that malignant ascites fluid induced potent *in vivo* neovascularization in Matrigel assay. We detected a sizable amount of vascular endothelial cell growth factor (VEGF) in malignant ascites. However, pathologic concentration of VEGF is insufficient to induce *in vivo* angiogenesis. We show that ovarian tumors strongly express CXC chemokine stromal-derived factor (SDF-1/CXCL12). High concentration of CXCL12, but not the pathologic concentration of CXCL12 induces *in vivo* angiogenesis. Strikingly, pathologic concentrations of VEGF and CXCL12 efficiently and synergistically induce *in vivo* angiogenesis. Migration, expansion, and survival of vascular endothelial cells (VEC) form the essential functional network of angiogenesis. We further provide a mechanistic basis for explaining the interaction between CXCL12 and VEGF. We show that VEGF up-regulates the receptor for CXCL12, CXCR4 expression on VECs, and synergizes CXCL12-mediated VEC migration. CXCL12 synergizes VEGF-mediated VEC expansion and synergistically protects VECs from sera starvation-induced apoptosis with VEGF. Finally, we show that hypoxia synchronously induces tumor CXCL12 and VEGF production. Therefore, hypoxia triggered tumor CXCL12 and VEGF form a synergistic angiogenic axis *in vivo*. Hypoxia-induced signals would be the important factor for initiating and maintaining an active synergistic angiogenic pathway mediated by CXCL12 and VEGF. Thus, interrupting this synergistic axis, rather than VEGF alone, will be a novel efficient antiangiogenesis strategy to treat cancer. (Cancer Res 2005; 65(2): 465-72)

Introduction

Tumor angiogenesis is essential for the growth of primary and metastatic tumors. Tumors and metastases may originate as small avascular masses that induce the development of new blood vessels once they grow to a few millimeters in size (1, 2). One of the most well characterized angiogenic factors is vascular endothelial cell growth

factor (VEGF). VEGF has angiogenic action in numerous *in vivo* and *in vitro* models (3, 4). Many antiangiogenic strategies have targeted VEGF activity. Some reports of tumor regression in experimental models of angiogenesis exist. The majority of studies show antiangiogenic therapy leads to an inhibition of tumor growth rather than a regression of established tumors (5, 6). Early clinical trials with antiangiogenic strategies, however, have not replicated the results observed from preclinical models (3, 7, 8). Previously identified angiogenic molecules $\beta 3$ and $\beta 5$ integrins have recently been shown not to support *in vivo* angiogenesis (9, 10). Angiogenic molecule basic fibroblast growth factor is found positively related to the prolonged survival of tumor patients (11). The reasons for these apparent discrepancies are that the extent of angiogenesis is determined by multiple factors in tumor microenvironment and each individual tumor may display a different angiogenic phenotype. Some other potential angiogenic factors may also have functionally been ignored in the designs of antiangiogenic strategies.

Ovarian carcinoma is the fifth leading cause of cancer among women and leading cause of mortality among cancers of the female reproductive system (12). Ovarian carcinomas have a poor prognosis, often associated with multifocal i.p. dissemination with potent neovascularization. The related mechanism remains poorly understood. Ovarian tumor cells produce a large amount of CXCL12 (13) and release into peritoneal cavity. In this report, we show that hypoxia importantly and synchronously induces CXCL12 and VEGF production by tumors, and CXCL12 and VEGF form a synergistic angiogenic axis to induce angiogenesis *in vivo*.

Materials and Methods

Human Subjects and Clinical Samples. We studied patients with ovarian carcinomas. Patients are given written informed consent. The study was approved by the local Institutional Review Board. No cancer patients received prior specific treatments. Ascites have been collected from consecutive patients with previously untreated ovarian carcinoma. Ascites were collected aseptically, and harvested cells by centrifugation over a Ficoll-Hypaque density gradient (13).

***In vivo* Matrigel Assay.** We established an *in vivo* Matrigel assay in mice (14–17). Briefly, 0.5 mL of iced Matrigel (Becton Dickinson, San Jose, CA) admixed with the relevant cytokines or ascites and heparin were injected into the right lower abdomen of female C57 mice (6–8 weeks). After 10 to 12 days (16), the Matrigel plugs were isolated and processed for quantifying microvessel density (18) with ImagePro Plus software (Image-Pro plus, Media Cybernetics, Silver Spring, MD). Microvessel density was expressed as mean percentage of microvessel surface area by confocal Leica TCS-NT SP microscope.

Requests for reprints: Weiping Zou, Section of Hematology and Medical Oncology, Tulane University Health Science Center, 1430 Tulane Avenue, New Orleans, LA 70112-2699. Phone: 504-988-5482; Fax: 504-988-5483; E-mail: wzou@tulane.edu.

©2005 American Association for Cancer Research.

Immunohistochemistry. Matrigel plugs were subjected to immunohistochemistry analysis with rabbit anti-human-vWF antibody (polyclonal, 1/100 dilution, DAKO, Carpinteria, CA), and further stained with goat anti-rabbit antibody (immunoglobulin G, 1/2,000 dilution, Molecular Probes, Eugene, Oregon). Surface occupied by vascular endothelial cells (vWF⁺ green cells) was quantified by confocal microscope as described above. Tumor tissues CXCL12 expression was analyzed by immunohistochemistry with 8- μ m cryosections of acetone-fixed ovarian tumor tissues as we described previously (13, 19). Tumor tissues were incubated for 2 hours at room temperature with anti-CXCL12 antibody (clone K15C, IgG2a, 10 μ g/mL), or control isotype. Antibody binding was detected with biotinylated anti-mouse antibodies and streptavidin conjugated to alkaline phosphatase (Biogenex, San Ramon, CA) using fast red substrate. Sections were counterstained with Mayer hematoxylin.

Reverse Transcriptase-PCR. CXCL12 and VEGF mRNA was detected by reverse transcriptase-PCR (RT-PCR) as we described (20). Briefly, β -actin was initially amplified and quantified with serial dilutions of cDNA from each sample. CXCL12 was then amplified in each sample containing identical amount of β -actin mRNA. β -Actin primers were sense 5'-gggtcagaaggattcc-tatg-3' and antisense 5'-gggtctcaaacatgatctggg-3'. CXCL12 primers were sense 5'-gggtctctgggtttgtatt-3' and antisense 5'-gtcctgagatccttttgcg-3'. The identical technique and primers were used to amplify each VEGF splice forms as previously published (21).

Migration Assay. Fresh human umbilical vascular endothelial cells (HUVEC) were purified from human umbilical cords as we described (22). HUVECs were transferred into the upper chambers of 8- μ m-pore transwell plates (Neuro Probe, Gaithersburg, MD). CXCL12 and VEGF (R&D System, Minneapolis, MN) were added to the lower chamber. After 40 hours at 37°C, migration was quantified by counting cells in the lower chamber and cells adhering to the bottom of the membrane (13).

Cell Proliferation. Fresh HUVECs (10^5 /mL) were cultured with the indicated cytokines for 72 hours. ³H thymidine was added at the last 16 hours, and cell proliferation was detected by thymidine incorporation as we described (13, 23, 24).

In vitro Apoptosis Assay. Fresh HUVECs (5×10^5 /mL) were cultured in 37°C with different concentrations of FCS in medium with the described conditions. After 24 hours, cells were harvested and stained with Annexin V and 7-AAD. Apoptosis of HUVEC was analyzed by fluorescence-activated cell sorting (13).

Hypoxia Experiments. Primary ovarian tumor cells (5×10^5 /mL or 2×10^6 /mL) were cultured in 37°C incubators with 1% oxygen (Coy Laboratory Products, Inc., Grass Lake, MI) or 21% oxygen with the described conditions. Cells were harvested for detecting VEGF and CXCL12.

ELISA. Cytokines/chemokines in cell supernatants and ascites were detected with commercial kits (R&D Systems). Hemoglobin content in Matrigel plugs was detected with a commercial kit (Sigma, St. Louis, MO).

Statistical Analysis. Differences in cell surface molecule expression were determined by χ^2 test, and in other variables by unpaired *t* test, with *P* < 0.05 considered significant.

Results

Malignant Ascites Fluid Induces Potent *In vitro* Angiogenesis.

To determine the angiogenic factors in malignant ascites, we established an *in vivo* Matrigel assay model (16, 17). As expected, recombinant VEGF (*n* = 8) and tumor necrosis factor- α (*n* = 8) induced a significant angiogenesis (positive control; *, *P* < 0.001, compared with PBS). Interestingly, both malignant ascites fluid (*n* = 12) and nontumor ascites (idiopathic cirrhosis; *n* = 6) induced *in vivo* angiogenesis (*, *P* < 0.001, compared with PBS; Fig. 1). The percentage of microvessel surfaces (Fig. 1A) is correlated with the hemoglobin contents per Matrigel (Fig. 1B; refs. 14, 25). However, malignant ascites were thrice more powerful to induce angiogenesis *in vivo* than cirrhotic ascites (Fig. 1). These data showed that malignant ascites contained angiogenic factor(s).

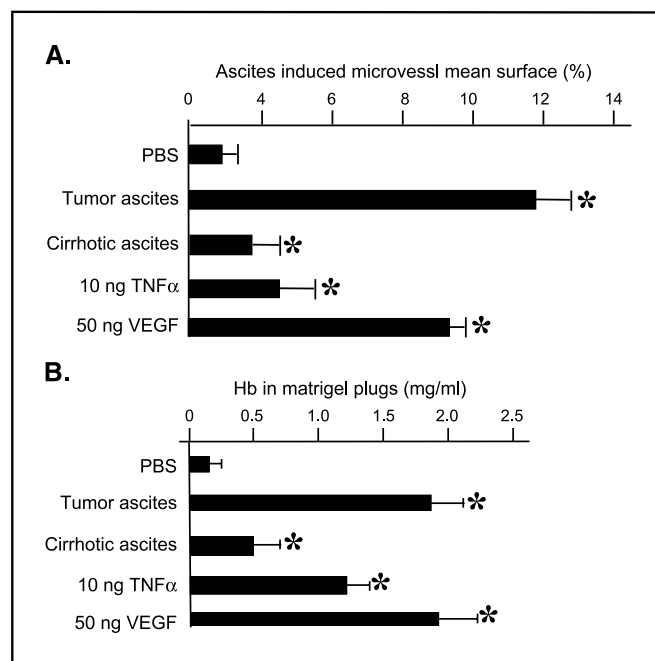


Figure 1. Malignant ascites fluid induces potent *in vivo* angiogenesis. C57 mice were inoculated with Matrigel plugs bearing malignant ascites fluid, cirrhotic ascites (0.5 mL), the indicated cytokines, or PBS. Day 12 Matrigel plugs were removed to study neovascularization as described in Methods. **A**, microvessel surface area in Matrigel plugs was quantified and expressed as % microvessel surface area as we described. **B**, Hb contents in Matrigel plugs were detected with a commercial kit. *, *P* < 0.05, compared with PBS.

CXCL12 in Malignant Ascites. To determine the angiogenic factors in malignant ascites, we screened malignant ascites for the important identified angiogenic factors. We observed significant amounts of VEGF (3.1 ng/mL), IL-8 (1.2 ng/mL), and moderate amounts of tumor necrosis factor- α (0.23 ng/mL), and MCP-1 (0.27 ng/mL) in malignant ascites (*n* = 28; Fig. 2A). Strikingly, we detected high level of CXCL12 (25 ng/mL) in malignant ascites (*n* = 28; *, *P* < 0.001, compared with other cytokines; Fig. 2A). Cirrhotic ascites (*n* = 6) contained moderate levels of these detected cytokines, suggesting that CXCL12 and VEGF may not be as critical as malignant ascites in inducing angiogenesis.

CXCL12 Expression in Tumor Tissues and Primary Tumor Cells. Consistent with our previous report (13), we observed that ovarian tumor tissues expressed potent CXCL12 mRNA (*n* = 12; Fig. 2B). Quantitative RT-PCR (20) revealed no significant difference of CXCL12 mRNA in tumors between FIGO stages I, II, III, and IV, as well as in tumors with different histology, including serous, mucinous, endometrioid, and undifferentiated ovarian tumors (Fig. 2B, data not shown). Immunohistochemistry analysis further confirmed that 100% ovarian tumor tissues expressed CXCL12 protein (*n* = 72; stage I, *n* = 14; stage II, *n* = 12; stage III, *n* = 28; stage IV, *n* = 18; Fig. 2C). No positive cells were observed in tissues stained with isotype antibody (data not shown). Notably, the level of CXCL12 protein expression was relatively variable and was not significantly different between different donors, between different disease stages, and between different tumor histologic types (Fig. 2C).

We further established 12 ovarian epithelial tumor cell lines from tumor ascites. We observed that all the primary tumor cell lines strongly expressed CXCL12 mRNA (*n* = 12; Fig. 2D). Intracellular

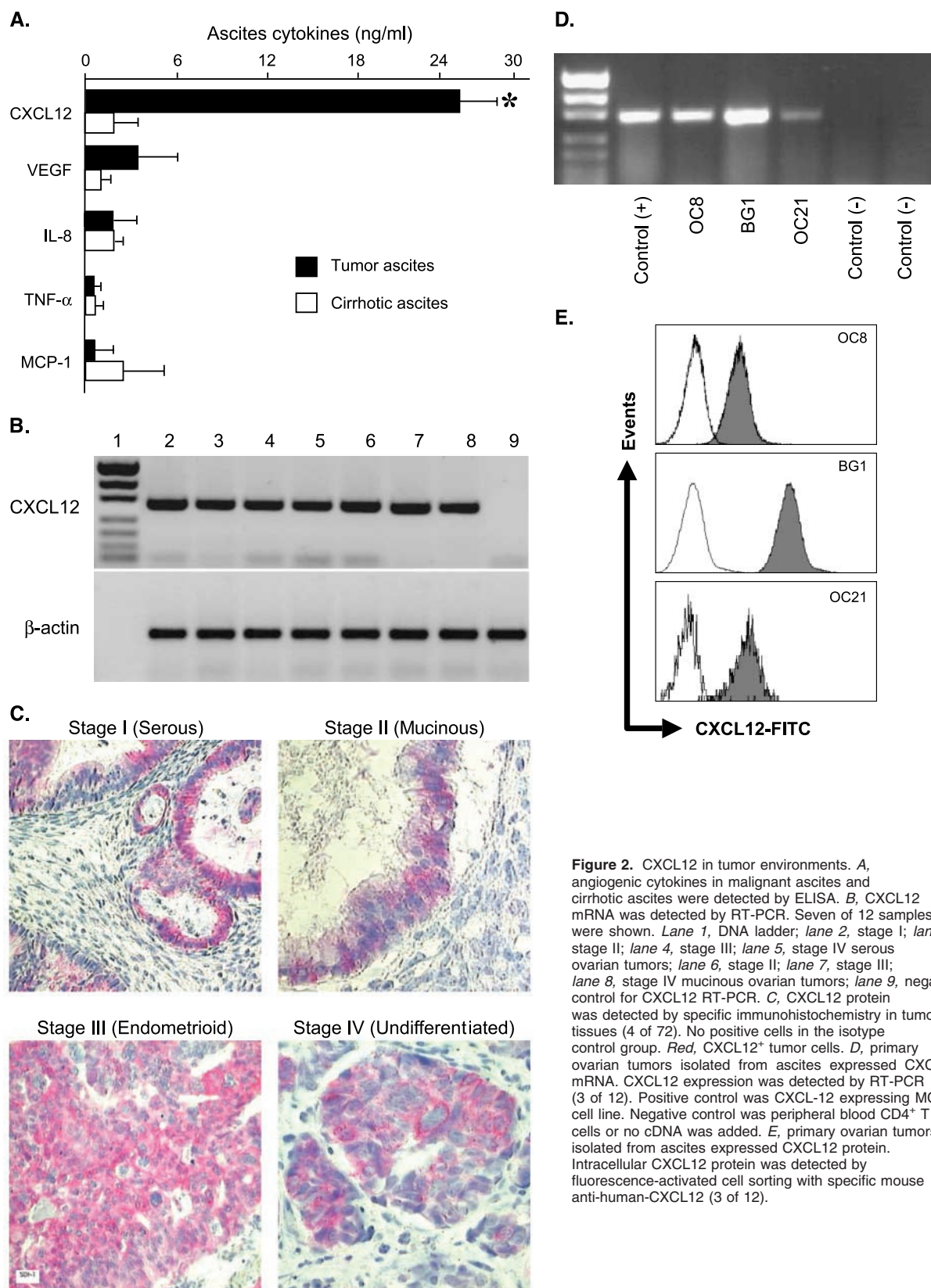


Figure 2. CXCL12 in tumor environments. **A**, angiogenic cytokines in malignant ascites and cirrhotic ascites were detected by ELISA. **B**, CXCL12 mRNA was detected by RT-PCR. Seven of 12 samples were shown. Lane 1, DNA ladder; lane 2, stage I; lane 3, stage II; lane 4, stage III; lane 5, stage IV serous ovarian tumors; lane 6, stage II; lane 7, stage III; lane 8, stage IV mucinous ovarian tumors; lane 9, negative control for CXCL12 RT-PCR. **C**, CXCL12 protein was detected by specific immunohistochemistry in tumor tissues (4 of 72). No positive cells in the isotype control group. Red, CXCL12⁺ tumor cells. **D**, primary ovarian tumors isolated from ascites expressed CXCL12 mRNA. CXCL12 expression was detected by RT-PCR (3 of 12). Positive control was CXCL-12 expressing MCF-7 cell line. Negative control was peripheral blood CD4⁺ T cells or no cDNA was added. **E**, primary ovarian tumors isolated from ascites expressed CXCL12 protein. Intracellular CXCL12 protein was detected by fluorescence-activated cell sorting with specific mouse anti-human-CXCL12 (3 of 12).

staining showed that these primary tumor cell lines actively expressed intracellular CXCL12 ($n = 12$; Fig. 2E). Therefore, ovarian tumor cells are the major cellular source in tumor environment.

CXCL12 and VEGF Synergistically Induced *In vivo* Angiogenesis. To determine the role of each individual cytokine in ascites-mediated *in vivo* angiogenesis (Fig. 1), we tested the *in vivo* angiogenesis in Matrigel assay with recombinant cytokines. CXCL12 induced a significant angiogenesis in a dose dependent manner ($n = 7-10$ for each point; Fig. 3A). Notably, the effective angiogenic concentrations of CXCL12 were superior to 25 ng/mL (Fig. 3A). We detected 25 ng/mL CXCL12 in malignant ascites (Fig. 2A). The data indicates that high concentration of CXCL12 is angiogenic *in vivo*, whereas pathologic concentration of CXCL12 is not.

As expected, recombinant VEGF induced a significant angiogenesis in a dose dependent manner ($n = 7-10$ for each point; Fig. 3B). However, consistent with other reports (14, 16), the effective angiogenic concentrations of VEGF were superior to 5 ng/mL in this experimental model (Fig. 3B). We detected 3.1 ng/mL VEGF in malignant ascites (Fig. 2A). The data indicates that pathologic concentration of VEGF is not able to induce a relevant *in vivo* angiogenesis in our model.

