

Targeting the Tumor Microenvironment: From Understanding Pathways to Effective Clinical Trials

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Abstract

It is clear that tumor cells do not act alone but in close interaction with the extracellular matrix and with stromal cells in the tumor microenvironment (TME). As our understanding of tumor cell–stroma interactions increased over the last two decades, significant efforts have been made to develop agents that interfere with these interactions. Here, we discuss four different therapeutic strategies that target the TME, focusing on agents that are at the most advanced stage of preclinical or clinical development. We end this review by outlining some of the lessons we have learned so far from the development of TME-targeting agents. *Cancer Res*; 73(16); 4965–77. ©2013 AACR.

Introduction

During the second half of the 20th century, much of our focus in cancer biology and therapy has been on genetic and epigenetic alterations in malignant cells that are drivers in the malignant process (1). However, it is now quite clear that tumor cells do not act alone but in close interaction with the extracellular matrix (ECM) and with nongenetically altered stromal cells that constitute the tumor microenvironment (TME; ref. 2)—thus, tumors are in fact "malignant organs." The interactions between tumor cells and the TME have a deep influence on cancer progression and contribute to almost all of the hallmarks of cancer (3).

The stromal cells that interact with tumor cells not only originate from neighboring tissues but can also be actively recruited from the bone marrow as endothelial progenitor cells, myeloid and lymphoid inflammatory cells, and mesenchymal cells. Once in the TME, they become "educated" as tumor-associated macrophages (TAM), tumor- (or cancer-) associated fibroblasts (TAF or CAF), or vascular and perivascular cells. Education of stromal cells is also a dynamic process where nonmalignant cells progressively switch from a neutral or antitumorogenic role toward a protumorogenic role. When these cells are targeted by therapies, it is therefore critical to take into consideration the specific stage at which they are in such an education process.

The mechanisms of communication between tumor cells and the TME are complex but fall into two main categories,

contact-dependent mechanisms that involve cell–cell and cell–ECM adhesion molecules and contact-independent mechanisms in which soluble molecules such as growth factors, chemokines and cytokines, and soluble subcellular organelles including microvesicles and exosomes play an essential role. Ultimately, these interactions activate via juxtacrine and paracrine mechanisms, signaling pathways in malignant cells and in nonmalignant stromal cells that can inhibit or favor tumor progression (4). As our understanding of tumor cell–stroma interactions has increased and pathways involved have been better characterized, significant efforts have been made over the last decade to identify, develop, and test therapeutic agents interfering either with the recruitment of stromal cells into the TME, with tumor cell–stromal interaction, or with specific pathways activated by the TME.

In this review, we will discuss four different therapeutic strategies that primarily target the TME, focusing on agents that are at the most advanced preclinical or clinical stages of development (Table 1). Agents that specifically target the immune system and are used for immunotherapy are not discussed here as they have been the subject of recent comprehensive reviews (5, 6).

Strategy 1: Targeting the Tumor Vasculature

The vascularization of a tumor is an intricate process that is tightly regulated by pro- and antiangiogenic factors produced by both malignant cells and nonmalignant cells through autocrine and paracrine signaling pathways. The onset of angiogenesis, known as "angiogenic switch," is induced when the proangiogenic factors are favored (7). VEGF/VEGF-A is the predominant proangiogenic factor involved in endothelial cell activation (8), but many other growth factors are also proangiogenic, such as fibroblast growth factor (FGF), platelet-derived growth factor (PDGF), and EGF (7). Different from the normal vasculature characterized by an organized formation of mature endothelial cell covered with pericytes, the tumor vasculature is typically abnormal with a deficit in

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pericytes and perivascular cells, and an increased permeability, resulting in a leaky vascular system (9). It is also now well recognized that bone marrow–derived endothelial progenitor cells contribute to the tumor vasculature through a process known as vasculogenesis (10).

Targeting VEGF signaling

Considering the important functions of VEGF signaling in tumor angiogenesis, growth, invasion, and metastasis, several VEGF- and VEGF receptor (VEGFR)-antagonists have been developed. The first effective agent, which is also the first one to provide clinical evidence supporting the validity of the concept of targeting the TME, is bevacizumab (Avastin). This recombinant humanized VEGF-neutralizing monoclonal antibody (mAb) was approved by the U.S. Food and Drug Administration (FDA) in 2004 for the treatment of metastatic colon cancer and subsequently several other metastatic cancers in combination with cytotoxic therapies. Other effective inhibitors of VEGF signaling include small-molecule receptor tyrosine kinase inhibitors (TKI; e.g., sunitinib/Sutent, sorafenib/Nexavar, and pazopanib/Votrient) and receptor-specific antibodies (e.g., IMC-1121B/Ramucirumab, a mAb against VEGFR-2). Sunitinib, sorafenib, and pazopanib have already been approved by the FDA, in most cases for advanced renal cell carcinoma. This type of cancer is not only highly angiogenic but its tumor angiogenesis is also predominantly driven by VEGF, which explains why four different VEGF-pathway–targeting drugs have all been approved for this type of malignancy (11). IMC-1121B/Ramucirumab has shown a favorable therapeutic index with early evidence of both stable disease and partial responses in a phase I trial of patients with advanced solid tumors (12) and is currently undergoing several phase III clinical trials in patients with breast and gastric cancer, but its efficacy has not yet been shown.

