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Publication Date

2018

DOI

10.1177/1753466618794133

Peer reviewed

Ther Adv Respir Dis
2018, Vol. 12: 1–29
DOI: 10.1177/1753466618794133

New strategies in immunotherapy for lung cancer: beyond PD-1/PD-L1

Nicolas Villanueva and Lyudmila Bazhenova

Abstract: Immunotherapy has significantly altered the treatment landscape for many cancers, including non-small cell lung cancer (NSCLC). Currently approved immuno-oncology agents for lung cancer are aimed at the reversal of immune checkpoints, programmed death protein-1 (PD-1) and programmed death ligand-1 (PD-L1). Although responses to checkpoint inhibitors are encouraging, and in some cases durable, these successes are not universal among all treated patients. In order to optimize our treatment approach utilizing immunotherapy, we must better understand the interaction between cancer and the immune system and evasion mechanisms. In this review, we will provide an overview of the immune system and cancer, and review novel therapies that promote tumor antigen release for immune system detection, activate the effector T-cell response, and reverse inhibitory antitumor signals.

Keywords: metabolites, myeloid cell factors, TNF receptor superfamily (TNFRSF), tumor microenvironment, tumor vaccine

Received: 8 January 2018; revised manuscript accepted: 9 July 2018.

Introduction

Lung cancer is the leading cause of cancer deaths in the United States (US) and worldwide.[1,2] Nearly 60% of lung cancers are diagnosed with metastatic disease where 5-year survival rates are still lower than 5%.[3] However, with improvements in smoking cessation, early detection, and treatment of lung cancer, mortality rates have steadily declined over the past two decades.[2] One of the treatment advances likely impacting survival is immunotherapy.

In 2015, two PD-1 inhibitors, nivolumab and pembrolizumab were US Food and Drug Administration (FDA) approved for metastatic non-small cell lung cancer (NSCLC) patients who progressed following first-line platinum-based therapy.[4–6] In 2016, the first programmed death ligand-1 (PD-L1) inhibitor, atezolizumab, was also approved for the same indication.[7,8] Unfortunately, objective response rates (ORRs) in the second-line setting still remain between 14–20% and median overall survival (OS) is reported at 9–13 months.[4,5,8,9] In the treatment-naïve setting, monotherapy with programmed death protein-1 (PD-1) inhibitors have demonstrated variable success. For patients with a PD-L1 expression ⩾50%, pembrolizumab monotherapy is associated with a superior progression-free survival (PFS), ORR, and median OS when compared with platinum-doublet chemotherapy.[10,11] The phase III, Keynote 042 trial, confirmed these findings in the PD-L1 ⩾ 50% expressers but failed to show an OS benefit for PD-L1 expression of 1–49%.[12] Contrary to pembrolizumab, nivolumab did not result in a similar benefit over chemotherapy when used as monotherapy for a PD-L1 expression ⩾5%.[13] Recent phase III studies have demonstrated favorable outcomes when immunotherapy is combined with platinum-doublet chemotherapy in the first-line. The phase III studies combining pembrolizumab with platinum-doublet chemotherapy in nonsquamous (Keynote 189) and squamous histologies (Keynote 407) demonstrate superior OS, PFS, and ORR over platinum-doublet chemotherapy.[14,15] The OS benefit persisted for PD-L1 expression of <1%. Atezolizumab is also being evaluated with platinum-doublet chemotherapy for squamous and nonsquamous histologies.[16,17] The recently published IMPower 150 phase III trial also