We hypothesized that tumor-derived VEGF and CXCL12 synergized to induce *in vivo* angiogenesis. We first examined whether VEGF synergized CXCL12-induced angiogenesis. Strikingly, 5 ng of VEGF significantly increased the angiogenic effects of CXCL12 (5-50 ng/mL) in a dose dependent

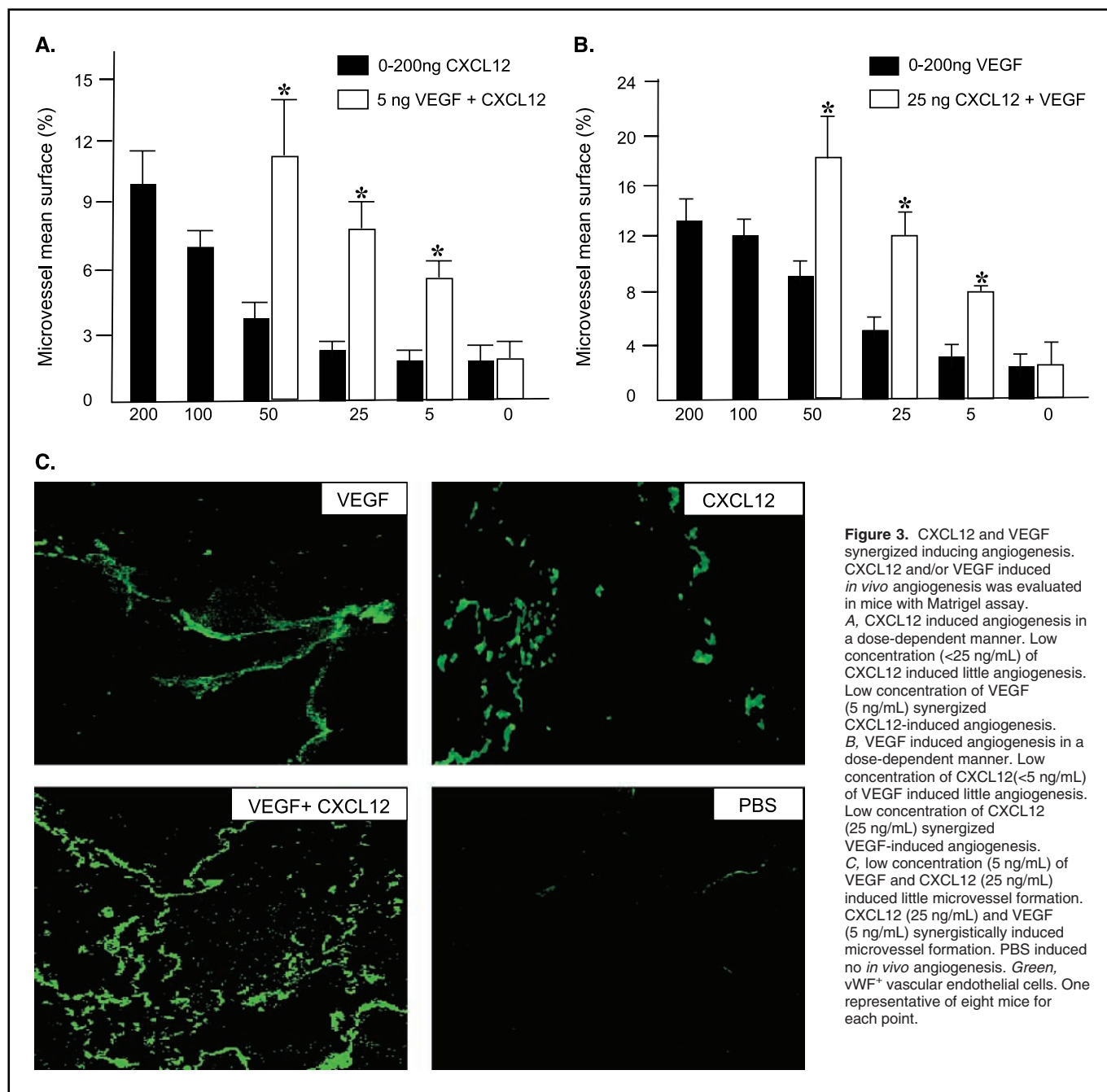
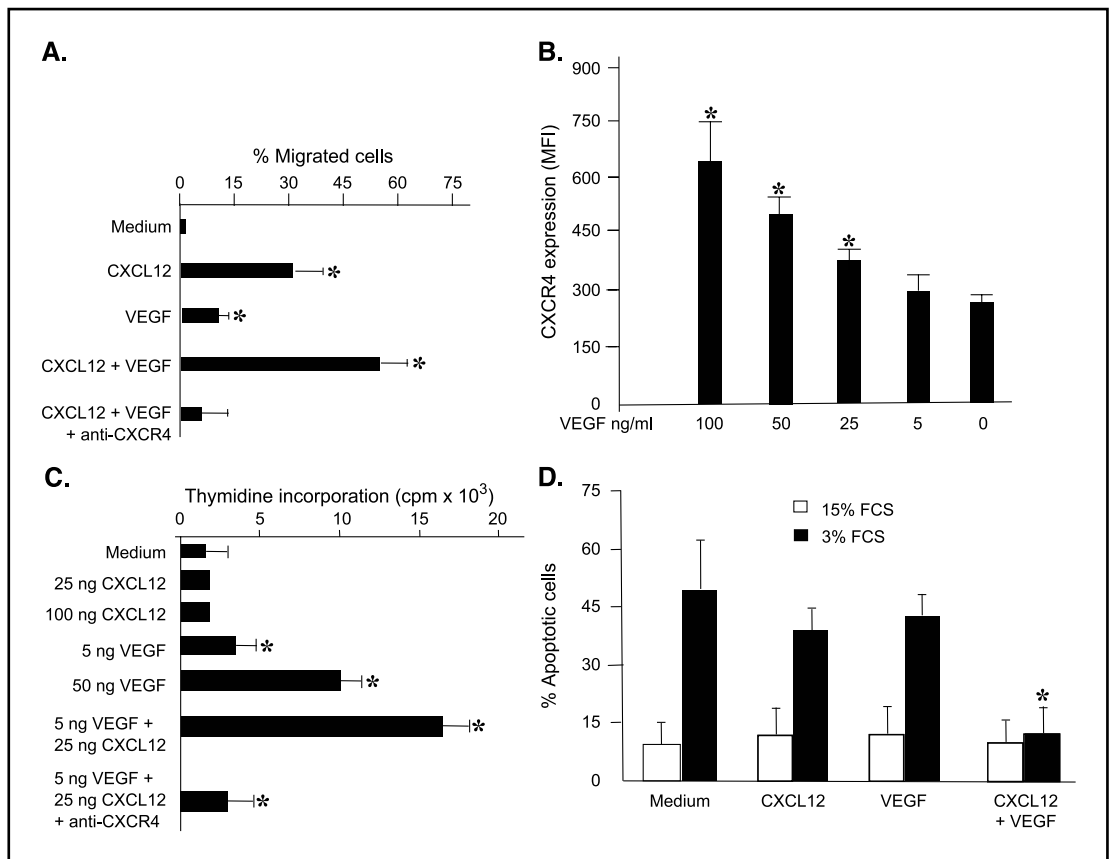


Figure 3. CXCL12 and VEGF synergized inducing angiogenesis. CXCL12 and/or VEGF induced *in vivo* angiogenesis was evaluated in mice with Matrigel assay. A, CXCL12 induced angiogenesis in a dose-dependent manner. Low concentration (<25 ng/mL) of CXCL12 induced little angiogenesis. Low concentration of VEGF (5 ng/mL) synergized CXCL12-induced angiogenesis. B, VEGF induced angiogenesis in a dose-dependent manner. Low concentration of CXCL12 (<5 ng/mL) of VEGF induced little angiogenesis. Low concentration of CXCL12 (25 ng/mL) synergized VEGF-induced angiogenesis. C, low concentration (5 ng/mL) of VEGF and CXCL12 (25 ng/mL) induced little microvessel formation. CXCL12 (25 ng/mL) and VEGF (5 ng/mL) synergistically induced microvessel formation. PBS induced no *in vivo* angiogenesis. Green, vWF⁺ vascular endothelial cells. One representative of eight mice for each point.

Figure 4. CXCL12 and VEGF synergistically promote angiogenic function of vascular endothelial cells. **A**, CXCL12 and VEGF synergistically induced HUVEC migration. CXCL12, 100 ng/mL; VEGF, 5 ng/mL. **B**, VEGF up-regulated CXCR4 expression on HUVEC. CXCR4 expression was analyzed by fluorescence-activated cell sorting. 100% cells express CXCR4. **MFI**, mean fluorescence intensity. One representative of six. **C**, CXCL12 synergized VEGF-mediated HUVEC proliferation. Cell proliferation was detected by thymidine incorporation (cpm). **D**, CXCL12 and VEGF synergistically protect HUVEC apoptosis. HUVEC were cultured with medium containing 3% and 15% FCS for 24 hours. CXCL12 (100 ng/mL) and VEGF (5 ng/mL) were added into the culture. Cellular apoptosis was analyzed by annexin V and 7-AAD staining and expressed as % apoptotic cells.



manner ($n = 8$ for each point; *, $P < 0.001$, compared with CXCL12 alone; Fig. 3A). The data indicate that pathologic concentration of VEGF synergized CXCL12-induced angiogenesis.

We next examined whether CXCL12 synergized VEGF-induced angiogenesis. Strikingly, 25 ng of CXCL12 significantly increased the angiogenic effects of VEGF (5–50 ng/mL) in a dose-dependent manner ($n = 8$ for each group; *, $P < 0.001$, compared with VEGF alone; Fig. 3B). The data indicate that pathologic concentration of CXCL12 synergized VEGF-induced angiogenesis. Histologic analysis showed significant vascular channel formation and tortuous neovessels in Matrigel plugs containing 25 ng of CXCL12 plus 5 ng of VEGF (Fig. 3C; ref. 17), but few microvessel formation in Matrigel plugs containing 25 ng of CXCL12 or 5 ng of VEGF. No microvessel formation was observed in Matrigel plugs containing PBS ($n = 8$ for each group; Fig. 3C; ref. 25). Therefore, tumor-derived CXCL12 and VEGF likely form a synergistic angiogenic pathway *in vivo*.

CXCL12 and VEGF Synergize to Promote Angiogenic Function of Vascular Endothelial Cells. We next examined the synergistic mechanism by which CXCL12 and VEGF induced angiogenesis. Vascular endothelial cell migration is a critical step of tumor angiogenesis (4). We studied the directional migration of HUVEC. Both CXCL12 and VEGF induced a notable migration of HUVEC ($n = 6$; *, $P < 0.0001$, compared with medium for all; Fig. 4A). Interestingly, CXCL12-mediated migration was significantly more efficient in the presence of low concentration of VEGF (5 ng). Preincubation with a neutralizing antibody against CXCR4 completely disabled CXCL12-mediated HUVEC migration in the presence of VEGF, confirming the involvement of CXCR4. Further experiments showed that VEGF increased CXCR4 expression on

HUVEC ($n = 5$; *, $P < 0.001$, compared with medium; Fig. 4B), indicating that VEGF sensitized CXCL12-mediated migration of vascular endothelial cells through up-regulating CXCR4.

Vascular endothelial cell growth is important for tumor angiogenesis. We examined whether CXCL12 and VEGF could synergize to stimulate HUVEC proliferation. Unexpectedly, 25 to 100 ng of CXCL12 induced little HUVEC proliferation. VEGF induced HUVEC proliferation in a dose-dependent manner ($n = 8$; *, $P < 0.001$, compared with medium or CXCL12 alone). Interestingly, pathologic concentrations of VEGF (5 ng) and CXCL12 (25 ng) were significantly more efficient to induce vascular endothelial cell proliferation than VEGF alone ($n = 5$; *, $P < 0.001$, compared with 5 ng VEGF; Fig. 4C). Again, preincubation with anti-CXCR4 completely cancelled the VEGF-mediated proliferation, which was sensitized by CXCL12 (Fig. 4C). Thus, tumor-derived CXCL12 sensitizes VEGF-mediated vascular endothelial cell expansion.

Survival of vascular endothelial cells is critical for forming stable neovascularization. Deprivation of nutrients results in vascular endothelial cell apoptosis (14). We show that tumor environmental CXCL12 protects plasmacytoid dendritic cells from apoptosis (13). We hypothesize that CXCL12 and VEGF synergistically protect vascular endothelial cell apoptosis. To test this hypothesis, fresh HUVEC were cultured with different concentrations of FCS medium. FCS medium (3%) induced 50% apoptotic cells ($n = 6$; $P < 0.01$, compared with 15% medium; Fig. 4D). CXCL12 and VEGF independently and marginally decreased the percentage of apoptotic cells induced by sera starvation ($n = 6$; $P < 0.05$, compared with 15% FCS; Fig. 4D). Strikingly, CXCL12 plus VEGF efficiently reduced the percentage of apoptotic cells induced by 3% FCS medium

($n = 6$; $P < 0.001$, compared with VEGF or CXCL12 alone; Fig. 4D), suggesting that VEGF and CXCL12 synergistically protected vascular endothelial cell apoptosis. The data indicate that multiple mechanisms are implicated in the *in vivo* synergistic angiogenic induction of CXCL12 and VEGF.

Hypoxia Triggered CXCL12 and VEGF Production. After determining that CXCL12 and VEGF form a synergistic angiogenic pathway, we next examined the potential regulatory mechanisms for this synergistic pathway. It is well documented that hypoxia induces VEGF production by tumor cells (4, 26, 27). We confirmed this finding. We showed that 4 to 6 hours after exposure to hypoxia, the level of VEGF165 and VEGF121 mRNA was 50- and 2.5-fold higher, respectively, in hypoxia-treated tumor cells than normoxia-treated tumor cells ($n = 4$; Fig. 5A). Hypoxia particularly triggered the expression of VEGF121 and VEGF165, but not VEGF189 and VEGF206 (Fig. 5A). The hypoxia-induced VEGF was maintained for >24 hours (data not shown). As confirmation, hypoxia-treated ovarian tumor cells released more VEGF protein than normoxia ($n = 8$, $P < 0.001$; Fig. 5B). Furthermore, 4 hours after exposure to hypoxia, CXCL12 mRNA was significantly induced ($n = 12$; Fig. 5C). At 6 hours, the level of CXCL12 mRNA was 100-fold higher in hypoxia than normoxia ($n = 12$; Fig. 5C). We observed similar

results in one commercialized ovarian tumor cell line (BG-1) and three primary ovarian tumors cell lines (OC8, OC21, and OC38) established in the laboratory. As confirmation, intracellular staining showed that the level of CXCL12 protein was significantly higher in tumor cells exposed to hypoxia than normoxia ($n = 8$, *, $P < 0.001$, compared with normoxia; Fig. 5D). Therefore, hypoxia activates the synergistic angiogenic pathway between VEGF and CXCL12 through synchronously triggering VEGF and CXCL12 production.

Discussion

CXCL12 was originally isolated from murine bone marrow stromal cells (28), and described for its activity as a chemotactic cytokine for leukocytes (29, 30), CD34⁺ progenitor cells (31–34), platelets (35, 36), and stem cells (33, 37). We previously showed that human ovarian epithelial tumor cells express high levels of CXCL12. Tumor-derived CXCL12 contributes to plasmacytoid dendritic cell trafficking and accumulation in tumor microenvironment (13). Tumor environmental plasmacytoid dendritic cells induce neoangiogenesis through IL-8 and tumor necrosis factor- α (25). We now show for the first time that pathologic concentration of

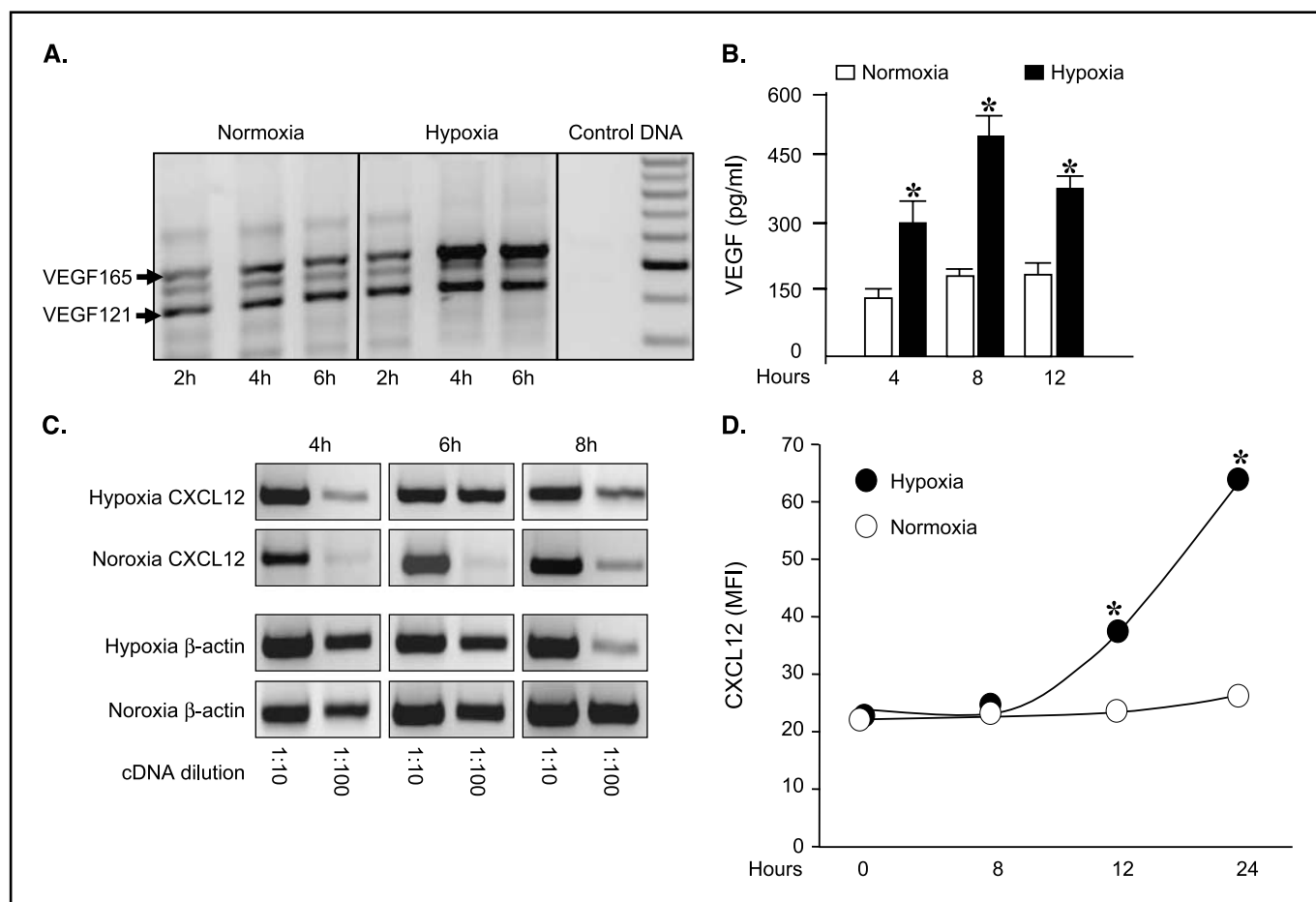


Figure 5. Hypoxia induces CXCL12 and VEGF production. Ovarian tumor cells (OC8) were exposed to normoxic (21% O₂) or hypoxic (1% O₂) for different times. A, hypoxia induced VEGF mRNA expression in tumor cells. Nested RT-PCR was done as described in Materials and Methods. VEGF165, 572 bp; VEGF121, 440 bp. Control, no DNA was added; DNA, DNA ladder. One of four representatives. B, hypoxia induced VEGF production by tumor cells. VEGF was detected in the culture supernatants by ELISA kit. *, $P < 0.001$, compared with normoxia. C, hypoxia induced CXCL12 mRNA expression in tumor cells. RT-PCR was done as described in Materials and Methods. One of six representatives. D, hypoxia induced CXCL12 protein by tumor cells. CXCL12 was analyzed by fluorescence-activated cell sorting. MFI, mean fluorescence intensity of CXCL12 expression.

tumor-derived CXCL12 plus VEGF synergistically induce potent neovascularization *in vivo*. The data suggest that this synergistic pathway would predominantly contribute to tumor vascularization *in vivo* in a real situation. The notion is supported by four lines of evidence: (1) High concentrations, but not pathologic concentrations of VEGF or CXCL12 induce angiogenesis in our *in vivo* model. (2) Pathologic concentrations of CXCL12 plus VEGF synergistically induce angiogenesis *in vivo*. (3) Hypoxia synchronously triggers both VEGF and CXCL12 production by tumor cells. (4) CXCL12 and VEGF synergistically promote vascular endothelial cell function, including migration, expansion, and survival. In support of the *in vivo* synergistic effects of tumor-derived CXCL12 and VEGF in angiogenesis that we report here, the interaction between recombinant CXCL12 and VEGF has been described in previous *in vitro* studies, including *in vitro* cultured umbilical vein endothelial cells (38, 39), lymphohematopoietic cells (40), and breast cancer cell lines (41). However, direct evidence showing the *in vivo* synergistic angiogenesis between VEGF and CXCL12 is missing.

CXCL12 does not contain the NH_2 -terminal Glu-Leu-Arg (ELR) motif with angiogenic function (42). The angiogenic potentiality of CXCL12 has been suggested in different settings of *in vitro* experiments (39, 43–46). Our *in vivo* data indicate that high concentration of CXCL12 directly induce angiogenesis. In support, mice lacking CXCL12 or CXCR4 have defective vascular system development (47, 48). S.c. injection of high concentration recombinant CXCL12 induced formation of local small blood vessels (38). However, our *in vitro* and *in vivo* data indicate that pathologic concentrations of CXCL12 and VEGF are not able to induce a pronounced *in vivo* angiogenesis, whereas pathologic concentrations of CXCL12 and VEGF induce potent *in vivo* angiogenesis in a synergistic manner. Apart from tumors (13), CXCL12 is constitutively expressed in stromal cells, vascular endothelial cells, osteoclast, and some epithelial cells, suggesting that CXCL12 would be important in different physiologic angiogenesis settings.

Anti-CXCR4 treatment significantly decreases the progression and metastasis of cancers in mice (49). The current explanation is that anti-CXCR4 blocks CXCR4 expressing tumor migration to CXCL12 expressing tissues (49–52). Our current data indicate that CXCL12/CXCR4 system is significantly involved in tumor angiogenesis by synergizing with VEGF. Thus, additional explanation is that anti-CXCR4 blocks tumor angiogenesis mediated by CXCL12 and VEGF synergistic pathway and in turn reduces tumor metastasis. In

further support of this notion, VEGF has been reported to be an autocrine survival factor and protects breast cancer cells from apoptosis induced by serum deprivation (53, 54). Hypoxia induces tumor VEGF (53). We now show for the first time that hypoxia triggers tumor CXCL12 expression. It may be a common mechanism in many human tumors that hypoxia synchronously induces VEGF and CXCL12, and VEGF and CXCL12 in turn synergistically protect tumor cell or vascular endothelial cell apoptosis from hypoxia in tumor environment and synergistically promote tumor vascularization and growth. Ovarian tumor cells produce a large amount of CXCL12 and VEGF, which are released into peritoneal cavity. The synergistic pathway between CXCL12 and VEGF would explain, at least partially the extensive tumor vascularization and metastasis in peritoneal cavity in most advanced ovarian cancers.

Therapeutically, the synergic axis between CXCL12 and VEGF has been ignored in prior antitumor angiogenesis strategies. Importantly, early human clinical cancer treatment trials with antiangiogenic molecules have not shown significant benefits predicted from preclinical models (3, 7, 8). More strikingly, recent reports (55–57) suggest that certain angiogenesis inhibitors (or antagonists) alone, by depriving tumors of oxygen, could have an unintended effect: promotion of tumor metastasis by increasing CXCR4 expression. These results reflect our growing understanding of the complexity of the tumor angiogenic process and suggest that blocking both CXCR4 and VEGF will be a novel, efficient strategy to treat human cancers.

In summary, we show in this report that tumors produced functional CXCL12 and VEGF, and tumor-derived CXCL12 and VEGF formed a synergistic angiogenesis axis *in vivo*, and hypoxia activates this axis through synchronously triggering tumor CXCL12 and VEGF production. The study suggests that CXCL12 and VEGF formed synergistic angiogenic pathway is critical for tumor neovascularization, and targeting both CXCL12 and VEGF signals may be a novel, efficient strategy for treating human cancers.

Acknowledgments

Received 7/1/2004; revised 10/15/2004; accepted 11/11/2004.