Beyond targeting VEGF signaling

Highlighting the need to develop more effective antiangiogenic agents was the recent decision by the FDA to withdraw Avastin from its previously approved indication for patients with metastatic HER2–negative breast cancer due to reports that Avastin had no favorable therapeutic efficacy and significant toxicity (bleeding, heart attack or heart failure, elevated blood pressure, and organ perforation; ref. 13). This again emphasizes the fact that we should not assume VEGF-dependent angiogenesis to be present in all cancer types at the same level as in renal cell carcinoma. For example, the results of an analysis of a large number of primary breast cancer specimens from various types of disease progression that identified six different proangiogenic growth factors, including VEGF and FGF, indicated that there was a greater level of proangiogenic growth factor redundancy in more advanced disease stage (14). This type of angiogenic pathway redundancy is now well accepted as the major resistance mechanism for VEGF-pathway–targeting agents (15–17).

Thus, multiple antiangiogenic agents targeting other proangiogenic signaling pathways are currently undergoing development.

Targeting FGF signaling

Emerging evidence suggests that the upregulation of FGF provides a mechanism of resistance to anti-VEGF therapy. The most advanced FGF/FGFR–targeting agent so far developed is BMS-582664 (brivanib), an oral dual inhibitor of VEGFR and FGF receptor (FGFR) tyrosine kinases, presently tested in multiple phase II/III clinical trials (18). In a recent phase II open-label study in patients with advanced hepatocellular carcinoma who had failed prior antiangiogenic treatment with sorafenib, brivanib has shown promising antitumor activity with a manageable safety profile (19).

Targeting PDGF signaling

PDGF and its receptors PDGFR have been detected in diverse human cancers, and PDGFR is upregulated in the tumor vasculature, particularly in pericytes, where it plays a central role in their proliferation, migration, and maturation (20). PDGF signaling also regulates angiogenesis by inducing VEGF expression and by recruiting pericytes to mature blood vessels (21). SU6668, a small-molecule kinase inhibitor for PDGFR, VEGFR, and FGFR, has currently completed phase I clinical trials in patients with advanced solid tumors. The results of this trial, however, have shown relatively low plasma levels of the free drug because of its high protein binding, discouraging further clinical development (22).

Targeting EGFR signaling

EGF receptor (EGFR) is a member of the HER growth factor receptor family, a group of homologous receptor tyrosine kinases known to modulate normal cell growth and differentiation (23). In solid tumors, VEGF and EGFR pathways are linked, thus promoting angiogenesis (24), and resistance to anti-EGFR therapy is accompanied by an increase in VEGF levels (25). Because tumor cells and tumor-associated endothelial cell both express EGFR, targeting EGFR has a dual function of inhibiting both tumor cells and endothelial cell. Several EGFR-neutralizing antibodies (e.g., cetuximab, panitumumab, etc.) and small-molecule inhibitors (e.g., erlotinib, gefitinib, etc.) have been approved by the FDA and have been incorporated into the standard care for different types of cancers, implying the significance of targeting both tumor cells and TME in cancer therapy.

Strategy 2: Targeting Cancer-Associated Inflammation

The presence of innate and adaptive immune cells in tumors was initially considered to be the sign of an effective attack of the immune system against cancer. It is now well recognized that immune cells can also promote cancer initiation, progression, and metastasis (26). Our understanding of this dual role of immune cells in cancer progression is centered on the concept of polarization. Immune cells can be polarized toward either a typically antitumorigenic T-helper cell type 1 (T_H1)-driven process or toward a T_H2 -driven process that is protumorigenic (27). The polarization of the immune system is characterized by changes in metabolic pathways and the production of cytokines by immune cells. TAMs, which can

be polarized toward a T_H2-type, have emerged as being among the most important players in a protumorigenic inflammatory reaction. Their contribution to cancer angiogenesis, cancer metastasis, and drug resistance is now well recognized (28). As a result, strategies to inhibit their protumorigenic activity have been actively pursued and two major strategies aimed at targeting TAM and targeting the protumorigenic inflammatory pathways have been developed so far.

Inhibiting TAM

The recruitment of macrophages by tumors is driven by chemokines such as chemokine (C-C motif) ligand 2 (CCL2), monocyte chemoattractant protein-1 (MCP-1), and colony-stimulating factor-1 (CSF-1; ref. 29), and these factors also promote the polarization of macrophages toward a T_H2-type (also reported as M2). Targeting these chemokines has thus been actively tested in cancer therapy. CNTO 888, a neutralizing antibody to human CCL2, has proven to have anticancer activity in a preclinical model of prostate cancer (30). Bindarit, a small-molecule inhibitor of CCL2, was recently shown to have anticancer activity in preclinical models of prostate and breast cancer, causing a significant decrease in the infiltration of TAM and myeloid-derived suppressor cells in tumors (31). Other studies have shown that anti-CSF-1 antibodies and antisense oligonucleotides suppress macrophage infiltration and the growth of xenografted mammary tumors in mice (32, 33). TKIs of CSF-1 receptor (also known as c-fms), Ki20227 and JNJ-28312141, suppress osteolysis in a bone metastasis mouse model (34) and inhibit angiogenesis and bone metastasis in preclinical models of solid tumors and acute myeloid leukemia, respectively (35). These favorable preclinical results support their further clinical development.