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demonstrated an OS, PFS, and ORR benefit of atezolizumab, carboplatin, paclitaxel, and bevacizumab *versus* carboplatin, paclitaxel and bevacizumab in nonsquamous NSCLC.[17] The PFS benefit continued to favor the atezolizumab-containing arm even for PD-L1 $< 1\%$ in both the tumor and immune cells; it remains to be seen if there will be a similar OS benefit for this subpopulation of patients. Lastly, attempts to combine PD-1/PD-L1 inhibitors with CTLA-4 inhibitors showed encouraging tumor responses despite increased toxicity in the initial phase I studies.[18,19] Checkmate 227, a multipart phase III study assesed the role of different combinations of nivolumab *versus* chemotherapy in the setting of variable PD-L1 expressions and tumor mutational burden (TMB) as measured by the FoundationOne next generation sequencing assay.[20] Using a predefined threshold of 10 mutations per megabase (mu/Mb) as a high TMB, the combination of nivolumab and ipilimumab demonstrated improved PFS and ORR compared with platinum-doublet chemotherapy. This benefit persisted regardless of tumor histology and PD-L1 status. Despite these initial encouraging findings, more patients in the immunotherapy arm discontinued therapy due to treatment-related toxicities (17.4% *versus* 8.9%). We are awaiting OS data for this study along with the phase III MYSTIC study [ClinicalTrials.gov identifier: NCT02453282]; the latter of which compared a durvalumab (a PD-L1 inhibitor) and tremelimumab (a CTLA-4 inhibitor). A list of selected first and second-line checkpoint immunotherapy trials are summarized in Table 1. Currently, the US FDA has approved pembrolizumab for the use in treatment-naïve metastatic NSCLC with a PD-L1 expression $\geqslant 50\%$ and in combination with platinum-doublet chemotherapy for metastatic nonsquamous lung cancer irrespective of PD-L1 expression.

The promise of immunotherapy with PD-1/PD-L1 inhibitors is encouraging, though we are still learning how to best utilize immunotherapy and balance the toxicities of treatment. These therapies have proven to be better tolerated than chemotherapy,[10,13] but immune-related adverse events do increase with combination therapies and may temper their use.[18,19] Unfortunately responses from immunotherapy are not always durable with only a minority of patients having a prolonged benefit.[8,9,24] Resistance can develop through various mechanisms including the persistence of a resistant clone or alterations in the tumor microenvironment (TME). Alternatively, the lack of tumor-infiltrating lymphocytes (TILs) can also explain the less than expected response.[25–27] How best to select these patients is still an active area of research, as current PD-L1 biomarkers do not consistently predict response to these therapies.[28]

We are learning that the immune system as it interacts with the TME, may not be simply solved by inhibiting the PD-1/PD-L1 axis alone. In fact, we have learned that there are many other regulators of this complex immune system. In this review, we will summarize the complex interplay between the immune system and cancer microenvironment along with potential targets outside of PD-1/PD-L1 axis.

Cancer and the immune system

The immune system is complex system which cancer exploits in order to evade detection and elimination. The cancer immunity cycle proposed by Chen and colleagues summarizes the various steps in which the immune system recognizes and kills cancer cells.[29]

This cycle relies on the recognition and processing of tumor-specific neoantigens by dendritic cells. The neoantigens are presented *via* the major histocompatibility (MHC) class I and II molecules on antigen presenting cells (APCs) and bind to the corresponding T-cell receptor (TCR). Naïve T-cells can then proliferate into effector memory T-cells, effector T-cells, or exhausted effector T-cells.[30] This response is balanced by the presence of regulatory T-cells (Tregs) that limit damage to nontumor self-antigens. These activated effector T-cells are subsequently recruited into the TME resulting in the targeted killing of tumor cells. The neoantigens released from destroyed tumor cells further renews and augments this cycle.

Cancer is able to alter this cycle to its advantage and promote its survival.[26,29] Chen and Mellman proposed that there exists a cancer-immune set point that is based upon the balance of immune stimulatory and inhibitory factors, both of which are influenced by the tumor and host genetics, and environment.[30] One example is the impact of smoking and NSCLC immunity; a retrospective study of 114 *KRAS*-mutated NSCLC patients found that PD-L1 expression

Table 1. Select first and second-line checkpoint inhibitor trials.