Grant support: Department of Defense grant OC020173 and National Cancer Institute grants CA092562 and CA100227 (W. Zou).

The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked advertisement in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

We thank Roy Weiner and Jules Puschett for their constant support.

References

- Hanahan D, Folkman J. Patterns and emerging mechanisms of the angiogenic switch during tumorigenesis. *Cell* 1996;86:353–64.
- Folkman J, D'Amore PA. Blood vessel formation: what is its molecular basis? *Cell* 1996;87:1153–5.
- Ellis LM, Liu W, Fan F, et al. Role of angiogenesis inhibitors in cancer treatment. *Oncology (Huntingt)* 2001;15:39–46.
- Carmeliet P, Jain RK. Angiogenesis in cancer and other diseases. *Nature* 2000;407:249–57.
- Warren RS, Yuan H, Matli MR, Gillett NA, Ferrara N. Regulation by vascular endothelial growth factor of human colon cancer tumorigenesis in a mouse model of experimental liver metastasis. *J Clin Invest* 1995;95:1789–97.
- Shaheen RM, Davis DW, Liu W, et al. Antiangiogenic therapy targeting the tyrosine kinase receptor for vascular endothelial growth factor receptor inhibits the growth of colon cancer liver metastasis and induces tumor and endothelial cell apoptosis. *Cancer Res* 1999;59:5412–6.
- Ellis LM, Liu W, Ahmad SA, et al. Overview of angiogenesis: biologic implications for antiangiogenic therapy. *Semin Oncol* 2001;28:94–104.
- Jung YD, Ahmad SA, Akagi Y, et al. Role of the tumor microenvironment in mediating response to antiangiogenic therapy. *Cancer Metastasis Rev* 2000;19:147–57.
- Reynolds LE, Wyder L, Lively JC, et al. Enhanced pathological angiogenesis in mice lacking $\beta 3$ integrin or $\beta 3$ and $\beta 5$ integrins. *Nat Med* 2002;8:27–34.
- Carmeliet P. Integrin indecision. *Nat Med* 2002;8:14–6.
- Obermair A, Speiser P, Reisenberger K, et al. Influence of intratumoral basic fibroblast growth factor concentration on survival in ovarian cancer patients. *Cancer Lett* 1998;130:69–76.
- Parkin DM, Pisani P, Ferlay J. Global cancer statistics. *CA Cancer J Clin* 1999;49:33–64.
- Zou W, Machelon V, Coulomb-L'Hermin A, et al. Stromal-derived factor-1 in human tumors recruits and alters the function of plasmacytoid precursor dendritic cells. *Nat Med* 2001;7:1339–46.
- Carmeliet P, Moons L, Luttmann A, et al. Synergism between vascular endothelial growth factor and placental growth factor contributes to angiogenesis and plasma extravasation in pathological conditions. *Nat Med* 2001;7:575–83.
- Passaniti A, Taylor RM, Pili R, et al. A simple, quantitative method for assessing angiogenesis and antiangiogenic agents using reconstituted basement membrane, heparin, and fibroblast growth factor. *Lab Invest* 1992;67:519–28.
- Lyden D, Hattori K, Dias S, et al. Impaired recruitment of bone-marrow-derived endothelial and hematopoietic precursor cells blocks tumor angiogenesis and growth. *Nat Med* 2001;7:1194–201.
- Montruccio G, Lupia E, Battaglia E, et al. Tumor necrosis factor α -induced angiogenesis depends on *in situ* platelet-activating factor biosynthesis. *J Exp Med* 1994;180:377–82.

18. Weidner N, Semple JP, Welch WR, Folkman J. Tumor angiogenesis and metastasis: correlation in invasive breast carcinoma. *N Engl J Med* 1991;324:1-8.
19. Curiel TJ, Wei S, Dong H, et al. Blockade of B7-H1 improves myeloid dendritic cell-mediated antitumor immunity. *Nat Med* 2003;9:562-7.
20. Zou W, Durand-Gasselin I, Dulioust A, Maillot MC, Galanaud P, Emilie D. Quantification of cytokine gene expression by competitive PCR using a colorimetric assay. *Eur Cytokine Netw* 1995;6:257-64.
21. Song M, Ramaswamy S, Ramachandran S, et al. Angiogenic role for glycodelin in tumorigenesis. *Proc Natl Acad Sci U S A* 2001;98:9265-70.
22. Marfaing-Koka A, Devergne O, Gorgone G, et al. Regulation of the production of the RANTES chemokine by endothelial cells. Synergistic induction by IFN- γ plus TNF- α and inhibition by IL-4 and IL-13. *J Immunol* 1995;154:1870-8.
23. Zou W, Borvak J, Marches F, et al. Macrophage-derived dendritic cells have strong Th1-polarizing potential mediated by β -chemokines rather than IL-12. *J Immunol* 2000;165:4388-96.
24. Zou W, Borvak J, Wei S, Isaeva T, Curiel DT, Curiel TJ. Reciprocal regulation of plasmacytoid dendritic cells and monocytes during viral infection. *Eur J Immunol* 2001;31:3833-9.
25. Curiel TJ, Cheng P, Mottram P, et al. Dendritic cell subsets differentially regulate angiogenesis in human ovarian cancer. *Cancer Res* 2004;64:5535-8.
26. Shweiki D, Itin A, Soffer D, Keshet E. Vascular endothelial growth factor induced by hypoxia may mediate hypoxia-initiated angiogenesis. *Nature* 1992;359:843-5.
27. Carmeliet P, Dor Y, Herbert JM, et al. Role of HIF-1 α in hypoxia-mediated apoptosis, cell proliferation and tumour angiogenesis. *Nature* 1998;394:485-90.
28. Tashiro K, Tada H, Heilker R, Shirozu M, Nakano T, Honjo T. Signal sequence trap: a cloning strategy for secreted proteins and type I membrane proteins. *Science* 1993;261:600-3.
29. Bleul CC, Fuhlbrigge RC, Casasnovas JM, Aiuti A, Springer TA. A highly efficacious lymphocyte chemoattractant, stromal cell-derived factor 1 (SDF-1). *J Exp Med* 1996;184:1101-9.
30. Bleul CC, Farzan M, Choe H, et al. The lymphocyte chemoattractant SDF-1 is a ligand for LESTR/fusin and blocks HIV-1 entry. *Nature* 1996;382:829-33.
31. Aiuti A, Webb IJ, Bleul C, Springer T, Gutierrez-Ramos JC. The chemokine SDF-1 is a chemoattractant for human CD34+ hematopoietic progenitor cells and provides a new mechanism to explain the mobilization of CD34+ progenitors to peripheral blood. *J Exp Med* 1997;185:111-20.
32. Mohle R, Bautz F, Rafii S, Moore MA, Brugger W, Kanz L. The chemokine receptor CXCR-4 is expressed on CD34+ hematopoietic progenitors and leukemic cells and mediates transendothelial migration induced by stromal cell-derived factor-1. *Blood* 1998;91:4523-30.
33. Peled A, Grabovsky V, Habler L, et al. The chemokine SDF-1 stimulates integrin-mediated arrest of CD34(+) cells on vascular endothelium under shear flow. *J Clin Invest* 1999;104:1199-211.
34. Kim CH, Broxmeyer HE. *In vitro* behavior of hematopoietic progenitor cells under the influence of chemoattractants: stromal cell-derived factor-1, steel factor, and the bone marrow environment. *Blood* 1998;91:100-10.
35. Hamada T, Mohle R, Hesselgesser J, et al. Transendothelial migration of megakaryocytes in response to stromal cell-derived factor 1 (SDF-1) enhances platelet formation. *J Exp Med* 1998;188:539-48.
36. Wang JF, Liu ZY, Groopman JE. The α -chemokine receptor CXCR4 is expressed on the megakaryocytic lineage from progenitor to platelets and modulates migration and adhesion. *Blood* 1998;92:756-64.
37. Peled A, Petit I, Kollet O, et al. Dependence of human stem cell engraftment and repopulation of NOD/SCID mice on CXCR4. *Science* 1999;283:845-8.
38. Salcedo R, Wasserman K, Young HA, et al. Vascular endothelial growth factor and basic fibroblast growth factor induce expression of CXCR4 on human endothelial cells: *In vivo* neovascularization induced by stromal-derived factor-1 α . *Am J Pathol* 1999;154:1125-35.
39. Salcedo R, Zhang X, Young HA, et al. Angiogenic effects of prostaglandin E2 are mediated by up-regulation of CXCR4 on human microvascular endothelial cells. *Blood* 2003;102:1966-77.
40. Kijowski J, Baj-Krzyworzeka M, Majka M, et al. The SDF-1-CXCR4 axis stimulates VEGF secretion and activates integrins but does not affect proliferation and survival in lymphohematopoietic cells. *Stem Cells* 2001;19:453-66.
41. Bachelder RE, Wendt MA, Mercurio AM. Vascular endothelial growth factor promotes breast carcinoma invasion in an autocrine manner by regulating the chemokine receptor CXCR4. *Cancer Res* 2002;62:7203-6.
42. Strieter RM, Polverini PJ, Kunkel SL, et al. The functional role of the ELR motif in CXC chemokine-mediated angiogenesis. *J Biol Chem* 1995;270:27348-57.
43. Heidemann J, Ogawa H, Rafiee P, et al. Mucosal angiogenesis regulation by CXCR4 and its ligand CXCL12 expressed by human intestinal microvascular endothelial cells. *Am J Physiol Gastrointest Liver Physiol* 2004;286:G1059-68.
44. Salcedo R, Oppenheim JJ. Role of chemokines in angiogenesis: CXCL12/SDF-1 and CXCR4 interaction, a key regulator of endothelial cell responses. *Microcirculation* 2003;10:359-70.
45. Hoshino M, Aoike N, Takahashi M, Nakamura Y, Nakagawa T. Increased immunoreactivity of stromal cell-derived factor-1 and angiogenesis in asthma. *Eur Respir J* 2003;21:804-9.
46. Curnock AP, Sotsios Y, Wright KL, Ward SG. Optimal chemotactic responses of leukemic T cells to stromal cell-derived factor-1 requires the activation of both class IA and IB phosphoinositide 3-kinases. *J Immunol* 2003;170:4021-30.
47. Tachibana K, Hirota S, Iizasa H, et al. The chemokine receptor CXCR4 is essential for vascularization of the gastrointestinal tract. *Nature* 1998;393:591-4.
48. Nagasawa T, Hirota S, Tachibana K, et al. Defects of B-cell lymphopoiesis and bone-marrow myelopoiesis in mice lacking the CXC chemokine PBSF/SDF-1. *Nature* 1996;382:635-8.
49. Muller A, Homey B, Soto H, et al. Involvement of chemokine receptors in breast cancer metastasis. *Nature* 2001;410:50-6.
50. Koshiba T, Hosotani R, Miyamoto Y, et al. Expression of stromal cell-derived factor 1 and CXCR4 ligand receptor system in pancreatic cancer: a possible role for tumor progression. *Clin Cancer Res* 2000;6:3530-5.
51. Rempel SA, Dudas S, Ge S, Gutierrez JA. Identification and localization of the cytokine SDF1 and its receptor, CXC chemokine receptor 4, to regions of necrosis and angiogenesis in human glioblastoma. *Clin Cancer Res* 2000;6:102-11.
52. Scotton CJ, Wilson JL, Milliken D, Stamp G, Balkwill FR. Epithelial cancer cell migration: a role for chemokine receptors? *Cancer Res* 2001;61:4961-5.
53. Chung J, Yoon S, Datta K, Bachelder RE, Mercurio AM. Hypoxia-induced vascular endothelial growth factor transcription and protection from apoptosis are dependent on $\alpha 6 \beta 1$ integrin in breast carcinoma cells. *Cancer Res* 2004;64:4711-6.
54. Bachelder RE, Crago A, Chung J, et al. Vascular endothelial growth factor is an autocrine survival factor for neuropilin-expressing breast carcinoma cells. *Cancer Res* 2001;61:5736-40.
55. Staller P, Sulitkova J, Lisztwan J, Moch H, Oakeley EJ, Krek W. Chemokine receptor CXCR4 downregulated by von Hippel-Lindau tumour suppressor pVHL. *Nature* 2003;425:307-11.
56. Schioppa T, Uranchimeg B, Sacconi A, et al. Regulation of the chemokine receptor CXCR4 by hypoxia. *J Exp Med* 2003;198:1391-402.
57. Steeg PS. Angiogenesis inhibitors: motivators of metastasis? *Nat Med* 2003;9:822-3.

Dendritic Cell Subsets Differentially Regulate Angiogenesis in Human Ovarian Cancer

Tyler J. Curiel,¹ Pui Cheng,¹ Peter Mottram,¹ Xavier Alvarez,¹ Lieve Moons,² Melina Evdemon-Hogan,¹ Shuang Wei,¹ Linhua Zou,¹ Ilona Kryczek,¹ Gary Hoyle,¹ Andrew Lackner,¹ Peter Carmeliet,² and Weiping Zou¹

¹Tulane University Health Science Center, New Orleans, Louisiana, and ²Center for Transgene Technology and Gene Therapy, Flanders Interuniversity Institute for Biotechnology, Leuven, Belgium

Abstract

Angiogenesis is essential for both primary and metastatic tumor growth. Tumor blood vessel formation is complex and regulated by many factors. Ovarian carcinomas have a poor prognosis, often associated with multifocal intraperitoneal dissemination accompanied by intense neovascularization. To examine tumor angiogenesis in the tumor microenvironment, we studied malignant ascites of patients with untreated ovarian carcinoma. We observed high numbers of plasmacytoid dendritic cells (PDCs) and significant stromal-derived factor (CXCL-12/SDF)-1 in their malignant ascites, attracting PDCs into the tumor environment. We now show that tumor-associated PDCs induced angiogenesis *in vivo* through production of tumor necrosis factor α and interleukin 8. By contrast, myeloid dendritic cells (MDCs) were absent from malignant ascites. MDCs derived *in vitro* suppressed angiogenesis *in vivo* through production of interleukin 12. Thus, the tumor may attract PDCs to augment angiogenesis while excluding MDCs to prevent angiogenesis inhibition, demonstrating a novel mechanism for modulating tumor neovascularization. Because dendritic cells (DCs) have long been known to affect tumor immunity, our data also implicate DCs in regulation of tumor neoangiogenesis, suggesting a novel role of DCs in tumor pathology.

Introduction

Angiogenesis is essential for both primary and metastatic tumor growth. Work to date suggests that vascular endothelial growth factor (VEGF) plays a central role in tumor angiogenesis. However, blood vessel formation is complex and regulated by many factors. For example, β_3 and β_5 integrins were thought to support angiogenesis based on *in vitro* work. However, recent *in vivo* experiments failed to show support for these molecules in angiogenesis *in vivo* (1, 2). Furthermore, the proangiogenic molecule basic fibroblast growth factor was found to be positively related to the prolonged survival of cancer patients (3). Importantly, early human clinical cancer treatment trials with antiangiogenic molecules have only demonstrated modest benefits (4–6). More strikingly, recent reports (7, 8) suggest that angiogenesis inhibitors (or antagonists) alone, by depriving tumors of oxygen, could have an unintended effect: promotion of tumor metastasis. These results reflect our growing understanding of the complexity of the tumor angiogenic process and metastasis process. Dendritic cells (DCs) prime naïve T cells and thereby activate antigen-specific immunity. The two principal human DC subtypes are MDCs (DC1) and plasmacytoid dendritic cells [PDCs (DC2; Ref. 9)]. MDCs expressing tumor antigens have been used in human clinical trials to

induce significant clinical responses against some tumors (10). Although much work has focused on the relevance of DCs to tumor immunity, there are no reports regarding how DCs influence tumor angiogenesis. Ovarian carcinomas have a poor prognosis, often associated with multifocal intraperitoneal dissemination accompanied by intense neovascularization. Because immune factors are known to modulate blood vessel formation in some settings (11), we hypothesized that specific DC subsets might differentially affect tumor neovascularization.

Materials and Methods

Human Subjects. We studied patients with International Federation of Gynecology and Obstetrics stage III or IV ovarian epithelial carcinomas. All patients gave written, informed consent. The study was approved by the local institutional review board. No patients received prior specific cancer treatments.

Plasmacytoid Dendritic Cells. We collected peripheral blood mononuclear cells and ovarian tumor ascites aseptically, harvested cells by centrifugation over a Ficoll-Hypaque density gradient (Amersham), and cryopreserved them at -86°C until use. CD3-, CD14-, CD16-, CD19-, and CD56-expressing cells were depleted using paramagnetic beads (Miltenyi, Auburn, CA), and blood PDCs or tumor ascites PDCs were sorted by flow cytometry gating on CD4⁺CD123⁺CD11c[−] cells. Cell populations were $\geq 99\%$ pure by flow cytometry.

Myeloid Dendritic Cells. MDCs were differentiated from CD14⁺ tumor ascites cells with granulocyte macrophage colony-stimulating factor plus interleukin (IL)-4 as described previously (12, 13).

Activation of Dendritic Cells and Detection of Dendritic Cell-Derived Cytokines. Tumor-associated PDCs or MDCs were activated for 24 h with CD40 ligand (CD40L) stimulation (200 ng/ml; Immunex) or without stimulation. In some cases, the culture plates were precoated with growth factor-reduced Matrigel (BD Bioscience, Bedford, MA). Dendritic cells were collected for *in vivo* Matrigel assay. Culture supernatants were collected for detecting cytokines with commercial enzyme-linked immunosorbent assay kits (all from R&D Systems, Minneapolis, MN).

***In vivo* Matrigel Assay.** NOD.SCID mice (6–8 weeks old; The Jackson Laboratory, Bar Harbor, ME) were inoculated with growth factor-reduced Matrigel Matrix (BD Bioscience) bearing fresh or CD40L-activated tumor-associated PDCs or MDCs and/or the indicated cytokines and/or mouse anti-human antibody. Recombinant human VEGF, fibroblast growth factor (FGF), tumor necrosis factor (TNF)- α , IL-8 (all at 10 ng/ml) were from R&D Systems. Mouse antihuman TNF- α (clone 1825; IgG1), mouse antihuman-IL-8 antibody (clone 6217; IgG1), and mouse antihuman IL-12 antibody [clone 24910; IgG1 (500 ng/ml each)] were from R&D Systems. After 12 days, we isolated the Matrigel plugs. Matrigel plugs were subjected to immunohistochemistry with anti-von Willebrand factor antibody (polyclonal antibody; 1:10 dilution; DAKO, Carpinteria, CA). Microvessel density was analyzed (14) and quantified with ImagePro Plus software (Media Cybernetics, Silver Spring, MD) and expressed as a mean percentage of microvessel surface area by confocal Leica microscope. Hemoglobin (Hb) content in Matrigel plugs was detected with a commercial kit (Sigma, St. Louis, MO).

Received 4/9/04; revised 6/12/04; accepted 7/7/04.

Grant support: National Cancer Institute Grants CA092562 and CA100227, Department of Defense Grant OC020173, Louisiana Board of Regents Grant 126A, the Concern Foundation (W. Zou), and Grant RR00164 (X. Alvarez and A. Lackner).

The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked *advertisement* in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Requests for reprints: Weiping Zou, Tulane University Health Science Center, 1430 Tulane Avenue, New Orleans, LA 70112. E-mail: wzou@tulane.edu.