Inhibiting inflammatory pathways

Numerous signaling pathways become activated upon interaction between tumor cells and immune stromal cells. Inhibitors for several of these pathways have been developed.

Targeting IL-6/JAK/STAT3 signaling pathway

Because of its central role in cancer-associated inflammation and other diseases such as rheumatoid arthritis and lupus, the interleukin (IL)-6/JAK/STAT3 signaling pathway has been the focus of much attention over the last several years (36). Strategies to inhibit this pathway have focused on (i) blocking IL-6/IL-6 receptor (IL-6/IL-6R) interaction, (ii) blocking Janus-activated kinase (JAK) phosphorylation of STAT3, and (iii) inhibiting STAT3 DNA-binding activity.

An IL-6-neutralizing mAb (siltuximab/CNTO-328) is being tested in a number of phase I/II clinical trials. When given in combination with mitoxantrone and prednisone in patients with metastatic castration-resistant prostate cancer, siltuximab was found to be of no additional benefit (37). However, it has been shown to stabilize disease and induce partial responses in patients with platinum-resistant ovarian cancer (38) and metastatic renal cell carcinoma (39). Further studies will be needed to show its clinical efficacy. Ruxolitinib (INCB018424), a JAK2-specific inhibitor, is currently being tested in a phase III clinical trial in patients with myelofibrosis

(40) and in phase II clinical trials in adults and children with a variety of cancers. A STAT3 transcription factor decoy that inhibits STAT3 DNA binding was tested in a phase 0 (biologic effect) clinical trial, in head and neck tumors, and shown to bind with high affinity to STAT3 protein, to reduce cellular viability, and to suppress STAT3-dependent gene expression in tumor cells (41).

Targeting NF- κ B signaling pathway

NF- κ B is a family of transcriptional factors that play pivotal roles in both inflammation-induced tumorigenesis and anti-tumor immunity (42, 43). NF- κ B signaling is also critical in bone metastasis, being activated in osteoclasts upon stimulation of the receptor activator of NF- κ B (RANK) by its ligand RANKL produced by tumor cells and by osteoblasts (44). Activation of most forms of NF- κ B depends on phosphorylation-induced ubiquitination of the inhibitor of κ B (I κ B) proteins, which is modulated by the inhibitor of I κ B kinase (IKK) complex (45).

To date, most efforts in targeting NF- κ B signaling have concentrated on the development of specific inhibitors for the IKK β subunit (46). PS-1145, a small-molecule inhibitor of IKK β , was found to be effective in subtypes of diffuse large B-cell lymphomas where NF- κ B is activated (47). Because IKK β has many NF- κ B-independent functions, including the induction of genes involved in autophagy, the alteration of actin dynamics, and the regulation of the phosphorylation of multiple proteins, its inhibition has resulted in undesired effects (45). Other approaches that target NF- κ B include (i) the inhibition of proteasomes to disrupt the degradation of I κ B, by agents such as bortezomib (Velcade) used in multiple myeloma (48), and (ii) the direct targeting of NF- κ B-dependent gene expression with agents such as curcumin and arsenic.

Targeting TNF- α signaling pathway

In animal models, TNF- α at high doses has a potent anti-cancer activity through stimulation of T-cell-mediated immunity and the destruction of blood vessels (49). Conversely, at physiologic doses, TNF- α enhances tumor growth and metastasis by inducing the production of proinflammatory cytokines and chemokines (e.g., IL-6), proangiogenic factors (e.g., VEGF, FGF, etc.), and proteases (e.g., matrix metalloproteinases or MMP; refs. 49, 50). TNF inhibition could thus have a dual effect.

At least two TNF- α antagonists have been tested in patients with advanced cancers. The first antagonist, etanercept (Enbrel), a recombinant humanized soluble p75 TNF- α -trapping receptor that binds to TNF- α , has been tested in several phase I/II clinical trials. Etanercept in combination with rituximab (a mAb against B cells) was well tolerated and produced durable remissions in patients with chronic lymphocytic leukemia (51). When used as a single agent in patients with recurrent ovarian cancer, it resulted in disease stabilization and some partial responses (52). It has also shown safety and biologic activity in patients with metastatic breast cancer (53). The second TNF- α antagonist, infliximab (cA2, Remicade), a chimeric human-mouse mAb, has been shown to produce stable disease or partial responses as a single agent in renal cell carcinoma (54). It did not provide additional

therapeutic benefits when combined with sorafenib in patients with advanced renal cell carcinoma (55).

Targeting COX2 signaling pathway

Cyclooxygenase 2 (COX2), an inducible enzyme responsible for the synthesis of prostanoids (prostaglandins, prostacyclin, and thromboxane) from the precursor arachidonic acid, is another major player in inflammation. COX2 overexpression is observed in both cancer cells and stromal cells during tumor progression and in response to anticancer therapies. Elevated levels of COX2 in tumors are associated with increased angiogenesis, tumor invasion, and tumor cell resistance to apoptosis (56, 57).