Trial	Histology	Drug	Median OS (mon)	Median PFS (mon)	ORR (%)	Tumor biomarker	Reference or NCT
Second line							
Checkmate 057 (phase III)	Nonsquamous	Nivo *versus* docetaxel	12.2 *versus* 9.4 (HR 0.73, 95% CI, 0.59–0.89, $p = 0.002$)	2.3 *versus* 4.2 (HR 0.92, 95% CI, 0.77–1.11, $p = 0.39$)	19 *versus* 12 ($p = 0.02$)	PD-L1: No threshold	Borghaei and colleagues[4]
Checkmate 017 (phase III)	Squamous	Nivo *versus* docetaxel	9.2 *versus* 6.0 (HR 0.59, 95% CI, 0.44–0.79, $p < 0.001$)	3.5 *versus* 2.8 (HR 0.62, 95% CI, 0.47–0.81, $p < 0.001$)	20 *versus* 9 ($p = 0.008$)	PD-L1: No threshold	Brahmer and colleagues[5]
Keynote 010 (phase III)	All	Pembro (2 mg/kg, 10 mg/kg) *versus* Docetaxel	10.4 *versus* 12.7 *versus* 8.5 (HR 0.71, 95% CI, 0.58–0.88, $p = 0.008$, HR 0.61, 95% CI, 0.49–0.75, $p < 0.0001$)	3.9 *versus* 4.0 *versus* 4.0 (HR 0.88, 95% CI, 0.74–1.05, $p = 0.07$, HR 0.79, 95% CI, 0.66–0.94, $p = 0.004$)	18 *versus* 18 *versus* 9 ($p = 0.0002$)	PD-L1: ⩾1%	Herbst and colleagues[9]
OAK (phase III)	All	Atezo *versus* docetaxel	13.8 *versus* 9.6 (HR 0.73, 95% CI, 0.62–0.87, $p = 0.0003$)	2.8 *versus* 4.0 (HR 0.95, 95% CI, 0.82–1.10, $p = 0.49$)	14 *versus* 15 (NS)	PD-L1: No threshold	Rittmeyer and colleagues[8]
First line (monotherapy)							
Keynote 024 (phase III)	All	Pembro *versus* PD	30 *versus* 14.2 (HR 0.63, 95% CI, 0.47–0.86, $p = 0.002$)	10.3 *versus* 6.0 (HR 0.50, 95% CI, 0.37–0.68, $p < 0.001$)	45.5 *versus* 29.8 ($p = 0.0031$)	PD-L1: ⩾50%	Reck and colleagues[10] Brahmer and colleagues[11]
Keynote 042 (phase III)	All	Pembro *versus* PD	PD-L1 ⩾1%: 16.7 *versus* 12.1 (HR 0.81, 95% CI, 0.71–0.093, $p = 0.0018$) PD-L1 ⩾1–49%: 13.4 *versus* 12.1 (HR 0.92, 95% CI, 0.77–1.11)	PD-L1 ⩾1%: 5.4 *versus* 6.5 (HR 1.07, 95% CI, 0.94–1.21)	PD-L1 ⩾1%: 27.3 *versus* 26.5 PD-L1 ⩾1–49%: 16.6 *versus* 21.7	PD-L1: ⩾1%	Lopes and colleagues[12] (NCT02220894)
Checkmate 026 (phase III)	All	Nivo *versus* PD	14.4 *versus* 13.2 (HR 1.02, 95% CI, 0.80–1.30)	4.2 *versus* 5.9 (HR 1.15, 95% CI, 0.91–1.45, $p = 0.25$)	26 *versus* 33 (IR 0.70, 95% CI, 0.46–1.06)	PD-L1: ⩾1% (results for ⩾5%)	Carbone and colleagues[13]
First line (combination)							
Keynote 021 G cohort (phase II)	Nonsquamous	Pembro + CP *versus* CP	NR *versus* 21.1 (HR 0.56, 95% CI, 0.32–0.95, $p = 0.0151$)	24 *versus* 9.3 (HR 0.53, 95% CI, 0.33–0.86, $p = 0.0049$)	57 *versus* 30 ($p = 0.0016$)	PD-L1: No threshold	Langer and colleagues[21] Gentzler and colleagues[22] (NCT02039674)

(Continued)

Table 1. (Continued)