Results

Tumor-Associated Plasmacytoid Dendritic Cells Induce Angiogenesis *In vivo*. To study the role of tumor-associated PDCs in angiogenesis, we purified tumor-associated PDCs from malignant ascites as we described previously (15). We tested the *in vivo* angiogenic effects of freshly isolated primary tumor-associated PDCs in Matrigel (16, 17). We observed significant neovascularization in

Matrigel plugs bearing 10^6 primary tumor PDCs ($P < 0.0001$, compared with PBS). Activated tumor PDCs (10^5 or 10^6) also induced *in vivo* neovascularization ($P < 0.0001$, compared with PBS). Interestingly, 10^6 activated tumor PDCs were significantly more efficient in inducing neoangiogenesis than 10^6 primary tumor PDCs ($P < 0.0001$), indicating the enhanced angiogenic capacity of activated tumor PDCs. Furthermore, 10^6 activated tumor PDCs induced

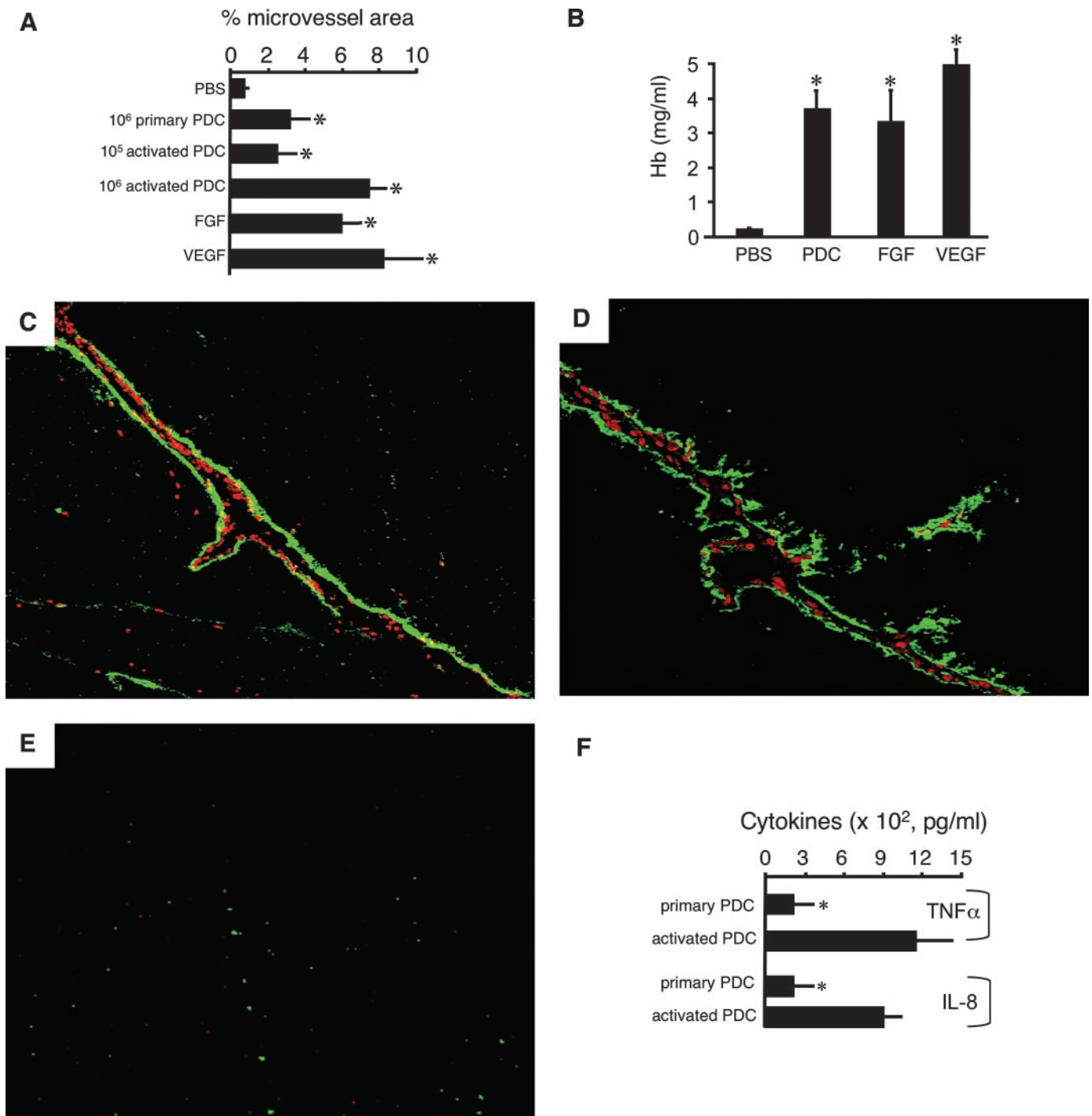


Fig. 1. Tumor PDCs induced angiogenesis *in vivo*. NOD.SCID mice were inoculated with Matrigel plugs bearing tumor-associated PDCs and/or the indicated reagents. A, day 12 Matrigel plugs were subjected to immunohistochemistry with anti-von Willebrand factor antibody. Microvessel density was analyzed and expressed as a mean percentage of microvessel surface area (*, $P < 0.0001$ for all, compared with PBS). B, Hb content in Matrigel plugs was detected (*, $P < 0.0001$ for all, compared with PBS). C–E, histological analysis showed vascular channel formation and tortuous neovessels in Matrigel plugs with (C) tumor-associated PDCs, (D) FGF, and (E) PBS. Green, von Willebrand factor; red, Topro. F, tumor-associated PDCs produced IL-8 and TNF- α (*, $P < 0.001$ for all, primary versus activated PDCs). G, tumor-associated PDC-derived IL-8 and TNF- α induced angiogenesis *in vivo* (*, $P < 0.01$ for all, compared with PDCs alone). B, C, F, and G, 10^6 PDCs. A–E and G, 7–10 mice/group.

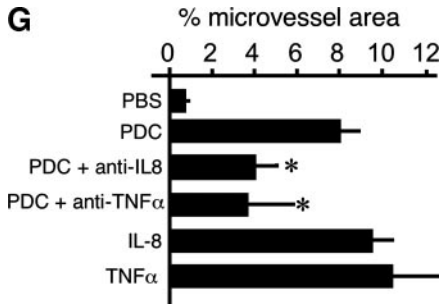


Fig. 1 Continued

more neoangiogenesis than 10^5 activated tumor PDCs ($P < 0.0001$), indicating a dose-dependent angiogenic induction. As positive controls, the angiogenic cytokines VEGF and FGF also induced strong angiogenesis *in vivo* ($P < 0.0001$, compared with PBS; Fig. 1A).

In our preliminary experiment, Spearman correlation coefficients were computed to assess the relationship between microvessel surfaces and Hb content in Matrigel plugs bearing different concentrations of VEGF (1–50 ng/ml). We showed that the percentage of microvessel surfaces highly correlated with Hb content in Matrigel plugs (Ref. 18; Spearman's $\rho = 0.32$; $P = 0.0097$). Therefore, as an alternative and confirmatory technique, we detected high levels of Hb content in Matrigel plugs containing 10^6 activated tumor PDCs, FGF, and VEGF ($P < 0.0001$ for all, compared with PBS; Fig. 1B). Histological analysis showed vascular channel formation and tortuous neovessels in Matrigel plugs bearing tumor PDCs (Fig. 1C) or FGF (Fig. 1D), but not PBS (Fig. 1E). These data demonstrate that tumor PDCs directly induced angiogenesis *in vivo*.

Tumor-Associated Plasmacytoid Dendritic Cells Produce Tumor Necrosis Factor α and Interleukin 8. We further explored the potential angiogenic mechanisms of tumor-associated PDCs. Strikingly, tumor-associated PDCs spontaneously produced high levels of the angiogenic cytokines TNF- α and IL-8 (Fig. 1F). Consistent with the induced *in vivo* neoangiogenesis, activated tumor PDCs (10^6 /ml) produced significantly more TNF- α and IL-8 ($n = 6$; $P < 0.001$ for primary PDCs *versus* activated PDCs; Fig. 1F). Tumor PDCs produced undetectable VEGF and IL-12 (data not shown). Furthermore, when tumor PDCs were placed in the plates precoated with growth factor-reduced Matrigel, we detected the identical amount of TNF- α and IL-8, suggesting that the *in vivo*-used growth factor-reduced Matrigel has no direct effects on PDC-derived cytokine production.

Tumor-Associated Plasmacytoid Dendritic Cell-Derived Tumor Necrosis Factor α and Interleukin 8 Are Angiogenic. We hypothesized that tumor PDC-derived TNF- α or IL-8 mediated PDC-driven angiogenesis. Consistent with this hypothesis, anti-TNF- α or anti-IL-8 antibody significantly decreased activated tumor PDC (10^6)-mediated angiogenesis *in vivo* ($P < 0.01$, compared with PDCs alone; Fig. 1G). In confirmation, recombinant TNF- α and IL-8 induced significant angiogenesis *in vivo* ($P < 0.0001$ for both, compared with PBS; Fig. 1G). Thus, tumor PDCs induce angiogenesis at least in part through TNF- α and IL-8 production *in vivo*.

Tumor-Associated Myeloid Dendritic Cells Inhibit Angiogenesis *In vivo*. We observed no significant numbers of MDCs in malignant ascites in patients with ovarian cancers (15). To evaluate the potential angiogenic role of tumor-associated MDCs *in vivo*, we differentiated tumor-associated MDCs from malignant ascites macrophages as we described previously (12, 13, 15). Tumor-associated MDCs did not induce angiogenesis *in vivo*, even after activation with CD40L. Recombinant human VEGF induced significant angiogenesis *in vivo* ($P < 0.0001$, compared with PBS; Fig. 2A). Interestingly,

VEGF mediated-angiogenesis was significantly reduced by 10^6 or 5×10^6 CD40L-activated tumor MDCs ($P < 0.01$, compared with VEGF alone; Fig. 2A), indicating that MDCs suppress angiogenesis *in vivo*. Tumor-associated MDCs (5×10^6) were more efficient in suppressing VEGF-mediated angiogenesis than 10^6 tumor-associated MDCs, indicating a dose-dependent angiogenic reduction ($P < 0.05$, 5×10^6 *versus* 10^6 MDCs; Fig. 2A). The Hb content (Fig. 2B) was also consistent with the percentage of microvessel quantification (Fig. 2A).

Additionally, we detected high levels of VEGF by enzyme-linked immunosorbent assay in malignant ascites (1440 ± 739 pg/ml; $n = 12$) and primary ovarian carcinoma tumor cell cultures (340 ± 139 pg/ml VEGF produced by 10^6 tumor cells/ml in 48 h). Thus, tumor-associated MDCs suppressed angiogenesis induced by tumor-derived VEGF.

Tumor-Associated Myeloid Dendritic Cell-Derived Interleukin 12 Suppresses Angiogenesis *In vivo*. We further studied the angiogenic suppressive factor derived from MDCs. Anti-IL-12 antibody blocked the suppressive effects of MDCs on angiogenesis ($P < 0.01$, 10^6 MDCs + VEGF *versus* 10^6 MDCs + VEGF + anti-IL-12), suggesting that MDC-derived IL-12 was the angiogenic suppressive factor (Fig. 2). In support of this, recombinant IL-12 inhibited VEGF-mediated angiogenesis ($P < 0.01$, VEGF *versus* VEGF + IL-12; Fig. 2). The data further support that MDCs are able directly to suppress angiogenesis *in vivo* through IL-12 production. In confirmation, we showed that after CD40L activation, tumor-associated MDCs produced significant IL-12 (1830 ± 250 pg/ml; $n = 8$). We observed the identical amount of IL-12 produced by MDCs cultured with the plates precoated with growth factor-reduced Matrigel. It indicates that the growth factor-reduced Matrigel has no detectable effects on MDC cytokine production.

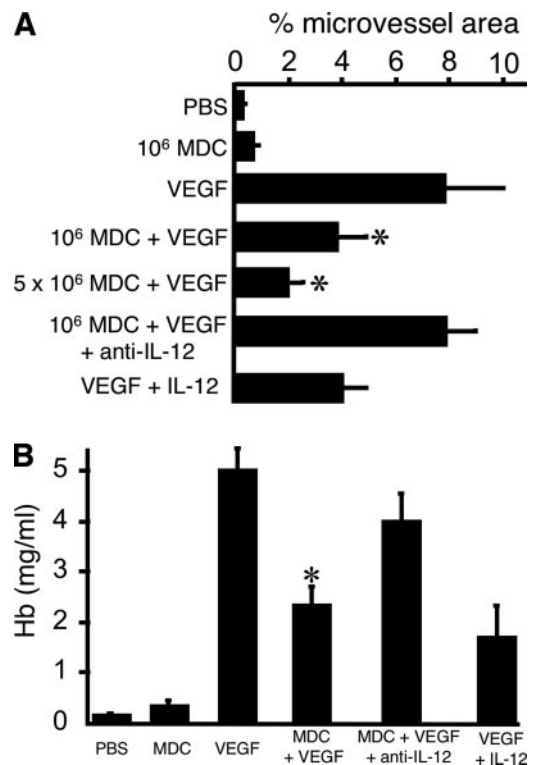


Fig. 2. Tumor MDCs suppress angiogenesis *in vivo*. NOD.SCID mice were inoculated with Matrigel plugs bearing activated tumor-associated MDCs plus the indicated reagents. Day 12 Matrigel plugs were removed to study neovascularization as described in the Fig. 1 legend. A, MDCs suppress VEGF-induced angiogenesis through IL-12. B, microvessel surface data are correlated with the Hb contents in Matrigel plugs. A total of 10^6 MDCs were used in B. A and B, 7–10 mice/group. *, $P < 0.001$, MDCs + VEGF *versus* VEGF.

Discussion

Tumor angiogenesis is essential for the growth of primary and metastatic tumors. The angiogenic process requires the coordinated activities of multiple factors and cell types (4, 11). Tumor angiogenesis occurs when the effect of angiogenic stimulatory factors outweighs that of inhibitory factors (11). Although vascular endothelial cells and their released angiogenic molecules have been studied extensively, the potential angiogenic roles of immune cells, particularly those of dendritic cells, in the tumor microenvironment have not been well defined.

There are substantial numbers of functional PDCs (but not MDCs) in tumor ascites in patients with ovarian carcinomas (15). MDCs produce significant amounts of IL-12 and induce high levels of T-cell interferon (IFN)- γ (15). IL-12 and IFN- γ are potent angiogenic inhibitory cytokines (11). We hypothesize that MDCs may suppress tumor angiogenesis *in vivo* through these cytokines. Lack of MDCs in the tumor microenvironment may be orchestrated by the tumor to minimize the angiogenesis-inhibiting effects of these MDCs. Consistent with our hypothesis, we showed here that MDCs significantly suppressed angiogenesis *in vivo*. MDC-derived IL-12 is a critical factor inhibiting tumor angiogenesis. These data may help explain the beneficial effects of MDCs in reducing tumor burden even when they do not bear tumor-associated antigens.

Cells resembling PDCs were observed in histological sections of lymphoid tumors, granulomas, and multicentric Castleman's disease (19–21). Apart from our recent report (15), however, functional PDCs have never been recovered from pathological tissues for study. There are no reports regarding whether PDCs have effects on tumor angiogenesis. After virus infection, PDCs produce a large amount of type I IFN [IFN- α , IFN- β , and IFN- ω (15, 22–24)]. IFN- α and IFN- β are potent tumor angiogenic inhibitory cytokines. Numerous functional PDCs accumulate in tumor ascites; however, type I IFNs are undetectable in tumor ascites (15). In contrast to MDCs, T-cell signal CD40L stimulates little or undetectable IL-12 production by human PDCs (25, 26). We recently demonstrated that PDCs, but not MDCs, accumulate in the tumor environment and that tumor PDCs inhibit antitumor immunity (15). We now show that tumor PDCs produce high levels of the angiogenic cytokines TNF- α and IL-8 and induce potent neovascularization *in vivo*. Thus, tumors manipulate DC distribution and alter DC function to support tumor angiogenesis. MDCs suppress tumor angiogenesis. PDCs enhance tumor angiogenesis.

In summary, our data demonstrate a novel role for DCs in human cancer. The DC system is relevant to tumor angiogenesis: MDCs inhibit tumor angiogenesis; and tumor-associated PDCs enhance tumor angiogenesis. Maximal vascularization of tumors may thus require the simultaneous accumulation of PDCs and the absence of MDCs, as observed in ovarian tumors. Blocking PDC-mediated neovascularization in tumors may be a novel strategy to treat human cancers.

Acknowledgments

We thank Dominique Emilie, Roy Weiner, and Jules Puschett for their constant support.

References

1. Reynolds LE, Wyder L, Lively JC, et al. Enhanced pathological angiogenesis in mice lacking beta3 integrin or beta3 and beta5 integrins. *Nat Med* 2002;8:27–34.
2. Carmeliet P. Integrin indecision. *Nat Med* 2002;8:14–6.
3. Obermair A, Speiser P, Reisenberger K, et al. Influence of intratumoral basic fibroblast growth factor concentration on survival in ovarian cancer patients. *Cancer Lett* 1998;130:69–76.
4. Ellis LM, Liu W, Ahmad SA, et al. Overview of angiogenesis: biologic implications for antiangiogenic therapy. *Semin Oncol* 2001;28:94–104.
5. Ellis LM, Liu W, Fan F, et al. Role of angiogenesis inhibitors in cancer treatment. *Oncology (Huntingt)* 2001;15:39–46.
6. Jung YD, Ahmad SA, Akagi Y, et al. Role of the tumor microenvironment in mediating response to anti-angiogenic therapy. *Cancer Metastasis Rev* 2000;19:147–57.
7. Staller P, Sulitkova J, Lisztwan J, et al. Chemokine receptor CXCR4 downregulated by von Hippel-Lindau tumour suppressor pVHL. *Nature (Lond)* 2003;425:307–11.
8. Schioppa T, Uranchimeg B, Saccani A, et al. Regulation of the chemokine receptor CXCR4 by hypoxia. *J Exp Med* 2003;198:1391–402.
9. Colonna M, Krug A, Cella M. Interferon-producing cells: on the front line in immune responses against pathogens. *Curr Opin Immunol* 2002;14:373–9.
10. Cerundolo V, Hermans IF, Salio M. Dendritic cells: a journey from laboratory to clinic. *Nat Immunol* 2004;5:7–10.
11. Carmeliet P, Jain RK. Angiogenesis in cancer and other diseases. *Nature (Lond)* 2000;407:249–57.
12. Curiel TJ, Wei S, Dong H, et al. Blockade of B7–H1 improves myeloid dendritic cell-mediated antitumor immunity. *Nat Med* 2003;9:562–7.
13. Zou W, Borvak J, Marches F, et al. Macrophage-derived dendritic cells have strong Th1-polarizing potential mediated by beta-chemokines rather than IL-12. *J Immunol* 2000;165:4388–96.
14. Weidner N, Semple JP, Welch WR, Folkman J. Tumor angiogenesis and metastasis: correlation in invasive breast carcinoma. *N Engl J Med* 1991;324:1–8.
15. Zou W, Machelon V, Coulomb-L'Hermin A, et al. Stromal-derived factor-1 in human tumors recruits and alters the function of plasmacytoid precursor dendritic cells. *Nat Med* 2001;7:1339–46.
16. Lyden D, Hattori K, Dias S, et al. Impaired recruitment of bone-marrow-derived endothelial and hematopoietic precursor cells blocks tumor angiogenesis and growth. *Nat Med* 2001;7:1194–201.
17. Montrucchio G, Lupia E, Battaglia E, et al. Tumor necrosis factor alpha-induced angiogenesis depends on in situ platelet-activating factor biosynthesis. *J Exp Med* 1994;180:377–82.
18. Carmeliet P, Moons L, Luttun A, et al. Synergism between vascular endothelial growth factor and placental growth factor contributes to angiogenesis and plasma extravasation in pathological conditions. *Nat Med* 2001;7:575–83.
19. Facchetti F, De Wolf-Peters C, De Vos R, et al. Plasmacytoid monocytes (so-called plasmacytoid T cells) in granulomatous lymphadenitis. *Hum Pathol* 1989;20:588–93.
20. Facchetti F, De Wolf-Peters C, Van den Oord JJ, Desmet VJ. Plasmacytoid monocytes (so-called plasmacytoid T cells) in Hodgkin's disease. *J Pathol* 1989;158:57–65.
21. Facchetti F, De Wolf-Peters C, Van den Oord JJ, De Vos R, Desmet VJ. Plasmacytoid monocytes (so-called plasmacytoid T-cells) in Kikuchi's lymphadenitis. An immunohistologic study. *Am J Clin Pathol* 1989;92:42–50.
22. Zou W, Borvak J, Wei S, et al. Reciprocal regulation of plasmacytoid dendritic cells and monocytes during viral infection. *Eur J Immunol* 2001;31:3833–9.
23. Cella M, Jarrossay D, Facchetti F, et al. Plasmacytoid monocytes migrate to inflamed lymph nodes and produce large amounts of type I interferon. *Nat Med* 1999;5:919–23.
24. Siegal FP, Kadowaki N, Shodell M, et al. The nature of the principal type 1 interferon-producing cells in human blood. *Science (Wash DC)* 1999;284:1835–7.
25. Krug A, Towarowski A, Britsch S, et al. Toll-like receptor expression reveals CpG DNA as a unique microbial stimulus for plasmacytoid dendritic cells which synergizes with CD40 ligand to induce high amounts of IL-12. *Eur J Immunol* 2001;31:3026–37.
26. Kadowaki N, Antonenko S, Lau JY, Liu YJ. Natural interferon alpha/beta-producing cells link innate and adaptive immunity. *J Exp Med* 2000;192:219–26.

IMMUNOSUPPRESSIVE NETWORKS IN THE TUMOUR ENVIRONMENT AND THEIR THERAPEUTIC RELEVANCE

Weiping Zou

Abstract | It is well known that many tumours are potentially immunogenic, as corroborated by the presence of tumour-specific immune responses *in vivo*. Nonetheless, spontaneous clearance of established tumours by endogenous immune mechanisms is rare. Therefore, the focus of most cancer immunotherapies is to supplement essential immunogenic elements to boost tumour-specific immunity. Why then has tumour immunotherapy resulted in a generally poor clinical efficiency? The reason might lie in the increasingly documented fact that tumours develop diverse strategies that escape tumour-specific immunity.

TOLERANCE

A state in which the immune system does not mount effective immune responses against specific antigens.

ANTIGEN-PRESENTING CELLS

Cells that uptake, process and present antigen to other immune cells to initiate and activate immune responses. Monocytes, macrophages, dendritic cells and B cells are antigen-presenting cells. Dendritic cells are the most potent of these.

The immune system can discriminate between a range of stimuli, allowing some to provoke immune responses, which leads to immunity, and preventing others from doing so, which leads to TOLERANCE. To this end, the immune system is highly organized and orchestrated at various levels (molecular, cellular and systemic).

In the context of tumour immunology, tumour immunity or tumour immune tolerance means the success or failure, respectively, of the immune system to reject a tumour. The tumour microenvironment, which is composed of immune cells, tumour cells, stromal cells and the extracellular matrix, is a main battleground during the neoplastic process, fostering proliferation, survival and migration of tumour cells. Not only can tumours survive and disseminate, but, more importantly, they can mimic some of the signalling pathways of the immune system to propagate conditions that favour tumour immune tolerance — ‘tolerizing’ conditions — and so escape tumour immunity. The focus of this review is the interaction between tumours and the immune system in the human tumour environment, showing how tumour immune tolerance starts gradually and locally, progresses and finally spreads to the whole organism. I suggest that tumour immune tolerance is initiated and maintained by a constitutive interaction between tumours and the host immune system, and controlled by variable modifications to the

immune response present in the tumour environment. Finally, I will summarize how tumour immune tolerance predominates and outweighs the effective immune response in patients with cancer, and how we might be able to subvert tumour tolerance to achieve a successful tumour immunotherapy.