Celecoxib, a COX2 inhibitor, has shown efficacy in preventing colon cancer in patients with inflammatory bowel disease, but was not adopted clinically due to its unacceptable cardiac toxicity (58). The therapeutic administration of celecoxib has been tested in a number of phase II/III clinical trials for multiple cancers with mixed clinical results. Although it has improved the efficacy of conventional therapy in patients with locally advanced undifferentiated nasopharyngeal carcinoma (59), it had no effect in hormone-sensitive prostate cancer (60) or advanced non-small cell lung cancer (61). Its value as a therapeutic agent is uncertain at this point.

The side effects of COX2 inhibitors may result from the suppression of prostanoid production, including the protumorigenic PGE₂. A possible way to selectively block PGE₂ is to inhibit prostaglandin E synthase (PGES; ref. 62). Selective inhibitors of this enzyme, which is overexpressed in cancer cells (63), may rationally be proposed in substitution for COX inhibitors. Another arachidonic acid-metabolizing enzyme, 5-lipoxygenase (5-LOX), also plays an important role in inflammation and inflammation-associated carcinogenesis and is overexpressed in many cancers. As a result, 5-LOX inhibitors have been developed. It was recently shown that the combination of zileuton (a specific 5-LOX inhibitor) and celecoxib prevented oral carcinogenesis through their joint inhibitory effects on arachidonic acid metabolism (64). Moreover, simultaneous treatment of premalignant and malignant human lung cell lines with a triple combination of one COX2 inhibitor (celecoxib) and two specific 5-LOX inhibitors, MK886 and REV5901, is more potent in suppressing growth and inducing cell death than a single or dual combination of these agents (65). Further clinical tests are however necessary to confirm the clinical effectiveness and safety of COX/LOX dual inhibitors.

Targeting TGF- β signaling pathway

TGF- β has a dual function in cancer. It is tumor suppressive in premalignant cells and at the early stage of cancer development, but strongly protumorigenic at later stages of cancer progression (66). Autocrine TGF- β signaling promotes epithelial-mesenchymal transformation (EMT), which increases cell invasion and metastasis. Paracrine TGF- β signaling stimulates angiogenesis and contributes to an immune-tolerant environment by suppressing T lymphocytes and natural killer cells (67). TGF- β also has a central function in bone metastasis. It is released from the bone matrix during bone resorption by

osteoclasts and contributes to a vicious circle that further fuels tumor growth and bone destruction (44, 68). Strategies to inhibit TGF- β activity include (69): (i) blocking the production of TGF- β with antisense molecules, (ii) blocking the activity of TGF- β with neutralizing antibodies, (iii) blocking the interaction between TGF- β and its receptors (TGF- β R) with soluble forms of TGF- β Rs, and (iv) blocking TGF- β -mediated receptor signaling by small-molecule TKIs of TGF- β RII and TGF- β RIII. AP12009 (trabedersen), an 18-oligomer antisense phosphorothioate oligodeoxynucleotide that prevents the production of TGF- β 2, is at the most advanced stage of development. On the basis of data showing that TGF- β 2 is overexpressed in more than 90% of high-grade gliomas, and that its levels are closely related to tumor progression, AP12009 was first tested in patients with high-grade glioma and showed an increase in 6 month median survival from 21.7 to 39.1 months (70, 71). Furthermore, inhibition of TGF- β 2 in tumor tissue leads to reversal of tumor-induced immune suppression as well as inhibition of tumor growth, invasion, and metastasis (72). In a phase II clinical trial for patients with brain tumors, the addition of AP12009 to conventional chemotherapy resulted in a significant increase in 14-month tumor control rate in patients with anaplastic astrocytoma and an increase in 2- and 3-year survival in a subgroup of patients with high-grade glioma (73).

Strategy 3: Targeting the Communication between Tumor Cells and TME

Targeting communication between tumor cells and ECM

Integrins are clustered at the cell surface in complexes known as focal adhesions, and play a central role in many normal physiologic processes such as growth, anchorage-dependent differentiation, adhesion, motility, apoptosis, and angiogenesis (74, 75). They are expressed by endothelial cell where they control angiogenesis and by tumor cells where they potentiate tumor metastasis by facilitating migration, survival, and invasion. Integrin inhibition can thus affect both tumor cells and endothelial cell.

Cilengitide (EMD 121974), a cyclic RGD (arginine-glycine-aspartic acid) pentapeptide, was the first potent integrin inhibitor for both $\alpha_v\beta_3$ and $\alpha_v\beta_5$ that reached clinical testing (76). In a phase II trial for patients with recurrent glioblastoma multiforme (77), cilengitide monotherapy was found to be well tolerated but exhibited modest antitumor activity. Intetumumab, (CNTO 95), a mAb against the human α_v integrin, has shown a favorable safety profile and a trend toward improved overall survival in a phase II clinical trial of patients with metastatic melanoma (78). In contrast, in another phase II trial of patients with stage IV melanoma, etaracizumab (MEDI-522), a mAb against the human $\alpha_v\beta_3$ integrin, did not provide any therapeutic benefit (79). Whether these inhibitors should be used alone or in combination with other therapeutic agents remains to be determined.

Targeting communication between tumor cells and the bone microenvironment

The bone is among the most common metastatic sites in many different types of cancer, and the mechanisms involved

in bone metastasis have been well characterized (80). Tumor cells secrete parathyroid hormone-related peptide (PTHrP), which promotes the expression of RANKL at the surface of osteoblasts. By binding to its receptor RANK present on osteoclast precursor cells, RANKL promotes their differentiation into mature osteoclasts and their activation. RANKL is inhibited by a natural inhibitor, osteoprotegerin (OPG). Osteoclasts, PTHrP, and RANKL have thus been considered as therapeutic targets.