Overview

In 1863, Rudolf Virchow observed leukocyte infiltration of tumours and for the first time suggested a possible functional relationship between inflammatory infiltrates and malignant growth. In 1957, Burnet and Thomas postulated the existence of tumour immunosurveillance: the immunological resistance of the host against the development of cancer. This concept has been challenged for decades because of the lack of direct experimental evidence^{1,2}. Between the mid-1970s and 1990s, experimental data from several groups seemed to support the existence of tumour surveillance, and by 2003 accumulating new evidence proved that the immune system is able to recognize and defeat tumours^{3–7}. However, spontaneous tumour eradication is rare. It was originally thought that the inefficiency of tumour-associated antigen (TAA)-specific immunity was due to intrinsic causes: tumours simply did not present enough TAA; ANTIGEN-PRESENTING CELLS (APCs) did not have sufficient stimulatory capacity; or there were

Tulane University Health Sciences Center,
Section of Hematology and Medical Oncology,
1430 Tulane Avenue
New Orleans, Louisiana
70112-2699, USA.
e-mail: wzou@tulane.edu
doi:10.1038/nrc1586
Published online 18 March 2005

Summary

- The pathological interactions between cancer cells and host immune cells in the tumour microenvironment create an immunosuppressive network that promotes tumour growth, protects the tumour from immune attack and attenuates immunotherapeutic efficacy.
- Poor tumour-associated antigen (TAA)-specific immunity is not simply due to a passive process whereby adaptive immunity is shielded from detecting TAAs. There is an active process of 'tolerization' taking place in the tumour microenvironment.
- Tumour tolerization is the result of imbalances in the tumour microenvironment, including alterations in antigen-presenting-cell subsets, co-stimulatory and co-inhibitory molecule alterations and altered ratios of effector T cells and regulatory T cells.
- Human tumorigenesis is a slow process that can occur over several years and in this respect is similar to chronic infection. The lack of an acute phase in the course of tumorigenesis might profoundly shape T-cell immune responses, including the quality of antigen release, T-cell priming and activation.
- Current immunotherapies often target patients with advanced-stage tumours, which have high levels of inflammatory molecules, cytokines, chemokines, tumour-infiltrating T cells, dendritic cells and macrophages. It is arguable whether we need to incorporate more of these components into tumour treatments.
- Immune tolerization is predominant in the immune system in patients with advanced-stage tumours. It is time to consider combinatorial tumour therapies, including those that subvert the immune-tolerizing conditions within the tumour.

not enough EFFECTOR T CELLS or effector cytokines. On this basis, attempts were made to bolster TAA-specific immunity through administration of stimulatory cytokines (interleukin-2 (IL-2), IL-12 or interferon- α (IFN α)) or tumour-associated antigens (peptides), or by using optimal APCs (dendritic-cell (DC) vaccines)^{4–13}. In a different approach, TAA-specific effector T cells from cancer patients were expanded *ex vivo* followed by adoptive transfer^{6,9,14–16}. These approaches were met with some success both in mouse models and in early clinical trials in humans. Therefore, the principle that experimentally induced TAA-specific immunity is a potentially efficacious approach to treat established human tumours is evident.

However, more recent work from our laboratory and others demonstrates that poor TAA-specific immunity is not due to a passive process whereby adaptive immunity is shielded from detecting TAA. On the contrary, there is an active process of 'tolerization' taking place in the tumour microenvironment. So if the goal is to produce active immunity, either naturally or experimentally, the tolerizing conditions must first be overcome. In BOX 1 several novel anticancer therapeutic strategies that attempt to reverse these tolerizing conditions are shown. Tolerization within the tumour microenvironment is a complex process and involves interactions between several different cell types.

TAAs and TAA-specific priming

CD8⁺ effector T cells have a central role in the elimination of tumours. These cells recognize 8–10 amino acid long peptides buried in the antigen-presenting groove of major histocompatibility complex class I molecules¹⁷. Recent studies of infection indicate that antigens are presented in the draining lymph nodes a few hours after the subcutaneous injection of a pathogen^{18,19}. Activation of

naive CD8⁺ T cells is a relatively rapid process — 2.5 hours of antigen exposure are sufficient to induce clonal expansion and differentiation of CD8⁺ T cells *in vitro*^{20,21}, and 24 hours of pathogen presence are sufficient for the induction of protective CD8⁺ T-cell responses *in vivo*²². Therefore, CD8⁺ T-cell priming takes place at a very early stage of infection — the acute infection phase. This rapid process seems to be crucial for effective expansion of antigen-specific T-cells, followed by contraction and formation of memory T cells. However, the T-cell priming process is poorly understood in the context of TAA-specific T-cell immunity. Human tumorigenesis is a slow process that, like chronic infection, might occur over several years. Acute infection might 'warm up' the immune system for subsequent contest. For instance, acute infection might be crucial for systemic antigen distribution and efficient induction of innate immunity including NATURAL KILLER CELL (NK cell) activation. It is well known that activated NK cells stimulate the maturation of DCs and facilitate adaptive antitumour immunity. Indeed, NK cells link innate immunity and adaptive immunity²³. Therefore, it could be speculated that induction of potent TAA-specific T-cell immunity needs an efficient early activation of NK cells, as is the case during infection. However, the lack of an acute phase in the course of tumorigenesis might lead to a poor early activation of NK cells, and thereafter profoundly reshape T-cell immune responses against the tumour.

Although it is controversial, it is suggested that before the development of systemic metastasis (including lymphoid metastasis), the antigenic cancer cells (expressing TAAs) are embedded in the solid tumour. The stroma of the tumour prevents the efficient release of TAAs²⁴, which are ignored in the conventional central priming sites — the draining lymph nodes^{25,26}. In the later stages of tumour development, TAAs are thought to be efficiently released, which induces the protective immune system to mount an effective response^{27,28}. However, tolerizing mechanisms already abound in the tumour microenvironment by this stage, disabling the functions of APCs and effector T cells. In support of this, recent studies have shown that effector CD8⁺ T-cell responses to common melanoma epitopes are generally weak, localized, and occur mostly in patients with advanced metastatic disease^{27,28}. Taken together, these data indicate that the quality of tumour-associated T-cell priming and the kinetics and temporal release of TAAs actively participate to elicit an effective tumour immune response.

Additionally, TAA-priming might happen in the tumour microenvironment to some degree, where naive T cells and APCs can be found. Indeed, extranodal TAA-specific priming has been reported^{29,30}. However, the tumour is a 'false' lymphoid organ, and T-cell priming in the tumour microenvironment has at least two basic defects. The APCs present in the tumour environment are either dysfunctional or induce T-cell tolerance, as discussed below, and the infrastructure of tumours is different from that of lymph nodes. Tumour tissues show increased

EFFECTOR T CELLS

T cells that exert a cytolytic function following engagement of their T-cell antigen receptor on target cells. CTLs express the co-receptor CD8 and recognize antigenic peptides that are presented by human leukocyte antigen class I molecules.

NATURAL KILLER CELLS

Natural killer cells are a type of cytotoxic lymphocyte that can be distinguished from CD8⁺ T cells by their lack of rearrangement of T-cell receptor genes. They have abundant granule-containing cytoplasm, induce target-cell death through direct contact or by cytokine production, and confer innate immunity.

Box 1 | Tumour immunotherapy

Improving the tumour-associated immune response can be achieved by either boosting components of the immune system that produce an effective immune response or by inhibiting components that suppress the immune response.

The treatments indicated in the table below are based on the hypothesis that immune elements are missing or not sufficient in patients with tumours. The strategy would be to supplement whatever is missing or not sufficient, thereby boosting tumour-associated antigen (TAA)-specific immunity, and improving patient outcome.

Immune elements	Enhancing 'the enhancers'
T cells	Injection of cytotoxic T lymphocytes
Dendritic cells (DCs)	DC vaccination
Natural killer cells	Injection of activated natural killer cells
TAA	Peptide, TAA-vector vaccination
Effector cytokines	Administration of interleukin-2, interferon- α and interleukin-12

The treatments indicated in table below are based on the hypothesis that immune tolerance is dominant in tumour patients. The strategy would be to block these suppressive mechanisms, followed by immune boosting as detailed above with the aim of recovering and boosting TAA-specific immunity and improving patient outcome.

Suppressive elements	Inhibiting 'the inhibitors'
Regulatory T (T_{Reg}) cells	Blocking T_{Reg} cell function (for example, using denileukin difitox to kills T_{Reg} cells)
Suppressive, dysfunctional DCs	Blocking suppressive pathways (for example, targeting cells that express B7-H1, B7-H4 or indoleamine-2,3-deoxygenase)
Self antigen or immodominant	Fostering antigen release by targeting the stroma antigen and/or improving antigen tumour priming
Suppressive cytokines	Blocking potential common cytokine signalling pathway (for example, targeting signal transducer and activator of transcription 3 and suppressor of cytokine signalling 1)

interstitial fluid pressure and contain defective blood vessels. There is fibrosis and contraction of the interstitial matrix. Many tumours lack lymph vessels. These structural defects would potentially contribute to the poor or dysfunctional T-cell priming in the tumour microenvironment. Fu *et al.* recently showed that forced expression of the tumour-necrosis factor (TNF) superfamily member **LIGHT** in the tumour environment induces priming of naive T cells and leads to the rejection of established, highly progressive tumours at local and distal sites in mice. These data indicate that an efficient T-cell priming in the tumour microenvironment is possible²⁹. Tumour immune vaccination has for a long time been focused on fostering T-cell central priming in draining lymph nodes. As peripheral TAA-specific T-cell priming is possible, although it is technically challenging, one could postulate that another alternative would be to restructure the tumour into a real functional 'lymphoid organ' and to engineer 'quality' peripheral TAA-specific priming (for example, T-cell priming within the tumour microenvironment), which would overcome the potential TAA ignorance in the draining lymph nodes of a tumour.

MYELOID DENDRITIC CELLS
A subset of dendritic cells that are lineage-negative CD11c⁺HLA-DR⁺ mononuclear cells with a monocytoïd appearance. Human myeloid dendritic cells might differentiate from myeloid precursors (for example, monocytes, macrophages and CD11c⁺ precursors).

PLASMACYTOID DENDRITIC CELLS
A subset of dendritic cells that are lineage negative HLA-DR⁺CD11c⁺ mononuclear cells with a microscopic appearance similar to plasmablasts. Plasmacytoid dendritic cells are the main producers of type I IFN.

Human APCs

APCs include DCs, monocytes/macrophages and B lymphocytes. DCs are a heterogeneous group of APCs that display differences in anatomic localization, cell-surface phenotype, and function^{31,32}. However, all DCs have several features in common. First, DCs are differentiated from CD34⁺ bone-marrow stem cells. Second, immature DCs are thought to localize in the periphery and are specialized in the uptake and processing of antigens. In turn, mature DCs are found in lymphoid organs, where they interact with antigen-specific T cells and initiate immune responses. Third, immature DCs present distinct chemokine receptors compared with mature DCs, and these regulate their transport into tissue sites. Human DCs are traditionally divided into two main populations: MYELOID DCs and PLASMACYTOID DCs^{10,32,33}.

DCs were initially thought to be exclusively immunogenic, actively inducing or upregulating immune responses. However, recent advances demonstrated that DCs possess dual functions, and can also show regulatory (suppressive) activity. DCs are able to actively downregulate an immune response or to induce immune tolerance by influencing the activity of other cell types. The biology of DCs and DC-based clinical trials has been extensively reviewed elsewhere^{8,10,13,31,34}. This review is limited to discussing the recent advances in the understanding of DCs present in the tumour microenvironment, including immature/partially differentiated myeloid DCs, B7-H1⁺ (also known as PD-L1⁺) myeloid DCs, INDOLEAMINE-2,3-DEOXYGENASE (IDO)⁺ myeloid DCs, tumour-associated plasmacytoid DCs, and vascular (CD11c⁺CD45⁺) DCs. It seems that these DCs within the tumour microenvironment possess a regulatory function. Although it is possible that professional 'regulatory' DCs exist, I favour the view that a regulatory function is not the intrinsic nature of a distinct DC subset^{35–39}. DCs recruited to the tumour microenvironment undergo changes that endow them with regulatory functions favourable for the tumour. Therefore, it can be hypothesized that through a different 'instruction' this process could be reversed.

Tumour environmental myeloid DCs

Myeloid DCs arise from the same progenitor cells that also give rise to monocytes and macrophages, and express, at least in humans, cell-surface markers characteristic of the myeloid lineage³¹. Mature myeloid DCs induce a strong T_H1 (T_H1)-type immune response and are considered potent inducers of TAA-specific immunity. However, the presence of functional immunogenic (mature) myeloid DCs is rare in human **ovarian tumours**³⁵, **breast tumours**^{40,41}, **prostate cancer**⁴² and **renal-cell carcinomas**⁴³. Various factors such as a defective DC recruitment, differentiation, maturation and survival could be the cause. Abundant evidence documents that the differentiation and maturation of myeloid DCs is profoundly suppressed by factors present in the tumour microenvironment. Cancer cells can be major producers of vascular endothelial growth factor (VEGF)^{44,45}, causing high VEGF levels in the tumour

B7-H1

A recently defined B7 family member that is found to be expressed in human epithelial tumours, and can be induced in antigen-presenting cells and in non-lymphoid organs. PD-1 is the identified receptor. Experimental evidence indicates the existence of an unidentified receptor for B7-H1. B7-H1 can mediate an inhibitory role as well as stimulatory role in T-cell-mediated immune responses.

INDOLEAMINE 2,3-DIOXYGENASE

An intracellular haeme-containing enzyme that catalyses oxidative catabolism of tryptophan.

T HELPER 1 CELLS AND T HELPER 2 CELLS

Two functionally defined CD4⁺ T-cell subsets. T helper 1 (T_H1) cells predominantly produce interferon- γ , and support cellular immunity. T_H2 cells predominantly produce interleukin-4, and support humoral immunity.

TUMOUR ASCITES

An accumulated fluid in the peritoneum due to cancer. In some cancers, the ascites fluid contains viable tumour cells, immune cells and soluble factors. Tumour ascites is an accessible tumour environment for research.

REGULATORY T CELLS

A T-cell population that can functionally suppress an immune response by influencing the activity of another cell type. There might exist several phenotypically distinct regulatory T cells. The classic ones are CD4⁺CD25⁺FOXP3⁺ T cells.

NOD/SCID MICE

Mice that do not have T cells or B cells. Tumour cells can be grown in these mice without rejection.

B7-H4

A newly defined B7 family member that is found to be expressed in human ovarian epithelial tumours, non-lymphoid organs and antigen-presenting cells within the tumour microenvironment. The receptor remains to be identified. The B7-H4 fusion protein can mediate a profound inhibitory role in T-cell-mediated immune responses.

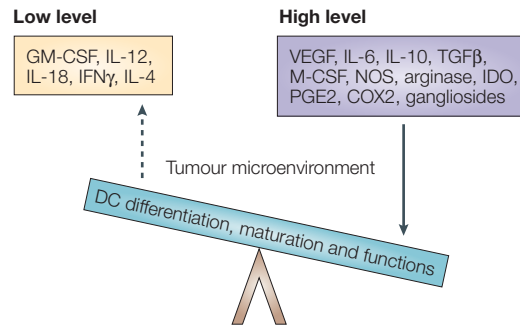


Figure 1 | An aberrant tumour microenvironmental molecule pattern and dendritic cells. The tumour microenvironment is characterized by a lack of molecules promoting dendritic cell (DC) differentiation and function (granulocyte-macrophage colony-stimulating factor (GM-CSF) and interleukin-4 (IL-4)) and cytokines inducing T helper 1 (T_H1)-type responses (IL-12, IL-18 and interferon- γ (IFN γ)), but is abundant in molecules suppressing DC differentiation and function (vascular endothelial growth factor (VEGF), IL-6, IL-10, transforming growth factor- β (TGF β), macrophage colony-stimulating factor (M-CSF), arginase, indoleamine-2,3-deoxygenase (IDO), prostaglandin E2 (PGE2), cyclooxygenase-2 (COX2) and nitric-oxide synthase 2 (NOS2). These suppressive molecules are largely produced by tumour cells, macrophages and stromal cells in the tumour microenvironment. This aberrant molecule pattern profoundly affects tumour-specific immunity.

microenvironment. VEGF was the first tumour-derived molecule reported to suppress DC differentiation and maturation³⁸. Subsequently, IL-6 and macrophage colony-stimulating factor (M-CSF) derived from tumour cells and macrophages from the tumour microenvironment were shown to switch DC differentiation towards macrophage differentiation by upregulating the expression of the M-CSF receptor in monocytes⁴⁶. High levels of IL-6 and C-reactive protein (CRP) can be found in the peripheral blood and malignant ascites of patients with ovarian cancer^{44,45,47,48}. Notably, IL-6 can promote B-cell differentiation and has been suggested to block the suppressive activity of regulatory T cells (T_{Reg} cells)⁴⁹. Moreover, a range of human tumours express high levels of cyclooxygenase-2 (COX2)^{50–52}. COX2 promotes prostaglandin E2 (PGE2) production in the tumour environment. PGE2 in turn suppresses DC differentiation and function^{53–56}. Additionally, tumour cells, tumour-associated macrophages and T_{Reg} cells often produce IL-10 and transforming growth factor- β (TGF β), which also suppress DC maturation and function. Human neuroblastoma, melanoma and many other tumours express high levels of gangliosides, which also suppress human DC differentiation^{57,58}. Strikingly, DC differentiation cytokines, such as granulocyte-macrophage colony-stimulating factor (GM-CSF) and IL-4, as well as the T_H1-type cytokines IL-12 and IFN γ , are rare in the human tumour microenvironment, at least in human ovarian cancer. Abundance of VEGF, IL-6, M-CSF, TGF β , IL-10, COX2, PGE2, gangliosides and other suppressive molecules versus negligible GM-CSF, IL-4,

IL-12, and IFN γ causes an aberrant cytokine pattern in the tumour environment (FIG. 1)^{47,48}. This cytokine imbalance in the tumour microenvironment blocks DC differentiation and maturation. Whereas functional mature myeloid DCs can induce potent TAA-specific immunity *in vivo*^{59,60}, immature or partially differentiated myeloid DCs induce either suppressive T_{Reg} cells^{61,62} or T-cell unresponsiveness⁶³. The induced suppressive T_{Reg} cells home to draining lymph nodes and, in turn, systemically disable TAA-specific immunity. Therefore, immature or partially differentiated myeloid DCs can function as regulatory DCs and are an important component of the immunosuppressive networks in the tumour microenvironment.

Tumour environmental B7-H1⁺ myeloid DCs

As well as inhibiting DC differentiation and maturation, tumour factors present in the local environment profoundly affect the functional capacity of DCs to activate T-cell TAA-specific immunity, by triggering myeloid DC B7-H1 expression³⁶. B7.1 and B7.2 (also known as CD80 and CD86, respectively) are B7 family members with co-stimulatory functions for T-cell activation. B7-H1 is a recently identified B7 family member. There is approximately 25% homology between B7.1, B7.2 and B7-H1 (REF. 64). Factors within the tumour microenvironment stimulate B7-H1 expression in myeloid DCs present in ovarian tumours and their draining lymph nodes. A significant fraction of tumour-associated T cells are T_{Reg} cells⁶⁵, which express PD-1, the ligand for B7-H1 (REF. 66). Tumour-associated T cells can then, through reverse signalling through B7-H1, suppress IL-12 production by myeloid DCs, and therefore reduce their immunogenicity³⁶. Blocking B7-H1 enhances myeloid-DC-mediated T-cell activation^{36,67} and reduces the growth of a transplanted human ovarian carcinoma in non-obese diabetic/severe combined immunodeficient (NOD/SCID) mice adoptively transferred with autologous human TAA-specific T cells³⁶. Induction of B7-H1 on myeloid DCs by factors within the tumour microenvironment is a novel mechanism for immune evasion by a tumour³⁶. On the other hand, expression of B7-H1 on human cancers such as ovarian cancer, lung cancer, melanoma, glioblastoma and squamous-cell carcinoma⁶⁸ also contributes to immune evasion by inducing apoptosis of effector T cells⁶⁸, so facilitating tumour growth⁶⁹. PD-1 is one of the ligands for B7-H1. PD-1 blockade by genetic manipulation (producing PD-1^{-/-} cells) or antibody treatment efficiently inhibits mouse B16 melanoma and CT26 colon cancer dissemination and metastasis accompanied with increased effector T-cell number and enhanced function^{70,71}. In summary, the significant influence of tumour environmental B7-H1 and PD-1 on the interaction between T cells, tumour cells and APCs constitutes a novel target for tumour immunotherapy.

The complex interactions between B7-H1, its receptors and other ligands, as well as between B7-H1-expressing cells and effector T cells, still remain largely unknown⁶⁶. B7-H4 (also known as B7X or B7S1) is a

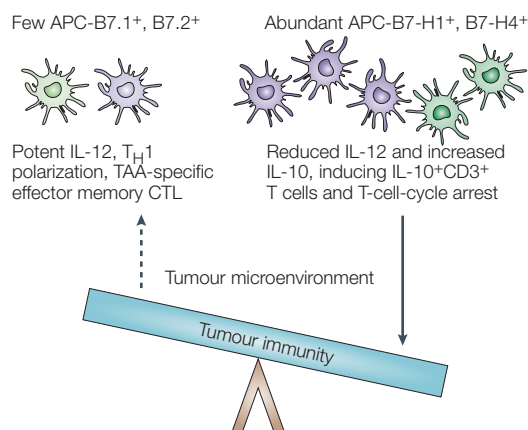


Figure 2 | Imbalance of co-stimulatory and co-inhibitory molecules on antigen-presenting cells within the tumour microenvironment. Antigen-presenting cells (APCs) within the tumour microenvironment express a low level of co-stimulatory molecules (B7.1 and B7.2) and a high level of co-inhibitory molecules (B7-H1 and B7-H4). Molecules within the tumour microenvironment selectively stimulate the expression of co-inhibitory molecules and inhibit co-stimulatory molecules on APCs. These co-inhibitory molecules disable APC immunogenicity and induce APCs to become regulatory APCs with diverse suppressive mechanisms. CTL, cytotoxic T lymphocyte; IL, interleukin; TAA, tumour-associated antigen; T_H1 , T helper 1.

recently discovered member of the B7 family. The ligand (or ligands) of B7-H4 remains unidentified. B7-H4 was shown to be a negative regulator of T-cell responses *in vitro* by inhibiting T-cell proliferation, cell-cycle progression and cytokine production^{66,72–74}. Antigen-specific T-cell responses were impaired in mice treated with a B7-H4–immunoglobulin fusion protein⁷² and we have found that ovarian epithelial tumour cells and tumour-infiltrating APCs including macrophages express high levels of B7-H4. Interestingly, B7-H4⁺ tumour-infiltrating macrophages potently suppress TAA-specific T-cell immunity (W.Z. *et al.*, unpublished observations). Collectively, cytokines within the tumour microenvironment might selectively suppress the expression of co-stimulatory molecules (B7.1 and B7.2) and trigger the expression of co-inhibitory molecules (B7-H1 and B7-H4) in APCs, so contributing to immune evasion by the tumour (FIG. 2).

Factors such as IL-10 within the tumour microenvironment selectively modulate the expression of B7 family members so as to tilt the balance towards immune suppression: co-inhibitory molecules (B7-H1 and B7-H4) are upregulated and co-stimulatory molecules (B7.1 and B7.2) are downregulated. Considering that B7-H1 can have an immune-stimulatory function^{75,76}, it remains to be defined why it mediates an immunosuppressive effect within the tumour microenvironment. Nonetheless, an imbalance between co-stimulatory molecules (B7.1 and B7.2) and co-inhibitory molecules (B7-H1 and B7-H4) is created in the tumour environment (FIG. 2), and spreads into tumour-draining lymph nodes, which

‘instructs’ immunogenic APCs to become regulatory APCs. Co-inhibitory molecules become the tumour’s ‘mask and weapon’, initially to avoid immune attack, and then to reduce T-cell priming and defeat the invasion of effector T cells.

Tumour environmental IDO⁺ myeloid DCs

IDO expression has been documented in human and murine myeloid DCs⁷⁷. IDO catalyses the oxidative catabolism of tryptophan, an amino acid essential for T-cell proliferation and differentiation. IDO⁺ DCs reduce access to free tryptophan and so block the cell-cycle progression of T-cells. This, in turn, prevents the clonal expansion of T cells and promotes T-cell death by apoptosis, ANERGY or immune deviation⁷⁷. IDO⁺ DCs can be generated *in vitro* from monocyte-derived DCs, and this has also been found *in vivo*, in breast tumour tissue and tumour-draining lymph nodes in patients with melanoma and patients with breast, colon, lung and pancreatic cancers⁷⁷. In light of findings by Munn, Mellor and colleagues, it is conceivable that IDO⁺ DCs contribute to tumour-mediated immunosuppression⁷⁷. In line with the role of IDO⁺ DCs, transfection of IDO renders tumour cell lines immunosuppressive *in vitro* and *in vivo*. Systemic treatment of mice with an inhibitor of IDO — 1-methyltryptophan — significantly delays tumour growth in mouse models⁷⁸. Notably, IDO expression by murine DCs is upregulated by the fusion protein CYTOTOXIC T-LYMPHOCYTE-ASSOCIATED PROTEIN 4 (CTLA4)–immunoglobulin⁷⁹, indicating that CTLA4-expressing cells, such as tumour-associated CTLA4⁺CD4⁺CD25⁺ T_{Reg} cells (see below)⁶⁵, induce IDO expression in DCs within the tumour microenvironment, and effectively convert them into regulatory DCs. It is unclear at present whether B7-H1- or B7-H4-expressing myeloid DCs are phenotypically identical to IDO-expressing myeloid DCs in the human tumour microenvironment. Nonetheless, the presence of IDO⁺ myeloid DCs in tumour-draining lymph nodes and within the tumour microenvironment would further tip the balance of tumour microenvironmental DC subsets in favour of tolerizing conditions (FIG. 3).

Tumour environmental plasmacytoid DCs

Functional plasmacytoid DCs are found in the local tumour environment of patients with ovarian cancer³⁵, melanoma⁸⁰ and head and neck squamous-cell carcinoma⁸¹. Tumour cells produce the chemokine ligand CXCL12 (also known as stromal-cell-derived factor 1) and plasmacytoid DCs express CXCR4, the receptor for CXCL12. Tumour-derived CXCL12 mediates trafficking of plasmacytoid DCs into the tumour (FIG. 4)³⁵. CXCL12 protects tumour plasmacytoid DCs from apoptosis³⁵. *In vitro*, activated peripheral-blood plasmacytoid DCs stimulate tumour-specific T-cell IFN γ production in patients with melanoma⁸⁰. Interestingly, plasmacytoid DCs within the tumour microenvironment show reduced expression of toll-like receptor 9 (TLR9)⁸¹, which is the most specific TLR pathway for inducing IFN α . IFN α not only triggers innate immunity, such as activating NK cells, but also promotes adaptive

ANERGY

A state in which lymphocytes can not respond to antigen-specific and non-specific stimulation.

CYTOTOXIC T-LYMPHOCYTE-ASSOCIATED PROTEIN 4

Following engagement by B7.1 or B7.2 on antigen-presenting cells, cytotoxic T-lymphocyte-associated protein 4 (CTLA4) signalling in activated T cells induces cell-cycle arrest, and reduces cytokine production, and diminishes T-cell responses. CD4⁺CD25⁺ regulatory T cells constitutively express CTLA4.

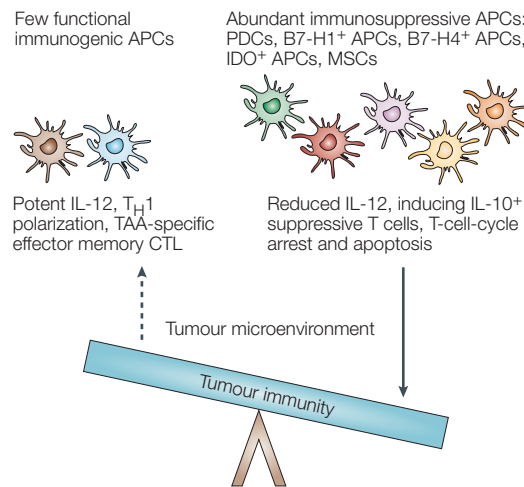


Figure 3 | Imbalances in antigen-presenting-cell subsets and tumour immunity. The tumour microenvironment lacks functionally mature myeloid dendritic cells (DCs) capable of inducing tumour-specific T-cell immunity, whereas it is abundant in immunosuppressive antigen-presenting cell (APC) subsets, including partially differentiated myeloid DCs, B7-H1⁺ DCs, indoleamine-2,3-deoxygenase (IDO)⁺ DCs, plasmacytoid DCs (PDCs) and myeloid suppressor cells (MSCs). These suppressive APC subsets induce arrest of the T-cell cycle, suppressive T cells and T-cell apoptosis. This APC-subset imbalance favours the formation of immune tolerance. CTL, cytotoxic T lymphocyte; IL, interleukin; TAA, tumour-associated antigen T_H1, T helper 1.

T_H1-type T-cell responses. This indicates that plasmacytoid DCs can be phenotypically and functionally modulated in the tumour microenvironment. In support of this, plasmacytoid DCs within the tumour microenvironment induce significant IL-10 production by T cells that suppresses myeloid-DC-induced TAA-specific T-cell effector functions³⁵. Our recent unpublished data reveal that tumour plasmacytoid DCs induce IL-10⁺CCR7⁺CD8⁺ T cells to home to draining lymph nodes, and suppress TAA-specific central priming (W.Z. *et al.*, unpublished observations). The fact that ALLOGENEIC plasmacytoid DCs are able to induce CD4⁺ (REF. 82) and CD8⁺ (REF. 83) suppressive T_{Reg} cells supports these data. A large amount of plasmacytoid DCs, but not functional mature myeloid DCs, accumulate in the tumour microenvironment³⁵. We suggest that the imbalanced distribution of APC subsets in the tumour microenvironment further contributes to immune evasion by a tumour (FIG. 3). We are currently exploring the underlying mechanisms by which tumour plasmacytoid DCs induce suppressive T cells.

Tumour vascular DCs

Functional myeloid DCs are able to produce IL-12 and induce potent cytokine production of IFN γ and IL-10. All three molecules are strong suppressors of tumour angiogenesis⁴⁵. Human myeloid DCs, but not plasmacytoid DCs, are the major producers of IL-12. It is not surprising then that myeloid DCs suppress tumour

neoangiogenesis³⁷, which is essential for tumour growth and metastasis⁴⁵. Strikingly, tumour environments seem to lack angiogenesis-inhibitory myeloid DCs, but present abundant angiogenesis-stimulatory DCs, such as plasmacytoid DCs³⁷ and vascular DCs⁸⁴. Tumour-derived CXCL12 attracts and protects plasmacytoid DCs in the tumour microenvironment and these cells can induce vascularization by spontaneously producing TNF α and IL-8 (REF. 37). Coukos *et al.* demonstrated that vascular DCs are recruited by β -defensin, and induce vasculogenesis under the influence of VEGF in mice. Vascular DCs are also found in ovarian tumours⁸⁴. Therefore, DCs are relevant not only in tumour immunopathogenesis, but also in tumour vascularization. Optimal vascularization of tumours might require the simultaneous accumulation of vascular DCs and the absence of anti-angiogenic myeloid DCs, as is observed in ovarian tumours. Imbalance between vascular-inhibitory DCs and vascular-stimulatory DCs in the tumour microenvironment also contributes to tumour immunopathogenesis (FIG. 5). The suppression of neovascularization of tumours mediated by vascular DCs might be a novel strategy to treat human cancer.

Tumour myeloid suppressor cells

Murine myeloid suppressor cells (MSCs) represent a phenotypically heterogeneous cell population that includes immature and mature myeloid cells, activated granulocytes, macrophages, as well as cells expressing markers of immature DCs. MSCs can function as APCs. Murine MSCs are distinct from suppressive lymphocytes and can be phenotypically identified as CD11b⁺Gr-1⁺CD31⁺ (REFS 85,86). Human MSCs were found in patients with head and neck squamous-cell carcinoma, non-small-cell lung carcinoma, and metastatic adenocarcinomas of the pancreas, colon and breast^{87,88}. However, there are no specific markers described for human MSCs⁸⁸. MSCs infiltrate into tumour-draining lymph nodes to inhibit priming of naive T cells, and also into tumour tissues^{89–92} (FIG. 3). Murine MSCs use two enzymes involved in L-arginine metabolism to control T-cell responses: inducible nitric-oxide synthase 2 (NOS2), which generates nitric oxide (NO) and arginase-1 (ARG1), which depletes the milieu of L-arginine. Induction of NOS2 is mainly controlled by IFN γ and TNF α . After inducing NOS2, MSCs subsequently release NO. NO acts at the level of IL-2 receptor signalling, blocking the phosphorylation and activation of several signalling molecules, which induces T-cell apoptosis^{85,86,90}. ARG1 is often induced by cytokines within the tumour microenvironment, such as TGF β and IL-10. L-arginine is essential for T-cell function, including the optimal use of IL-2 and the development of a T-cell memory phenotype^{91,92}. Depletion of nutrients is a strategy used throughout nature to control the growth of organisms competing for the same biological niche. Unfortunately, this strategy is incidentally available in tumours and defeats the immune response.

ALLOGENEIC

Allogeneic tissues or cells are genetically different from the host and can elicit an immune response when transplanted into immune-competent hosts.

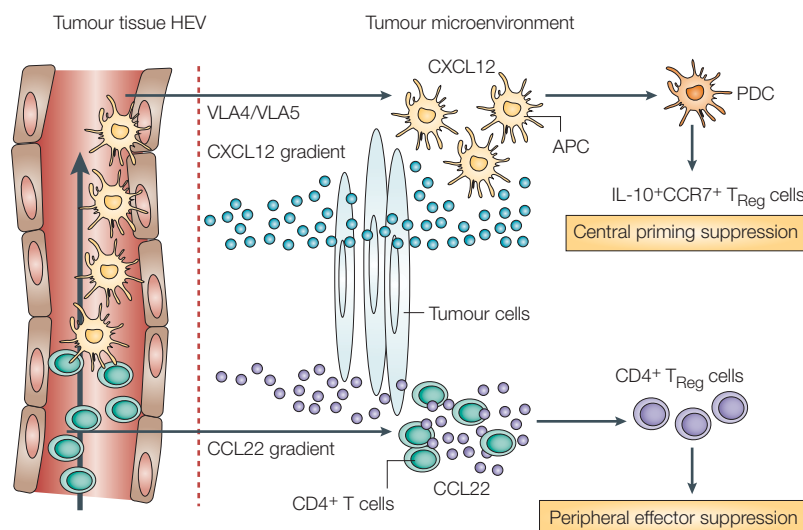


Figure 4 | Specific recruitment and tumour immune evasion. Tumour-derived chemokine CXCL12 mediates the trafficking of plasmacytoid dendritic cells (PDCs) into tumours. Tumour PDCs induce interleukin-10 (IL-10)⁺CCR7⁺ suppressive CD8⁺ T cells, which traffic into tumour-draining lymph nodes and inhibit tumour-specific central priming. The chemokine CCL22, derived from tumour cells and associated macrophages, mediates CD4⁺CD25⁺FOXP3⁺ regulatory T (T_{Reg}) cell trafficking into tumours. CD4⁺T_{Reg} cells predominantly inhibit effector T-cell function in the tumour environment. HEV, high endothelial venule.

Tumour APCs and immunotherapy

It is evident that there is an imbalance of APC subsets in the tumour environment (FIG. 3). Lack of functional mature DCs and abundance of suppressive DCs significantly reduce the TAA-specific T-cell priming in draining lymph nodes, as well as the TAA-specific effector immunity in the tumour microenvironment. An aberrant molecule network further contributes to this detrimental situation. Absence of DANGER SIGNALS, including inflammatory cytokines, molecular and cellular T-cell

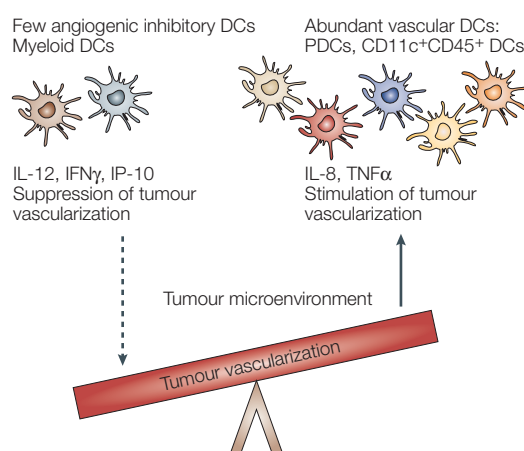


Figure 5 | Imbalances in antigen-presenting-cell subsets and tumour vascularization. The tumour microenvironment lacks functional angiogenesis-inhibitory myeloid dendritic cells (DCs), whereas it is abundant in angiogenesis-stimulatory macrophages and DC subsets, including plasmacytoid DCs (PDCs) and CD11c⁺CD45⁺ vascular DCs, are present. The imbalance of antigen-presenting cell subsets in the tumour microenvironment promotes tumour vascularization.

DANGER SIGNALS
Triggers that are associated with host-cell damage. These 'danger signals' induce the activation of antigen-presenting cells. The danger signals could be intracellular components that are released when cells are damaged, such as DNA and proteins, or inflammatory molecules and cytokines, such as interferon- γ .

activation signals in the tumour microenvironment, has been considered the main cause of poor tumour immunity^{2,93,94}. Therefore, incorporation of danger signals as a strategy to boost tumour immunity has been suggested^{2,93,94}. However, high levels of IL-6, COX2, CRP and other danger signals are observed in many stage I tumours, including ovarian cancer^{47,48}, in accordance with the idea that cancer can be accompanied by chronic inflammatory reactions^{95,96}. There are at least three danger signals associated with tumours: hypoxic stress, metabolic stress and immune-attack stress. As these signals are mostly present in late tumour stages, it is possible that danger signals might be more limited in microscopic tumours before clinical diagnosis. This might also account for the poor immunogenicity of micrometastases.

Notably, current immunotherapies often target patients with advanced-stage tumours, manifesting high levels of danger signals in the tumour microenvironment, including inflammatory molecules, cytokines, chemokines, tumour-infiltrating T cells, DCs and macrophages. As discussed above, insufficient arousal of fully functional effector T cells as well as lack of fully immunogenic APCs are evident in tumour microenvironment in these patients. However, tolerization has been established and is predominant in these patients. It is therefore arguable whether we need to further enhance these danger signals in tumours. Indeed, non-steroidal anti-inflammatory agents, including aspirin, sulindac and NS398, are able to reduce tumour formation in mouse models and in patients at high risk for colon carcinoma^{97–100}. COX2 inhibitors are able to suppress human tumour growth in mice^{101,102}, and enhance the efficiency of radiotherapy¹⁰³. More importantly, one cannot definitively rule out that danger signals or passively supplemented immune elements alone could enhance immune stress in tumours⁶, and strengthen the aberrant cytokine network in some circumstance. For instance, IFN γ is an effector cytokine released by TAA-specific T cells. However, IFN γ strongly stimulates B7-H1 (REFS 68,104), IDO⁷⁷ and arginase^{85,86,90} expression on APCs. Such APCs could induce suppressive tumour immunity. So it is not a surprise that *Ifn γ* ^{−/−} mice manifest autoimmune diseases. Furthermore, certain strategies of tumour vaccination induce IL-10-expressing CD4⁺CD25⁺ T cells in mice¹⁰⁵ and patients with melanoma¹⁰⁶. Therefore, as suggested previously^{4,6}, current immunotherapy strategies including cytokine administration, DC vaccination and adoptive T-cell transfusion might possibly contain elements that counteract therapeutic efficiency. The occasional marked clinical efficacy of immunotherapies might represent cases in which immune tolerance is not dominant.

As mentioned above, tumour immunotherapies including DC vaccines often target late-stage tumours with the aim of boosting TAA immunity. Fully activated DCs are less sensitive to suppression and able to rescue suboptimal activated T cells^{8,10,13,34,107}. However, it remains to be defined whether fully activated DCs alone would subvert the suppressive capacity of T_{Reg} cells and of regulatory (or dysfunctional) APCs in tumour-bearing patients. For instance, in patients with ovarian cancer,

Table 1 | Subversion of 'tolerizing' conditions

Targets	Suggested potential treatments	References
Tumour microenvironmental plasmacytoid DCs and tumour	AMD3100 blocks CXCR4 signal <i>in vivo</i> ; AMD3100 could reduce the trafficking of plasmacytoid DCs into the tumour by blocking the CXCR4 signal; AMD3100 might also suppress tumour vascularization/metastasis	35,44,109,110
	CpG nucleotides activate plasmacytoid DCs and trigger production of type I IFN by plasmacytoid DCs	35,112,113
B7-H1 ⁺ myeloid DCs and tumours	Neutralizing anti-B7-H1	36,66,68,70,71
B7-H4 ⁺ macrophages and tumours	Neutralizing anti-B7-H4	64,72–74
	Specific B7-H4-blocking oligonucleotides	W.Z. <i>et al.</i> , unpublished observations
IDO ⁺ MSCs and tumours	IDO inhibitor (1-methyltryptophan)	39,77,78
Suppressive cytokines IL-6 and IL-10	Blocking the common pathway STAT3 or SOCS1	141,142
Arginase ⁺ MSCs	Arginase inhibitor (<i>N</i> -hydroxy-nor-L-arginine)	92
T _{Reg} cells	Denileukin diftitox (Ontak) kills CD25 ⁺ leukaemia cells, indicating that it might kill CD25 ⁺ T _{Reg} cells	140
	Anti-CD25 depletes CD25 ⁺ T _{Reg} cells	125,126
	Anti-CTLA4 blocks CTLA4 signal	127,136–139,143
	Anti-CCL22 reduces trafficking of T _{Reg} cells into the tumour	65

DC, dendritic cell; IDO, indoleamine-2,3-deoxygenase; IFN, interferon; IL, interleukin; MSC, myeloid suppressor cell; SOCS1, suppressor of cytokine signalling 1; STAT3, signal transducer and activator of transcription 3; T_{Reg} cell, regulatory T cell.

repetitive stimulation with fully matured myeloid DCs is not able to recover T-cell dysfunction mediated by tumour-associated plasmacytoid DCs (Zou *et al.*, unpublished observations). Even after a successful surgical intervention, many patients will present with residual disease. Tolerizing conditions will have already been established in these patients and will remain present after surgery. Adoptively transferred DCs will face identical tolerizing situations as the 'original' DCs did in the tumour microenvironment and could partially explain the poor clinical efficiency of DC vaccinations. Furthermore, fully activated DCs would possibly expand and activate CD4⁺CD25⁺ T_{Reg} cells¹⁰⁸. Tackling these tolerizing conditions might improve the efficacy of DC vaccines. AMD3100 is a CXCR4 antagonist, and has been used in human clinical trials for treatment of human immunodeficiency virus (HIV) infection¹⁰⁹. CXCR4–CXCL12 signals are implicated in the trafficking of plasmacytoid DCs into tumours³⁵ and CXCL12–CXCR4 signals are further involved in tumour vascularization⁴⁴ and metastasis¹¹⁰. It is tempting to speculate that administration of AMD3100 or other CXCR4–CXCL12 signalling antagonists could block the trafficking of plasmacytoid DCs into tumours, interrupt the interaction between tumours and plasmacytoid DCs, and in turn disable tumour plasmacytoid-DC-mediated immunosuppression and vascularization. CXCL12–CXCR4 antagonists would further suppress CXCL12–CXCR4-mediated tumour neoangiogenesis⁴⁴ and metastasis¹¹⁰. In addition, activated plasmacytoid DCs in the tumour microenvironment remain as a chief source of type I IFN³⁵, potentially bridging innate and adaptive immunity. IFN α derived from plasmacytoid

DCs might induce maturation of myeloid DCs and activate NK cells in the tumour microenvironment, and also provide important T-cell survival signals¹¹¹. IFN α is also a potent inhibitor of tumour angiogenesis⁴⁵. Given the potential benefit of activating plasmacytoid DCs, the use of oligonucleotides as an adjuvant to activate plasmacytoid DCs has been suggested to treat various diseases including human tumours^{112,113}. CpG OLIGONUCLEOTIDE 7909 is now in Phase I/II clinical trial in patients with basal-cell carcinoma or with melanoma¹¹³.