Targeting osteoclasts with bisphosphonates has been among the first successful strategies targeting the TME in cancer bone metastasis. Zoledronic acid, a nitrogen-binding bisphosphonate, is FDA approved for the treatment of patients with multiple myeloma and documented bone metastases from solid tumors, in conjunction with standard antineoplastic therapy. Despite having a limited effect on overall survival, this agent significantly decreases the number of skeletal morbidities in these patients (81). A humanized mAb-targeting PTHrP, CAL, has completed a phase I/II study for breast cancer with bone metastasis but its clinical efficacy has not yet been reported. Denosumab, a fully humanized mAb that specifically targets RANKL and was originally approved by the FDA in postmenopausal women with risk of osteoporosis, is now approved for patients with cancer bone metastasis and for the prevention of skeletal-related events in patients with solid tumors (82). In 2011, the FDA also granted approval for denosumab to increase bone mass in patients who are at high risk of fracture from receiving androgen-deprivation therapy for nonmetastatic prostate cancer or in patients receiving adjuvant aromatase inhibitor therapy for breast cancer.

Strategy 4: Targeting Hypoxia in the TME

A major metabolic feature of the TME is that it is hypoxic. Tumor cells adapt to this hypoxic environment using mechanisms that promote genomic instability and deregulate DNA repair systems and the expression of proto-oncogenes (83). Altogether these mechanisms promote therapeutic resistance. There is also recent evidence that hypoxia through the expression of hypoxia-inducible factor (HIF)-1 α and HIF-2 α regulates the polarization of macrophages (84).

Bioreductive prodrugs

A first therapeutic strategy that takes advantage of the unique hypoxic environment of tumors consists of the use of bioreductive prodrugs, which are activated by enzymatic reduction (bioreduction) into toxic products in hypoxic tissues (85). Among those bioreductive prodrugs was tirapazamine that, despite promising results from preclinical studies and early-phase clinical trials, was abandoned as it failed to show any benefit in combination with chemotherapy or radiotherapy in several phase III trials in patients with non-small cell lung and head and neck cancer (86). Other bioreductive prodrugs currently being investigated in phase I/II clinical trials include TH-302 and AQ4N, which have both shown minimal toxicity in a phase I trial in patients with advanced malignancies (87, 88). In contrast, others like PR-104 have shown severe hematologic toxicities that may limit their use

in the clinic (89). The future of these agents is thus uncertain and further preclinical and clinical testing is required.

Targeting HIF-1 α signaling

Multiple agents developed as HIF inhibitors are currently being evaluated in clinical trials. Among the most advanced ones are EZN-2968, a HIF-1 α antisense mRNA, and PX-478, a small-molecule inhibitor of HIF derived from melphalan by oxidation of the nitrogen mustard moiety (90). Both of these agents have completed phase I clinical testing but no data on toxicity and efficacy have been reported yet.

Targeting unfolded protein response signaling

Severe hypoxia leads to increased levels of unfolded proteins in the endoplasmic reticulum, leading to the induction of unfolded protein response (UPR). UPR suppresses protein synthesis, stimulates protein degradation in the endoplasmic reticulum, and activates apoptosis or autophagy to resolve endoplasmic reticulum stress (91). One therapeutic strategy to target UPR signaling seeks to exacerbate endoplasmic reticulum stress to overwhelm the UPR on the assumption that it is near capacity in hypoxic cells (91).

Agents having such action include inhibitors of 26S proteasome (such as bortezomib, nelfinavir, etc.) and inhibitors of HSP90 (such as IPI-504, 17-AAG, etc.). Bortezomib has been approved by the FDA for multiple myeloma and mantle cell lymphoma and nelfinavir is still under investigation in phase I trials. When tested in a phase II trial, IPI-504 (retaspimycin), used as a single agent, had a minimal effect on tumor burden and an unacceptable toxicity in patients with castration-resistant prostate cancer (92). In contrast, 17-AAG (tanespimycin) had significant anticancer efficacy when combined with trastuzumab in patients with HER2-positive metastatic breast cancer in a phase II trial (93), clearly warranting further clinical investigation.

What Have We Learned So Far?

With more than a decade of experience using drugs that more specifically target the TME, it is appropriate to ask the question of "what we have learned?" as we continue to move forward. Among the many lessons learned, we want to highlight three in particular in this review.

Lesson 1: targeting the TME can be toxic

As clinical studies using agents targeting the TME were initiated, it was somewhat assumed that these agents would be much less toxic than cytotoxic agents used in chemotherapy. It is now clear that this is not the case as many initially promising studies on agents targeting the TME had to be discontinued because of unacceptable and often unanticipated toxicity. The reasons are multiple and complex.