The immunosuppressive activity of IDO-expressing APCs or tumour cells can be inhibited by the IDO inhibitor 1-methyltryptophan. The D-isomer of 1-methyltryptophan is the candidate for human clinical trials (D. Munn, personal communication). The immunosuppressive activity of arginase-expressing MSCs might be inhibited by an arginase inhibitor, *N*-hydroxy-nor-L-arginine (Nor-NOHA). The injection of Nor-NOHA and Nor-NOHA plus L-arginine in tumour-bearing mice significantly inhibits tumour growth in a dose-dependent manner⁹². As most of human epithelial tumours and APCs express B7-H1 and B7-H4 (REFS 36,64,68,72), these molecules represent additional attractive new targets for cancer immunotherapy. As *in vitro* and *in vivo* experiments in mice demonstrate that blocking B7-H1 (REFS 36,67,69,70) and B7-H4 (W.Z., unpublished observations) pathways improves TAA-specific T-cell immunity, it would be therapeutically meaningful to develop the related signal pathway blocking molecules for human clinical trials. These and other potential novel immunotherapeutic strategies are listed in TABLE 1.

CpG OLIGONUCLEOTIDES
Synthetic oligodeoxynucleotides (CpG-ODNs) that contain CpG motifs that are similar to those found in bacterial DNA that can stimulate an immune response. These CpG-ODNs have various potential therapeutic uses.

Tumour T_{Reg} cells

A T_{Reg} cell is functionally defined as a T cell that inhibits an immune response by influencing the activity of another cell type¹¹⁴. The most well-defined T_{Reg} cells are CD4⁺CD25⁺ T cells. The field of T_{Reg} cells is a rapidly evolving area of investigation and has been extensively reviewed in the context of basic biology, autoimmune diseases, organ transplantation and infectious diseases^{115–117}.

Although T_{Reg} cells were originally identified in mice, a population with identical phenotypic and functional properties has been identified in humans. CD4⁺ T_{Reg} cell subsets include naturally occurring CD4⁺CD25⁺ T_{Reg} cells as well as peripherally induced CD4⁺ T_{Reg} cells, or IL-10-expressing T_{Reg} cells^{115,116,118–121}. As discussed above, IL-10 and TGFβ produced by ovarian tumours favour the induction and differentiation of T_{Reg} cells. Dysfunctional myeloid DCs³⁶ and tumour-conditioned plasmacytoid DCs³⁵ would directly contribute to T_{Reg} cell induction in the tumour microenvironment. Tumour-bearing patients have increased numbers of both peripherally circulating and tumour-associated CD4⁺CD25⁺ T_{Reg} cells^{122–124}. These T_{Reg} cells are functional, as shown by inhibition of non-specific T-cell activation *in vitro*.

Experimental administration of antibodies against CD25 (REFS 125,126) and of antibodies against CTLA4 (REFS 127,128) in tumour-bearing mice improves immune-mediated tumour clearance and enhances the response to immune-based therapy. These original studies indicate that CD25⁺ and CTLA4⁺ cells might be detrimental to tumour immunity in mice. Notably, although mouse CD4⁺CD25⁺ T cells constitutively express CTLA4 (REFS 129,130), the link has not been demonstrated between anti-CTLA4 treatment and the reduction of the number or function of CD4⁺CD25⁺ T cells. Furthermore, depletion of CD25⁺ cells and CTLA4 blockade were shown to act synergistically¹³¹, indicating that CTLA4 blockade directly promotes T-cell function. On the other hand, anti-CD25 administration in humans also prevents transplant rejection, indicating that the CD25 marker does not discriminate between effector T cells and T_{Reg} cells¹¹⁶, suggesting that anti-CD25 might deplete CD25⁺ effector T cells.

The role of CD4⁺CD25⁺ T_{Reg} cells was recently investigated in mice bearing B16 melanoma cells. The study clearly demonstrates that CD4⁺ T_{Reg} cells are the major regulators of concomitant tumour immunity against this weakly immunogenic tumour¹³². In addition, our recent study in humans provides the first direct *in vitro* and *in vivo* evidence that human T_{Reg} cells have an important immunopathological role in human cancer by 'lowering' the endogenous TAA-specific T-cell immunity, contributing to tumour growth. Accumulation of T_{Reg} cells in the tumour tilts another tumour environmental balance — the balance between T_{Reg} cells and effector T cells — in favour of immunosuppression (FIG. 6). Tumour T_{Reg} content is linked with a striking reduction of patient survival, providing evidence linking T_{Reg} cells to the pathogenesis of human cancer⁶⁵.

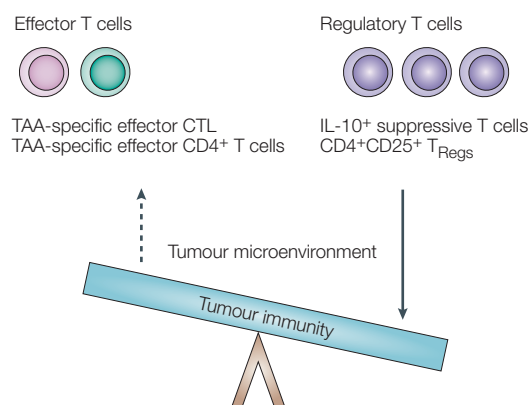


Figure 6 | T-cell-subset imbalance and tumour-specific immunity. Tumour-associated antigen (TAA)-specific effector T cells are able to kill tumour cells. Regulatory T (T_{Reg}) cells reduce the killing capacity of TAA-specific T cells. A large amount of T_{Reg} cells infiltrating into tumours tilts the balance of T-cell subsets within the tumour microenvironment in favour of 'tolerizing' conditions.

How do T_{Reg} cells traffic to the tumour microenvironment? Ovarian tumour T_{Reg} cells express functional CCR4, the receptor for CCL22, and migrate towards it in response to CCL22 in the tumour microenvironment, which is produced by tumour cells and associated macrophages (FIG. 4). Homeostatic and tumour T_{Reg} cells express similar amounts of the lymphoid-homing molecules CCR7 and CD62L. However, whether these molecules have roles in the lymphoid homing by T_{Reg} cells is unknown. Furthermore, trafficking and distribution of T_{Reg} cells could be dynamically variable during tumour progression. One would predict that in the very early phase of tumorigenesis (earlier than clinically defined tumour stage I), T_{Reg} cells might predominantly localize in draining lymph nodes, whereas in late stages of tumour progression T_{Reg} cells will predominantly reside in the tumour microenvironment. The former would primarily suppress priming of naive T cells, whereas the latter would mainly inhibit the function of extranodal effector cells.

Under the stress of an immune response it seems likely that tumours that recruit and activate host T_{Reg} cells are more likely to survive — T_{Reg} cells would disarm T-cell effector mechanisms. Infectious pathogens have evolved the same strategy to escape immune attack and maintain a chronic infection¹³³. Interestingly, cancer has also been considered a chronic inflammatory disease¹³⁴. Not only do 15% of cancers worldwide have a direct infectious origin¹³⁵, but also many human tumours are related to chronic irritation and inflammation. This hypothesis is of the utmost importance when designing tumour immunotherapy.

Tumour T_{Reg} cells and immunotherapy

Given that T_{Reg} cells within the tumour microenvironment are a crucial component of the tumour immunosuppressive network, the clinical depletion of

T_{Reg} cells in patients with tumours could become a promising strategy for boosting TAA-specific immunity.

Depletion of CD25⁺ cells using an antibody against CD25 resulted in improved tumour rejection in mice^{125,126}. CTLA4 attenuates the potency of TAA-specific T-cell immunity and, in mice, administration of an antibody that blocks CTLA4 function inhibited the growth of moderately immunogenic tumours¹³⁶. In addition, suppression of CTLA4 in combination with cancer vaccines or depletion of CD25⁺ cells increases the rejection of poorly immunogenic tumours, albeit with evidence of an autoimmune response^{131,136,137}. Administration of an inhibitory antibody to CTLA4 in previously vaccinated cancer patients resulted in effective antitumour immunity¹³⁸. The human anti-CTLA4 antibody (MDX-010) in conjunction with peptide vaccination improved tumour immunity and tumour regression in patients with metastatic melanoma¹³⁹. Although blocking CTLA4 can induce significant autoimmune manifestations^{138,139}, the studies provide the proof of principle for CTLA4 suppression in treatment of human cancer. Notably, similar to mouse T_{Reg} cells, human CD4⁺CD25⁺ T_{Reg} cells in the tumour microenvironment constitutively express CTLA4 (REF. 65). However, it has not been demonstrated that treatment with antibodies against CTLA4 reduces the content of CD4⁺CD25⁺ T_{Reg} cells or alters the function T_{Reg} cells either in mice or in humans. Nonetheless, these studies indicate that the depletion of CD4⁺ T_{Reg} cells or/and a suppression of T_{Reg} cell function could weaken T_{Reg}-cell-mediated tolerance.

Denileukin diftitox (Ontak) is a ligand toxin fusion consisting of full-length IL-2 fused to the enzymatically active and translocating domains of diphtheria toxin¹⁴⁰. This complex is internalized into CD25⁺ cells by endocytosis. The ADP-ribosyltransferase activity of diphtheria toxin is cleaved in the endosome and is translocated into the cytosol, where it inhibits protein synthesis, leading to apoptosis¹⁴⁰. This drug has been approved by the Food and Drug Administration in the United States for treatment of CD4⁺CD25⁺ cutaneous T-cell leukaemia/lymphoma. Predictably, denileukin diftitox depletes CD4⁺CD25⁺ T_{Reg} cells, and our and other laboratories are now testing this concept in patients with lung, ovarian or other cancers, where levels of such T_{Reg} cells are greatly increased^{65,122,123}. Therefore, depletion of T_{Reg} cells

or blockade of T_{Reg}-cell-specific transport represents a novel means to augment tumour immunity, which might be used in a range of novel therapeutic approaches. Denileukin diftitox represents the first agent that is potentially useful for humans in this regard.

Future directions

Although 'black and white' signals have been identified in tumour immunity, it is evident from the discussions above that this is an oversimplification and that interactions between tumour cells and immune cells would be best represented by a multitude of colours. Therefore, experimental interpretations are mostly qualitative. It is time to move on to characterize molecules and cells, and their activities and their interactions in a quantitative way, temporally and spatially. In this regard, we need rigorous methods and models to dissect the complicated suppressive *in situ* network, and to make decisions considering all (or most) molecular and cellular components. For instance, scientists have successfully applied mathematical models to define the *in vivo* dynamics of HIV replication, and the *in vivo* turnover of its target — CD4⁺ T cells. These findings facilitated the establishment of highly active antiretroviral therapy to treat HIV-infected patients. Similarly, quantitative and dynamic models will be essential to dissect the differentiation, expansion, trafficking, half-life and function of T_{Reg} cells, as well as the distribution, expression, regulation and interaction of 'inhibitory' (B7-H1, B7-H4, CTLA4 and IDO) and 'stimulatory' (B7.1 and B7.2) molecules. How do all these factors form the immunosuppressive network in the course of tumour development and progression? A better understanding of these kinetic aspects could be used to develop and refine novel immune-boosting strategies.

Finally, after many years of effort, a 'proof of principle' for boosting antitumour immunity in humans has been established. However, it might not be sufficient to passively supplement the essential immune elements, including adoptively transferring tumour antigens, T cells, cytokines and DCs. It is time to consider combinatorial tumour therapies. I suggest a '3S' therapeutic strategy: subversion of tolerizing conditions (S1), supplementation of immune elements (S2), and suppression of tumour angiogenesis and growth (S3).

- Dunn, G. P., Bruce, A. T., Ikeda, H., Old, L. J. & Schreiber, R. D. Cancer immunoeediting: from immunosurveillance to tumor escape. *Nature Immunol.* **3**, 991–998 (2002).
- Smyth, M. J., Godfrey, D. I. & Trapani, J. A. A fresh look at tumor immunosurveillance and immunotherapy. *Nature Immunol.* **2**, 293–299 (2001).
- References 1 and 2 re-visit and refine the concept of tumour immune surveillance. The authors provide their own opinions and views on this subject.**
- Melief, C. J. *et al.* Strategies for immunotherapy of cancer. *Adv. Immunol.* **75**, 235–282 (2000).
- Pardoll, D. Does the immune system see tumors as foreign or self? *Annu. Rev. Immunol.* **21**, 807–839 (2003).
- Finn, O. J. Cancer vaccines: between the idea and the reality. *Nature Rev. Immunol.* **3**, 630–641 (2003).
- Khong, H. T. & Restifo, N. P. Natural selection of tumor variants in the generation of 'tumor escape' phenotypes. *Nature Immunol.* **3**, 999–1005 (2002).
- Gilboa, E. The promise of cancer vaccines. *Nature Rev. Cancer* **4**, 401–411 (2004).
- Schuler, G., Schuler-Thurner, B. & Steinman, R. M. The use of dendritic cells in cancer immunotherapy. *Curr. Opin. Immunol.* **15**, 138–147 (2003).
- Yee, C. & Greenberg, P. Modulating T-cell immunity to tumours: new strategies for monitoring T-cell responses. *Nature Rev. Cancer* **2**, 409–419 (2002).
- O'Neill, D. W., Adams, S. & Bhardwaj, N. Manipulating dendritic cell biology for the active immunotherapy of cancer. *Blood* **104**, 2235–2246 (2004).
- Knutson, K. L., Schiffman, K. & Disis, M. L. Immunization with a HER-2/neu helper peptide vaccine generates HER-2/neu CD8 T-cell immunity in cancer patients. *J. Clin. Invest.* **107**, 477–484 (2001).
- Hwu, P. & Freedman, R. S. The immunotherapy of patients with ovarian cancer. *J. Immunother.* **25**, 189–201 (2002).
- Figdor, C. G., de Vries, I. J., Lesterhuis, W. J. & Melief, C. J. Dendritic cell immunotherapy: mapping the way. *Nature Med.* **10**, 475–480 (2004).
- Melief, C. J. Tumor eradication by adoptive transfer of cytotoxic T lymphocytes. *Adv. Cancer Res.* **58**, 143–175 (1992).
- Rosenberg, S. A. *et al.* Use of tumor-infiltrating lymphocytes and interleukin-2 in the immunotherapy of patients with metastatic melanoma. A preliminary report. *N. Engl. J. Med.* **319**, 1676–1680 (1988).
- Dudley, M. E. *et al.* Cancer regression and autoimmunity in patients after clonal repopulation with autologous lymphocytes. *Science* **298**, 850–854 (2002).