The first and most obvious reason is that many agents targeting the TME alter the homeostatic balance in normal organs and tissues, as was well illustrated in the case of small-molecule inhibitors of MMPs. Cell and ECM proteins in tissues are not static but are subject to a constant and dynamic turnover that requires a delicate balance between growth and

Table 1. Agents targeting the TME

Category	Pathway	Molecular target	Agent	Mechanism of action	Indication	Clinical status
Tumor vasculature	VEGF signaling	VEGF	Bevacizumab (Avastin)	Humanized mAb against VEGF	Metastatic colorectal cancer, metastatic renal cell carcinoma, non-small cell lung cancer, glioblastoma	FDA approved
		VEGFR	IMC-1121B (Ramucirumab)	VEGFR-2-neutralizing antibody	HER2-negative breast cancer, non-small cell lung cancer, hepatocellular carcinoma, gastric adenocarcinoma	Phase III
		VEGFR	Sunitinib (Sutent)	TKI of VEGFR1-3, PDGFR, c-Kit	Advanced renal cell carcinoma, pancreatic neuroendocrine tumors, gastrointestinal stromal tumors	FDA approved
		VEGFR	Sorafenib (Nexavat)	TKI of VEGFR2, PDGFR β , Raf	Advanced renal cell carcinoma, unresectable hepatocellular carcinoma	FDA approved
		VEGFR	Pazopanib (Votrient)	TKI of VEGFR1-3, PDGFR, c-Kit	Advanced renal cell carcinoma, soft tissue sarcoma	FDA approved
	FGF signaling	FGFR	BMS-582664 (Brivanib)	FGFR and VEGFR	Hepatocellular carcinoma, colorectal cancer	Phase II/III
	PDGF signaling	PDGF	SU6668	PDGFR, VEGFR, and FGFR	Not specific	Phase I
	EGFR signaling	EGFR	Cetuximab (Erbixux)	mAb against EGFR	Metastatic colorectal cancer, head and neck squamous carcinoma	FDA approved
		EGFR	Panitumumab	mAb against EGFR	Metastatic colorectal cancer	FDA approved
		EGFR	Erlotinib	TKI of EGFR	Non-small cell lung cancer and pancreatic cancer	FDA approved
		EGFR	Gefitinib	TKI of EGFR	Non-small cell lung cancer	FDA approved
Inflammation	Macrophage recruitment	CCL2	CNTO888	Neutralizing antibody to human CCL2	Prostate cancer model	Preclinical
		CCL2	Bindarit	A small-molecule inhibitor of CCL2	Prostate and breast cancer model	Preclinical
		CSF-1	Mouse CSF-1 antisense oligonucleotides, CSF-1 or CSF-1 receptor siRNAs	CSF-1 antibodies and antisense oligonucleotides	Breast cancer model	Preclinical
		CSF-1 receptor	KI20227	TKI of CSF-1 receptor	Bone metastasis mouse model	Preclinical
		CSF-1 receptor	JNJ-28312141	TKI of CSF-1 receptor	Lung adenocarcinoma, breast cancer, acute myeloid leukemia models	Preclinical
	IL-6/JAK/STAT3 signaling	IL-6	CNTO-328 (Siltuximab)	Monoclonal neutralizing antibody against IL-6	Prostate cancer, multiple myeloma, metastatic renal cell carcinoma, ovarian cancer	Phase I/II
		IL-6R	Tocilizumab	An IL-6R blocking antibody	N/A	Preclinical

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Table 1. Agents targeting the TME (Cont'd)

Category	Pathway	Molecular target	Agent	Mechanism of action	Indication	Clinical status
		JAK1/2	AZD1480	Small-molecule inhibitor of Jak1/2	Solid tumors	Phase I
		JAK1/2	Ruxolitinib (INCB018424)	Small-molecule inhibitor of Jak1/2	Advanced breast cancer, advanced hematologic malignancies, metastatic pancreatic adenocarcinoma	Phase II
	NF-κB signaling	STAT3 IKK	STAT3 decoy PS-1145	STAT3 DNA competitor Small-molecule inhibitor of IKK kinases	Head and neck cancer B-cell lymphoma cells	Phase 0 Preclinical
		26S proteasome	Bortezomib (Velcade)	Inhibitor of 26S proteasome disrupting IκB degradation	Multiple myeloma, mantle cell lymphoma	FDA approved
		NF-κB	Curcumin	Phytochemical extract from turmeric that suppress NF-κB activation and NF-κB-dependent gene expression	Colon cancer	Phase I/II
	TNF-α signaling	NF-κB TNF-α	Arsenic Etanercept (Enbrel)	NF-κB inhibitor Recombinant inhibitory TNF-α receptors	Acute promyelocytic leukemia Recurrent ovarian cancer, metastatic breast cancer, chronic lymphocytic leukemia	Phase I/II Phase I/II
	COX2 signaling	TNF-α	Infliximab (cA2, Remicade)	Neutralizing antibody against TNF-α	Renal cell carcinoma	Phase II
		COX2	Celecoxib	COX2 inhibitor	Non-small cell lung cancer, nasopharyngeal carcinoma, hormone-sensitive prostate cancer	Phase II/III
	TGF-β signaling	TGF-β	AP12009 (trabedersen)	Antisense phosphorothioate oligodeoxynucleotide for TGF-β2	Anaplastic astrocytoma	Phase II/III
		TGF-β	Soluble TGF-βRII/III	TGF-β ligand traps	Metastatic pancreatic cancer model, colon cancer model	Preclinical
		TGF-β	Soluble TGF-βRIII fusion protein	TGF-β ligand traps	Pancreatic cancer and melanoma model	Preclinical
		TGF-βR	LY2109761	Small-molecule inhibitor for TGF-β-receptor kinase	Metastatic pancreatic and colorectal cancer model	Preclinical
		TGF-βR	SB-431542	Small-molecule inhibitor for TGF-β-receptor kinase	N/A	Preclinical
	Interaction between TGF-β ligands and receptors		2G7	Neutralizing antibody minimizing the interaction between ligands and receptors	Breast cancer model	Preclinical
	Interaction between TGF-β ligands and receptors		1D11	Neutralizing antibody minimizing the interaction between ligands and receptors	Breast cancer model	Preclinical