17. Pamer, E. & Cresswell, P. Mechanisms of MHC class I-restricted antigen processing. *Annu. Rev. Immunol.* **16**, 323–358 (1998).
18. Itano, A. A. & Jenkins, M. K. Antigen presentation to naive CD4 T cells in the lymph node. *Nature Immunol.* **4**, 733–739 (2003).
19. Mueller, S. N., Jones, C. M., Smith, C. M., Heath, W. R. & Carbone, F. R. Rapid cytotoxic T lymphocyte activation occurs in the draining lymph nodes after cutaneous herpes simplex virus infection as a result of early antigen presentation and not the presence of virus. *J. Exp. Med.* **195**, 651–656 (2002).
20. Kaech, S. M. & Ahmed, R. Memory CD8⁺ T cell differentiation: initial antigen encounter triggers a developmental program in naive cells. *Nature Immunol.* **2**, 415–422 (2001).
21. van Stipdonk, M. J., Lemmens, E. E. & Schoenberger, S. P. Naive CTLs require a single brief period of antigenic stimulation for clonal expansion and differentiation. *Nature Immunol.* **2**, 423–429 (2001).
22. Wong, P. & Pamer, E. G. CD8 T cell responses to infectious pathogens. *Annu. Rev. Immunol.* **21**, 29–70 (2003).
23. Degli-Esposti, M. A. & Smyth, M. J. Close encounters of different kinds: dendritic cells and NK cells take centre stage. *Nature Rev. Immunol.* **5**, 112–124 (2005).
24. Spiotto, M. T. et al. Increasing tumor antigen expression overcomes 'ignorance' to solid tumors via crosspresentation by bone marrow-derived stromal cells. *Immunity* **17**, 737–747 (2002).
25. Ochsenbein, A. F. et al. Roles of tumour localization, second signals and cross priming in cytotoxic T-cell induction. *Nature* **411**, 1058–1064 (2001).
26. Ochsenbein, A. F. et al. Immune surveillance against a solid tumor fails because of immunological ignorance. *Proc. Natl Acad. Sci. USA* **96**, 2233–2238 (1999).
27. Palmowski, M., Salio, M., Dunbar, R. P. & Cerundolo, V. The use of HLA class I tetramers to design a vaccination strategy for melanoma patients. *Immunol. Rev.* **188**, 155–163 (2002).
28. Romero, P. et al. *Ex vivo* staining of metastatic lymph nodes by class I major histocompatibility complex tetramers reveals high numbers of antigen-experienced tumor-specific cytolytic T lymphocytes. *J. Exp. Med.* **188**, 1641–1650 (1998).
29. Yu, P. et al. Priming of naive T cells inside tumors leads to eradication of established tumors. *Nature Immunol.* **5**, 141–149 (2004).
- Demonstrates that efficient TAA-specific priming in the tumour microenvironment is possible.**
30. Feuerer, M. et al. Bone marrow as a priming site for T-cell responses to blood-borne antigen. *Nature Med.* **9**, 1151–1157 (2003).
31. Banchereau, J. & Steinman, R. M. Dendritic cells and the control of immunity. *Nature* **392**, 245–252 (1998).
32. Lanzavecchia, A. & Sallusto, F. The instructive role of dendritic cells on T cell responses: lineages, plasticity and kinetics. *Curr. Opin. Immunol.* **13**, 291–298 (2001).
33. Colonna, M., Trinchieri, G. & Liu, Y. J. Plasmacytoid dendritic cells in immunity. *Nature Immunol.* **5**, 1219–1226 (2004).
34. Cerundolo, V., Hermans, I. F. & Salio, M. Dendritic cells: a journey from laboratory to clinic. *Nature Immunol.* **5**, 7–10 (2004).
35. Zou, W. et al. Stromal-derived factor-1 in human tumors recruits and alters the function of plasmacytoid precursor dendritic cells. *Nature Med.* **7**, 1339–1346 (2001).
- The first functional study of human tumour-associated plasmacytoid DCs. This paper shows that tumour-derived CXCL12 attracts plasmacytoid DCs and that tumour plasmacytoid DCs induce IL-10⁺ suppressive T cells.**
36. Curiel, T. J. et al. Blockade of B7-H1 improves myeloid dendritic cell-mediated antitumor immunity. *Nature Med.* **9**, 562–567 (2003).
37. Curiel, T. J. et al. Dendritic cell subsets differentially regulate angiogenesis in human ovarian cancer. *Cancer Res.* **64**, 5535–5538 (2004).
38. Gabrilovich, D. I. et al. Production of vascular endothelial growth factor by human tumors inhibits the functional maturation of dendritic cells. *Nature Med.* **2**, 1096–1103 (1996).
- The first study showing that VEGF inhibits DC differentiation from CD34⁺ progenitor cells.**
39. Munn, D. H. & Mellor, A. L. IDO and tolerance to tumors. *Trends Mol. Med.* **10**, 15–18 (2004).
40. Bell, D. et al. In breast carcinoma tissue, immature dendritic cells reside within the tumor, whereas mature dendritic cells are located in peritumoral areas. *J. Exp. Med.* **190**, 1417–1426 (1999).
41. Iwamoto, M. et al. Prognostic value of tumor-infiltrating dendritic cells expressing CD83 in human breast carcinomas. *Int. J. Cancer* **104**, 92–97 (2003).
42. Troy, A., Davidson, P., Atkinson, C. & Hart, D. Phenotypic characterisation of the dendritic cell infiltrate in prostate cancer. *J. Urol.* **160**, 214–219 (1998).
43. Troy, A. J., Summers, K. L., Davidson, P. J., Atkinson, C. H. & Hart, D. N. Minimal recruitment and activation of dendritic cells within renal cell carcinoma. *Clin. Cancer Res.* **4**, 585–593 (1998).
44. Kryczek, I. et al. CXCL12 and vascular endothelial growth factor synergistically induce neoangiogenesis in human ovarian cancers. *Cancer Res.* **65**, 465–472 (2005).
45. Carmeliet, P. & Jain, R. K. Angiogenesis in cancer and other diseases. *Nature* **407**, 249–257 (2000).
46. Menetrier-Caux, C. et al. Inhibition of the differentiation of dendritic cells from CD34⁺ progenitors by tumor cells: role of interleukin-6 and macrophage colony-stimulating factor. *Blood* **92**, 4778–4791 (1998).
47. Kryczek, I., Grybos, M., Karabon, L., Klimczak, A. & Lange, A. IL-6 production in ovarian carcinoma is associated with histiotype and biological characteristics of the tumour and influences local immunity. *Br. J. Cancer* **82**, 621–628 (2000).
48. Freedman, R. S., Deavers, M., Liu, J. & Wang, E. Peritoneal inflammation — a microenvironment for Epithelial Ovarian Cancer (EOC). *J. Transl. Med.* **2**, 23 (2004).
49. Pasare, C. & Medzhitov, R. Toll pathway-dependent blockade of CD4⁺CD25⁺ T cell-mediated suppression by dendritic cells. *Science* **299**, 1033–1036 (2003).
50. Shono, T., Tofilon, P. J., Bruner, J. M., Owolabi, O. & Lang, F. F. Cyclooxygenase-2 expression in human gliomas: prognostic significance and molecular correlations. *Cancer Res.* **61**, 4375–4381 (2001).
51. Wolff, H. et al. Expression of cyclooxygenase-2 in human lung carcinoma. *Cancer Res.* **58**, 4997–5001 (1998).
52. Joki, T. et al. Expression of cyclooxygenase 2 (COX-2) in human glioma and *in vitro* inhibition by a specific COX-2 inhibitor, NS-398. *Cancer Res.* **60**, 4926–4931 (2000).
53. Kalinski, P., Schuitmaker, J. H., Hilkens, C. M. & Kapsenberg, M. L. Prostaglandin E2 induces the final maturation of IL-12-deficient CD11a⁺CD83⁺ dendritic cells: the levels of IL-12 are determined during the final dendritic cell maturation and are resistant to further modulation. *J. Immunol.* **161**, 2804–2809 (1998).
54. Sombroek, C. C. et al. Prostanoids play a major role in the primary tumor-induced inhibition of dendritic cell differentiation. *J. Immunol.* **168**, 4333–4343 (2002).
55. Jozefowski, S., Bobek, M. & Marcinkiewicz, J. Exogenous but not endogenous prostanoids regulate cytokine secretion from murine bone marrow dendritic cells: EP2, DP, and IP but not EP1, EP3, and FP prostanoid receptors are involved. *Int. Immunopharmacol.* **3**, 865–878 (2003).
56. Akasaki, Y. et al. Induction of a CD4⁺ T regulatory type 1 response by cyclooxygenase-2-overexpressing glioma. *J. Immunol.* **173**, 4352–4359 (2004).
57. Shurin, G. V. et al. Neuroblastoma-derived gangliosides inhibit dendritic cell generation and function. *Cancer Res.* **61**, 363–369 (2001).
58. Peguet-Navarro, J. et al. Gangliosides from human melanoma tumors impair dendritic cell differentiation from monocytes and induce their apoptosis. *J. Immunol.* **170**, 3488–3494 (2003).
59. Lebeur, M. S. et al. Generation of tumor immunity by bone marrow-derived dendritic cells correlates with dendritic cell maturation stage. *J. Immunol.* **162**, 168–175 (1999).
60. Dhodapkar, M. V. et al. Rapid generation of broad T-cell immunity in humans after a single injection of mature dendritic cells. *J. Clin. Invest.* **104**, 173–180 (1999).
61. Jonuleit, H., Schmitt, E., Schuler, G., Knop, J. & Enk, A. H. Induction of interleukin 10-producing, nonproliferating CD4⁺ T cells with regulatory properties by repetitive stimulation with allogeneic immature human dendritic cells. *J. Exp. Med.* **192**, 1213–1222 (2000).
62. Dhodapkar, M. V., Steinman, R. M., Krasovsky, J., Munz, C. & Bhardwaj, N. Antigen-specific inhibition of effector T cell function in humans after injection of immature dendritic cells. *J. Exp. Med.* **193**, 233–238 (2001).
63. Hawiger, D. et al. Dendritic cells induce peripheral T cell unresponsiveness under steady state conditions *in vivo*. *J. Exp. Med.* **194**, 769–779 (2001).
64. Choi, I. H. et al. Genomic organization and expression analysis of B7-H4, an immune inhibitory molecule of the B7 family. *J. Immunol.* **171**, 4650–4654 (2003).
65. Curiel, T. J. et al. Specific recruitment of regulatory T cells in ovarian carcinoma fosters immune privilege and predicts reduced survival. *Nature Med.* **10**, 942–949 (2004).
- Provides a direct functional and clinical link between regulatory T cells and human tumour immunopathogenesis.**
66. Chen, L. Co-inhibitory molecules of the B7-CD28 family in the control of T-cell immunity. *Nature Rev. Immunol.* **4**, 336–347 (2004).
67. Brown, J. A. et al. Blockade of programmed death-1 ligands on dendritic cells enhances T cell activation and cytokine production. *J. Immunol.* **170**, 1257–1266 (2003).
68. Dong, H. et al. Tumor-associated B7-H1 promotes T-cell apoptosis: a potential mechanism of immune evasion. *Nature Med.* **8**, 793–800 (2002).
69. Strome, S. E. et al. B7-H1 blockade augments adoptive T-cell immunotherapy for squamous cell carcinoma. *Cancer Res.* **63**, 6501–6505 (2003).
70. Iwai, Y. et al. Involvement of PD-L1 on tumor cells in the escape from host immune system and tumor immunotherapy by PD-L1 blockade. *Proc. Natl Acad. Sci. USA* **99**, 12293–12297 (2002).
71. Iwai, Y., Terawaki, S. & Honjo, T. PD-1 blockade inhibits hematogenous spread of poorly immunogenic tumor cells by enhanced recruitment of effector T cells. *Int. Immunol.* **17**, 133–144 (2005).
- Reference 36 and 68–71 report that B7-H1 or PD-1 in the tumour microenvironment attenuates tumour-specific immunity and that blocking B7-H1 improves tumour immunity *in vivo*.**
72. Sica, G. L. et al. B7-H4, a molecule of the B7 family, negatively regulates T cell immunity. *Immunity* **18**, 849–861 (2003).
73. Prasad, D. V., Richards, S., Mai, X. M. & Dong, C. B7S1, a novel B7 family member that negatively regulates T cell activation. *Immunity* **18**, 863–873 (2003).
74. Zang, X. et al. B7x: a widely expressed B7 family member that inhibits T cell activation. *Proc. Natl Acad. Sci. USA* **100**, 10388–10392 (2003).
75. Tamura, H. et al. B7-H1 costimulation preferentially enhances CD28-independent T-helper cell function. *Blood* **97**, 1809–1816 (2001).
76. Subudhi, S. K. et al. Local expression of B7-H1 promotes organ-specific autoimmunity and transplant rejection. *J. Clin. Invest.* **113**, 694–700 (2004).
77. Munn, D. H. et al. Potential regulatory function of human dendritic cells expressing indoleamine 2,3-dioxygenase. *Science* **297**, 1867–1870 (2002).
78. Uytendove, C. et al. Evidence for a tumoral immune resistance mechanism based on tryptophan degradation by indoleamine 2,3-dioxygenase. *Nature Med.* **9**, 1269–1274 (2003).
- Reference 77 and 78 document the relevance of IDO-expressing dendritic cells or tumours in tumour immune responses.**
79. Grohmann, U. et al. CTLA-4-Ig regulates tryptophan catabolism *in vivo*. *Nature Immunol.* **3**, 1097–1101 (2002).
80. Salio, M. et al. Plasmacytoid dendritic cells prime IFN- γ -secreting melanoma-specific CD8 lymphocytes and are found in primary melanoma lesions. *Eur. J. Immunol.* **33**, 1052–1062 (2003).
81. Hartmann, E. et al. Identification and functional analysis of tumor-infiltrating plasmacytoid dendritic cells in head and neck cancer. *Cancer Res.* **63**, 6478–6487 (2003).
82. Moseman, E. A. et al. Human plasmacytoid dendritic cells activated by CpG oligodeoxynucleotides induce the generation of CD4⁺CD25⁺ regulatory T cells. *J. Immunol.* **173**, 4433–4442 (2004).
83. Gilliet, M. & Liu, Y. J. Generation of human CD8 T regulatory cells by CD40 ligand-activated plasmacytoid dendritic cells. *J. Exp. Med.* **195**, 695–704 (2002).
84. Conejo-Garcia, J. R. et al. Tumor-infiltrating dendritic cell precursors recruited by a β -defensin contribute to vasculogenesis under the influence of Vegf-A. *Nature Med.* **10**, 950–958 (2004).
85. Kusmartsev, S. A., Li, Y. & Chen, S. H. Gr-1⁺ myeloid cells derived from tumor-bearing mice inhibit primary T cell activation induced through CD3/CD28 costimulation. *J. Immunol.* **165**, 779–785 (2000).
86. Mazzoni, A. et al. Myeloid suppressor lines inhibit T cell responses by an NO-dependent mechanism. *J. Immunol.* **168**, 689–695 (2002).
87. Schmielau, J. & Finn, O. J. Activated granulocytes and granulocyte-derived hydrogen peroxide are the underlying mechanism of suppression of T-cell function in advanced cancer patients. *Cancer Res.* **61**, 4756–4760 (2001).
88. Almand, B. et al. Increased production of immature myeloid cells in cancer patients: a mechanism of immunosuppression in cancer. *J. Immunol.* **166**, 678–689 (2001).
89. Bronte, V., Serafini, P., Apolloni, E. & Zanovello, P. Tumor-induced immune dysfunctions caused by myeloid suppressor cells. *J. Immunother.* **24**, 431–446 (2001).
90. Saio, M., Radoja, S., Marino, M. & Frey, A. B. Tumor-infiltrating macrophages induce apoptosis in activated CD8⁺ T cells by a mechanism requiring cell contact and mediated by both the cell-associated form of TNF and nitric oxide. *J. Immunol.* **167**, 5583–5593 (2001).

91. Rodríguez, P.C. *et al.* L-arginine consumption by macrophages modulates the expression of CD3 ζ chain in T lymphocytes. *J. Immunol.* **171**, 1232–1239 (2003).
92. Rodríguez, P.C. *et al.* Arginase I production in the tumor microenvironment by mature myeloid cells inhibits T-cell receptor expression and antigen-specific T-cell responses. *Cancer Res.* **64**, 5839–5849 (2004).
93. Matzinger, P. The danger model: a renewed sense of self. *Science* **296**, 301–305 (2002).
94. Fuchs, E. J. & Matzinger, P. Is cancer dangerous to the immune system? *Semin. Immunol.* **8**, 271–280 (1996).
95. Vakkila, J. & Lotze, M. T. Inflammation and necrosis promote tumour growth. *Nature Rev. Immunol.* **4**, 641–648 (2004).
96. Balkwill, F. & Mantovani, A. Inflammation and cancer: back to Virchow? *Lancet* **357**, 539–545 (2001).
97. Jacoby, R. F., Seibert, K., Cole, C. E., Kelloff, G. & Lubet, R. A. The cyclooxygenase-2 inhibitor celecoxib is a potent preventive and therapeutic agent in the min mouse model of adenomatous polyposis. *Cancer Res.* **60**, 5040–5044 (2000).
98. Levin, G., Kariv, N., Khomiak, E. & Raz, A. Indomethacin inhibits the accumulation of tumor cells in mouse lungs and subsequent growth of lung metastases. *Chemotherapy* **46**, 429–437 (2000).
99. Steinbach, G. *et al.* The effect of celecoxib, a cyclooxygenase-2 inhibitor, in familial adenomatous polyposis. *N. Engl. J. Med.* **342**, 1946–1952 (2000).
100. Duperron, C. & Castonguay, A. Chemopreventive efficacies of aspirin and sulindac against lung tumorigenesis in A/J mice. *Carcinogenesis* **18**, 1001–1006 (1997).
101. Leahy, K. M. *et al.* Cyclooxygenase-2 inhibition by celecoxib reduces proliferation and induces apoptosis in angiogenic endothelial cells *in vivo*. *Cancer Res.* **62**, 625–631 (2002).
102. Tsubouchi, Y. *et al.* Meloxicam inhibits the growth of non-small cell lung cancer. *Anticancer Res.* **20**, 2867–2872 (2000).
103. Choy, H. & Milas, L. Enhancing radiotherapy with cyclooxygenase-2 enzyme inhibitors: a rational advance? *J. Natl Cancer Inst.* **95**, 1440–1452 (2003).
104. Dong, H., Zhu, G., Tamada, K. & Chen, L. B7-H1, a third member of the B7 family, co-stimulates T-cell proliferation and interleukin-10 secretion. *Nature Med.* **5**, 1365–1369 (1999).
105. Hussain, S. F. & Paterson, Y. CD4⁺CD25⁺ regulatory T cells that secrete TGF β and IL-10 are preferentially induced by a vaccine vector. *J. Immunother.* **27**, 339–346 (2004).
106. Chakraborty, N. G., Chattopadhyay, S., Mehrotra, S., Chhabra, A. & Mukherji, B. Regulatory T-cell response and tumor vaccine-induced cytotoxic T lymphocytes in human melanoma. *Hum. Immunol.* **65**, 794–802 (2004).
107. van Mierlo, G. J. *et al.* Activation of dendritic cells that cross-present tumor-derived antigen licenses CD8⁺ CTL to cause tumor eradication. *J. Immunol.* **173**, 6753–6759 (2004).
108. Yamazaki, S. *et al.* Direct expansion of functional CD25⁺CD4⁺ regulatory T cells by antigen-processing dendritic cells. *J. Exp. Med.* **198**, 235–247 (2003).
109. Donzella, G. A. *et al.* AMD3100, a small molecule inhibitor of HIV-1 entry via the CXCR4 co-receptor. *Nature Med.* **4**, 72–77 (1998).
110. Muller, A. *et al.* Involvement of chemokine receptors in breast cancer metastasis. *Nature* **410**, 50–56 (2001).
111. Le Bon, A. *et al.* Cross-priming of CD8⁺ T cells stimulated by virus-induced type I interferon. *Nature Immunol.* **4**, 1009–1015 (2003).
112. Klinman, D. M. Immunotherapeutic uses of CpG oligodeoxynucleotides. *Nature Rev. Immunol.* **4**, 249–258 (2004).
113. Krieg, A. M. CpG motifs: the active ingredient in bacterial extracts? *Nature Med.* **9**, 831–835 (2003).
114. Shevach, E. M. Fatal attraction: tumors beckon regulatory T cells. *Nature Med.* **10**, 900–901 (2004).
115. Shevach, E. M. CD4⁺CD25⁺ suppressor T cells: more questions than answers. *Nature Rev. Immunol.* **2**, 389–400 (2002).
116. Von Herrath, M. G. & Harrison, L. C. Regulatory lymphocytes: antigen-induced regulatory T cells in autoimmunity. *Nature Rev. Immunol.* **3**, 223–232 (2003).
117. Sakaguchi, S. *et al.* Immunologic tolerance maintained by CD25⁺CD4⁺ regulatory T cells: their common role in controlling autoimmunity, tumor immunity, and transplantation tolerance. *Immunol. Rev.* **182**, 18–32 (2001).
118. Homann, D. *et al.* Autoreactive CD4⁺ T cells protect from autoimmune diabetes via bystander suppression using the IL-4/Stat6 pathway. *Immunity* **11**, 463–472 (1999).
119. Bluestone, J. A. & Abbas, A. K. Opinion-regulatory lymphocytes: natural versus adaptive regulatory T cells. *Nature Rev. Immunol.* **3**, 253–257 (2003).
- Discusses the concept of natural versus adaptive regulatory T cells.**
120. Barrat, F. J. *et al.* *In vitro* generation of interleukin 10-producing regulatory CD4⁺ T cells is induced by immunosuppressive drugs and inhibited by T helper type 1 (Th1)- and Th2-inducing cytokines. *J. Exp. Med.* **195**, 603–616 (2002).
121. Groux, H. *et al.* A CD4⁺ T-cell subset inhibits antigen-specific T-cell responses and prevents colitis. *Nature* **389**, 737–742 (1997).
- References 120 and 121 provide evidence that T_{Reg} cells can be induced and that they can be functionally suppressive *in vivo*.**
122. Woo, E. Y. *et al.* Regulatory CD4⁺CD25⁺ T cells in tumors from patients with early-stage non-small cell lung cancer and late-stage ovarian cancer. *Cancer Res.* **61**, 4766–4772 (2001).
123. Woo, E. Y. *et al.* Regulatory T cells from lung cancer patients directly inhibit autologous T cell proliferation. *J. Immunol.* **168**, 4272–4276 (2002).
124. Liyanage, U. K. *et al.* Prevalence of regulatory T cells is increased in peripheral blood and tumor microenvironment of patients with pancreas or breast adenocarcinoma. *J. Immunol.* **169**, 2756–2761 (2002).
125. Onizuka, S. *et al.* Tumor rejection by *in vivo* administration of anti-CD25 (interleukin-2 receptor α) monoclonal antibody. *Cancer Res.* **59**, 3128–3133 (1999).
126. Shimizu, J., Yamazaki, S. & Sakaguchi, S. Induction of tumor immunity by removing CD25⁺CD4⁺ T cells: a common basis between tumor immunity and autoimmunity. *J. Immunol.* **163**, 5211–5218 (1999).
- References 125 and 126 were the first to report that depletion of CD25-expressing cells promotes tumour regression.**
127. van Elsas, A. *et al.* Elucidating the autoimmune and antitumor effector mechanisms of a treatment based on cytotoxic T lymphocyte antigen-4 blockade in combination with a B16 melanoma vaccine: comparison of prophylaxis and therapy. *J. Exp. Med.* **194**, 481–489 (2001).
128. Steitz, J., Bruck, J., Lenz, J., Knop, J. & Tuting, T. Depletion of CD25⁺CD4⁺ T cells and treatment with tyrosinase-related protein 2-transduced dendritic cells enhance the interferon α -induced, CD8⁺ T-cell-dependent immune defense of B16 melanoma. *Cancer Res.* **61**, 8643–8646 (2001).
129. Takahashi, T. *et al.* Immunologic self-tolerance maintained by CD25⁺CD4⁺ regulatory T cells constitutively expressing cytotoxic T lymphocyte-associated antigen 4. *J. Exp. Med.* **192**, 303–310 (2000).
130. Read, S., Malmstrom, V. & Powrie, F. Cytotoxic T lymphocyte-associated antigen 4 plays an essential role in the function of CD25⁺CD4⁺ regulatory cells that control intestinal inflammation. *J. Exp. Med.* **192**, 295–302 (2000).
131. Suttmoller, R. P. *et al.* Synergism of cytotoxic T lymphocyte-associated antigen 4 blockade and depletion of CD25⁺ regulatory T cells in antitumor therapy reveals alternative pathways for suppression of autoreactive cytotoxic T lymphocyte responses. *J. Exp. Med.* **194**, 823–832 (2001).
132. Turk, M. J., Guevara-Patino, J. A., Rizzuto, G. A., Engelhorn, M. E. & Houghton, A. N. Concomitant tumor immunity to a poorly immunogenic melanoma is prevented by regulatory T cells. *J. Exp. Med.* **200**, 771–782 (2004).
133. Mendez, S., Reckling, S. K., Piccirillo, C. A., Sacks, D. & Belkaid, Y. Role for CD4⁺CD25⁺ regulatory T cells in reactivation of persistent leishmaniasis and control of concomitant immunity. *J. Exp. Med.* **200**, 201–210 (2004).
134. Coussens, L. M. & Werb, Z. Inflammation and cancer. *Nature* **420**, 860–867 (2002).
135. Kuper, H., Adami, H. O. & Trichopoulos, D. Infections as a major preventable cause of human cancer. *J. Intern. Med.* **248**, 171–183 (2000).
136. Leach, D. R., Krummel, M. F. & Allison, J. P. Enhancement of antitumor immunity by CTLA-4 blockade. *Science* **271**, 1734–1736 (1996).
- The first published study to show that CTLA4 blockade enhances tumour immunity. Human clinical trials from this group and others further prove this concept.**
137. Hurwitz, A. A., Yu, T. F., Leach, D. R. & Allison, J. P. CTLA-4 blockade synergizes with tumor-derived granulocyte-macrophage colony-stimulating factor for treatment of an experimental mammary carcinoma. *Proc. Natl Acad. Sci. USA* **95**, 10067–10071 (1998).
138. Hodi, F. S. *et al.* Biologic activity of cytotoxic T lymphocyte-associated antigen 4 antibody blockade in previously vaccinated metastatic melanoma and ovarian carcinoma patients. *Proc. Natl Acad. Sci. USA* **100**, 4712–4717 (2003).
139. Phan, G. Q. *et al.* Cancer regression and autoimmunity induced by cytotoxic T lymphocyte-associated antigen 4 blockade in patients with metastatic melanoma. *Proc. Natl Acad. Sci. USA* **100**, 8372–8377 (2003).
140. Foss, F. M. DAB(389)IL-2 (ONTAK): a novel fusion toxin therapy for lymphoma. *Clin. Lymphoma* **1**, 110–106 (2000).
141. Wang, T. *et al.* Regulation of the innate and adaptive immune responses by Stat-3 signaling in tumor cells. *Nature Med.* **10**, 48–54 (2004).
142. Shen, L., Evel-Kabler, K., Strube, R. & Chen, S. Y. Silencing of SOCS1 enhances antigen presentation by dendritic cells and antigen-specific anti-tumor immunity. *Nature Biotechnol.* **22**, 1546–1553 (2004).
143. Kwon, E. D. *et al.* Elimination of residual metastatic prostate cancer after surgery and adjunctive cytotoxic T lymphocyte-associated antigen 4 (CTLA-4) blockade immunotherapy. *Proc. Natl Acad. Sci. USA* **96**, 15074–15079 (1999).

Acknowledgements

I would thank my father, Y. Zou for his precious support, M. von Herrath, V. Cerundolo and C.J.M. Melief for critical reading the manuscript, and the collaborators for their intellectual input and hard work. The review focuses on human tumour immunopathogenesis; owing to the plethora of literature related to this topic, a complete and extensive review is extremely challenging. I apologize in advance for any inadvertent omission. The work described in this review was supported by grants from the United States National Institutes of Health and the Department of Defense.

Competing interests statement

The author declares no competing financial interests.

Online links

DATABASES

The following terms in this article are linked online to:

Entrez Gene:

<http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?db=gene>
ARG1 | B7.1 | B7.2 | B7-H1 | CCL22 | CCR4 | CCR7 | CD62L | COX2 | CRP | CTLA4 | CXCL12 | CXCR4 | GM-CSF | IFN γ | IL-10 | IL-12 | IL-4 | IL-6 | LIGHT | M-CSF | NOS2 | PGE2 | TGF β | TLR9 | VEGF

National Cancer Institute: <http://cancer.gov/>
breast cancer | melanoma | ovarian cancer | prostate cancer | renal-cell cancer

FURTHER INFORMATION

Weiping Zou's lab:

<http://www.som.tulane.edu/medhemonc/members/WZOU/index.html>

Access to this interactive links box is free online.