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Table 1. Agents targeting the TME (Cont'd)

Category	Pathway	Molecular target	Agent	Mechanism of action	Indication	Clinical status	
Interactions between tumor cells and their microenvironment	Integrin signaling	$\alpha_v\beta_3$ and $\alpha_v\beta_5$	Cilengitide	RGD peptide as an inhibitor of $\alpha_v\beta_3$ and $\alpha_v\beta_5$ integrins	Glioblastoma, prostate cancer	Phase II	
		$\alpha_v\beta_3$	Etaracizumab (Medi-522)	mAb against $\alpha_v\beta_3$ integrin	Prostate cancer, colorectal cancer, melanoma	Phase I/II	
Hypoxia	Osteoclast survival signaling RANK/RANKL signaling	α_v	Intetumumab (CANTO 95)	mAb against α_v integrin	Prostate cancer, melanoma	Phase I/II	
		Farnesyl pyrophosphate synthase	Zoledronic acid (Zoledronate, Zometa, Reclast, Aclasta)	Nitrogen-binding bisphosphonate	Multiple myeloma, bone metastases from solid tumors, hypercalcemia caused by malignant tumors	FDA approved	
		RANKL	Denosumab (Prolia, Xgeva)	mAb against RANKL	Bone metastases from solid tumors, patients at high risk of fracture with nonmetastatic prostate cancer on androgen-deprivation therapy or adjuvant aromatase inhibitor therapy for breast cancer	FDA approved	
		PTHrP	CAL	mAb against PTHrP	Bone metastatic breast cancer	Phase I/II	
Hypoxia	Hypoxic environment	Hypoxia	Tirapazamine (SR4233)	Bioreductive prodrug of an aromatic NO generating a DNA-reactive free radical	Cervix cancer, advanced head and neck squamous carcinoma	Phase III (closed)	
		Hypoxia	TH-302	Bioreductive prodrug of a 2-nitroimidazole-based nitrogen mustard	Multiple myeloma, advanced renal cell carcinoma, soft tissue sarcoma, pancreatic adenocarcinoma, non-small cell lung cancer	Phase I/II/III	
	Hypoxia	Hypoxia	PR-104	Bioreductive prodrug of a 3,5-dinitrobenzamide nitrogen mustard	Leukemia, solid tumors	Phase I/II	
			AQ4N	Bioreductive prodrug of an aliphatic NO generating a DNA intercalator	Glioblastoma, non-Hodgkin's lymphoma, leukemia	Phase I/II	
	Hypoxia	HIF-1 α signaling	EZN-2968	HIF-1 α antisense mRNA	Advanced solid tumors, lymphoma	Phase I	
		UPR signaling	PX-478	Small-molecule inhibitor of HIF-1 α	Advanced solid tumors, lymphoma	Phase I	
	Hypoxia	26S proteasome	26S proteasome	Bortezomib (Velcade)	Inhibitor of 26S proteasome that cause endoplasmic reticulum stress	Multiple myeloma, mantle cell lymphoma	FDA approved
				Nelfinavir	Inhibitor of 26S proteasome that causes endoplasmic reticulum stress, impairs HIF-1 α , and VEGF expression	Colorectal cancer	Phase I/II

(Continued on the following page)

Table 1. Agents targeting the TME (Cont'd)

Category	Pathway	Molecular target	Agent	Mechanism of action	Indication	Clinical status
		HSP90	IPI-504 (Retaspimycin)	Small-molecule inhibitor of HSP90 that is in part responsible for protein folding	Castration-resistant prostate cancer, gastrointestinal stromal tumors, breast cancer, lung cancer	Phase I/II
		HSP90	17-AAG (Tanespimycin)	Small-molecule inhibitor of HSP90 that is in part responsible for protein folding	Metastatic breast cancer	Phase II/III

Abbreviation: N/A, not available.

death, synthesis and degradation, and activation and inhibition of specific proteolytic processes or pathways. By disturbing the balance between MMP activation and inhibition, inhibitors of MMPs were found to increase collagen deposition in tissues and to cause musculoskeletal pain and inflammation that although reversible, necessitated stopping their use in one third of the patients (94). Similarly, the use of Avastin in clinical trials has been associated with significant toxicities, in particular hypertension, proteinuria, thromboembolism, and congestive heart failure, caused in part by a decrease in nitric oxide (NO) production associated with vasoconstriction and a lack of vascular integrity causing proteinuria, hemorrhage, and thrombosis. As previously discussed, these side effects have resulted in the FDA's decision to remove Avastin from previous approval in breast cancer (95). In contrast, one would have anticipated that inhibition of proteasomes by drugs such as bortezomib would be associated with major toxicities, considering the central role the proteasome complex is playing in degradation of ubiquitinated proteins. Somewhat surprisingly this drug, which has been tested in more than 200 clinical trials, is relatively well tolerated and has controllable toxicity, primarily neuropathy and thrombocytopenia (96).

A second reason is that agents targeting the TME often target cells or pathways that are not always the enemy of cancer cells. This is again well illustrated in the case of MMP inhibitors, which were found to inhibit not only MMPs used by tumor cells for invasion but also MMPs involved in the production of antiangiogenic peptides by cleavage of precursor proteins (94). Similarly, targeting NF- κ B or TGF- β can have significant side effects as these pathways, depending on the state of tumor progression, can either promote or inhibit tumor growth. As agents targeting inflammation trail behind antiangiogenic therapies in clinical development, it will be important to remember the lessons learned from the testing of MMP and angiogenesis inhibitors and to consider the role of these agents within the dynamic context of an immune system that can be pro- as well as antitumorogenic.

Lesson 2: targeting the TME does not prevent resistance

Because agents targeting the TME are affecting nonmalignant cells, it was initially assumed that—in contrast to their malignant counterparts—they would not be subjected to genomic instability, and that the acquisition of resistance would not be a significant problem. This, however, has not been the case as we have seen with Avastin. On the basis of a systems biology approach, it could in fact be predicted that the redundancy of angiogenic signals might limit the efficacy of antiangiogenic monotherapies (97). In support of this idea, it has been recently shown that tumors become refractory or even evade the inhibition of a single proangiogenic pathway like VEGF by upregulating compensatory angiogenic factors or other pathways that are favorable to tumor cells (16, 98). Another important consideration is that drugs that target the TME often target pathways activated not only in nonmalignant cells but also in malignant cells, which are prone to become intrinsically drug-resistant or to activate by-pass mechanisms.

Lesson 3: targeting the TME requires knowing the optimal biologic dose

Somewhat unfortunately, agents targeting the TME have been tested in clinical trials often at their maximal-tolerated dose (MTD), which has been the strategy for chemotherapy trials where it is often assumed that more is better. However, this may not be the case when targeting the TME. One of the objectives in targeting the TME is in fact to reestablish a disrupted homeostasis in a "malignant organ" rather than to flip the balance in an entirely opposite direction by "over-hitting" the target at MTD. The complex relationship between the ECM and tumor cells illustrates this latter point well.

Determining the optimal biologic dose of TME-targeting agents may thus be more important than finding their MTD. This requires that: (i) the drug hits the target, (ii) the target is altered by the drug, (iii) the tumor is altered by hitting the target, and (iv) giving a higher dose fails to improve outcomes further (99). It will therefore be critical to develop "companion" biomarkers that can serve as indicators of the effect of agents targeting the TME. Sensitive functional imaging techniques and molecular markers such as cytokines, chemokines profiles, immunometrics, and immunoscore (6) are likely to play an important role in our evaluation of clinical trials targeting the TME.

Conclusions

It has now been almost 10 years since the FDA's approval of Avastin as the first drug specifically targeting the TME in cancer. Since this milestone, we have witnessed a dramatic increase in the preclinical development and clinical testing of agents that target the TME. Several of them are already part of the standard treatment in patients with specific cancers, whereas others are still at the early stages of clinical testing. So far, strategies targeting the tumor vasculature seem to be the most successful, as shown by the large number of agents approved by the FDA. Strategies inhibiting the protumorigenic inflammatory response of the TME are rapidly being developed with agents either targeting TAM and their recruitment or protumorigenic inflammatory pathways activated in tumor cells and stromal cells. Inhibition of tumor cell–stroma interactions is another strategy where new agents are also rapidly emerging.

As more agents targeting the TME are proposed for clinical trials, it is important to remember that there are several questions in regard to their activity and place in our therapeutic arsenal against cancer that remain to be answered. One,

for example, is whether these agents are most effective when used alone or in combination with chemotherapy, radiotherapy, or other molecular-targeted therapy. Recent data suggest that the TME is an important contributor to therapeutic resistance (100). Thus combining agents targeting the TME with chemotherapeutic agents to prevent the emergence of minimal residual disease from drug-resistant tumor cells may be critical. If those TME-targeting agents are used in combination with myeloablative agents, it will be important to determine whether some agents such as those inhibiting the recruitment of bone marrow–derived cells should be specifically used between courses of intensive and myelosuppressive therapy to prevent the release of precursor cells into the blood circulation (101). Another question is whether some agents would be more effective at early stages on cancer progression and others at later stages (i.e., TGF- β inhibitors), considering the dynamic changes in the pro- or antitumorigenic functions of the TME during cancer progression. As discussed earlier, the question of the development of resistance to agents targeting the TME remains an important consideration.

As we are rapidly entering the era of precision cancer treatment and are using a genomic and biomarker-integrated approach to determine the best first-line therapies for patients with cancer, it will be equally important to develop reliable biomarkers that indicate the type of TME present in a specific tumor. For example, precise molecular or cellular information on the nature of immune cells present in a specific tumor and on their polarization could be as critical as the identification of the driver(s) mutation(s) that should be targeted. The development of such TME biomarkers and molecular signatures should be an exciting and valuable research direction in the TME over the next several years.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Authors' Contributions

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