Trial	Histology	Drug	Median OS (mon)	Median PFS (mon)	ORR (%)	Tumor biomarker	Reference or NCT
Keynote 189 (phase III)	Nonsquamous	Pembro + CP *versus* CP	NR *versus* 11.3 (HR 0.49, 95% CI, 0.38–0.64, $p < 0.001$)	8.8 *versus* 4.9 (HR 0.652, 95% CI, 0.43–0.64, $p < 0.001$)	47.6 *versus* 18.9 ($p < 0.001$)	PD-L1: No threshold	Gandhi and colleagues[14]
Keynote 407 (phase III)	Squamous	Pembro + CPac or CnPac *versus* CPac or CnPac	15.9 *versus* 11.3 (HR 0.64, 95% CI, 0.49–0.85, $p = 00008$)	6.4 *versus* 4.8 (HR 0.56, 95% CI, 0.45–0.70, $p < 0.0001$)	58.4 *versus* 35.0 ($p = 0.0004$)	PD-L1: No threshold	Paz-Ares and colleagues[15] (NCT02775435)
Checkmate 227 (phase III)	All	PD-L1 ⩾1%: Nivo + Ipi *versus* Nivo *versus* PD PD-L1 ⩽1%: Nivo + Ipi *versus* Nivo + PD *versus* PD	Data pending	High TMB (⩾10 mu/Mb) Nivo + Ipi *versus* PD: 7.2 *versus* 5.5 (HR 0.58, 95% CI, 0.41–0.81, $p < 0.001$)	High TMB (⩾10 mu/Mb) Nivo + Ipi *versus* PD: 45.3 *versus* 26.9	PD-L1: No threshold TMB: No threshold	Hellman and colleagues[20] (NCT02477826)
IMPower 131	Squamous	Atezo + CPac *versus* Atezo + CnPac *versus* CnPac	Atezo + CnPac *versus* CnPac: 14.0 *versus* 13.9 (HR 0.96, 95% CI, 0.78–1.18, $p = 0.6931$)	Atezo + CnPac *versus* CnPac: 6.3 *versus* 5.6 (HR 0.71, 95% CI, 0.60–0.85, $p = 0.0001$)	Atezo + CnPac *versus* CnPac: 49 *versus* 41%	PD-L1: No threshold	Jotte and colleagues[16] (NCT02367794)
IMPower 150 (phase III)	Nonsquamous	Atezo + CPacB *versus* CPacB *versus* Atezo + CP	Atezo + CPacB *versus* CPacB: 19.2 *versus* 14.7 months ($p = 0.02$)	Atezo + CPacB *versus* CPacB: 8.3 *versus* 6.8 (HR 0.62, 95% CI, 0.52–0.74, $p < 0.0001$)	Atezo + CPacB *versus* CPacB: 63.5 *versus* 48	PD-L1: No threshold Teff gene signature: No threshold	Reck and colleagues[23] Socinski and colleagues[17] (NCT02366143)
MYSTIC	All	Durvalumab + tremilimuab *versus* durvalumab *versus* PD					NCT02453282

Atezo, atezolizumab; B, bevacizumab; C, carboplatin; CI, confidence interval; CnPac, carboplatin, nab-paclitaxel; CPac, carboplatin, paclitaxel; CPacB, carboplatin, paclitaxel, bevacizumab; HR, hazard ratio; Ipi, ipilimumab; NCT, ClinicalTrials.gov; Nivo, nivolumab; nPac, nab-paclitaxel; NR, not reached; NS, not significant; ORR, overall response rate; OS, overall survival; P, pemetrexed; Pac, paclitaxel; PD, platinum doublet; PD-L1, programmed death ligand-1; Pembro, pembrolizumab; PFS, progression-free survival; Teff, effector T-cell; TMB, tumor mutational burden.

was reported in 64% of current or former smokers as compared with 13% of never-smokers.[31] In addition, the strength of PD-L1 expression by immunohistochemistry (IHC) 2+/3+ *versus* 0/1+ was also associated with a higher smoking pack-year history. The explanation for a high PD-L1 expression may have to do with the increased mutational burden as seen in smokers *versus* nonsmokers.[32,33] Therefore, targeting the hyperactive PD-1/PD-L1 axis would promote tumor specific T cell responses and help to rebalance the cancer-immune set point.

Currently, the most clinically recognized immunotherapy agents target PD-1/PDL-1 and CTLA-4. CTLA-4 is found on T-cells and is important in the initial T-cell activation by competing with the costimulatory receptor CD28 on APCs through the binding of CD80 (B7.1) or CD86 (B7.2).[34] In this manner, CTLA-4 is important in preventing the overactivation of the immune system. In contrast, PD-L1 is found on tumor-infiltrating T-cells along with tumor cells, in the TME.[35,36] Typically, PD-L1 binds to its receptor, PD-1, found on numerous cells including effector T-cells, Tregs, B-cells, and natural killer (NK) cells.[35] The binding of PD-L1 to PD-1 acts to limit excessive immune activity in situations such as with chronic viral infections and cancer.[37] Both PD-1/PD-L1 and CTLA-4 mechanisms are effective mechanisms by which the cancer can halt the cancer–immunity cycle.[35]

Unfortunately, PD-L1 expression can vary depending on the cancer type and may have treatment implications with immunotherapy.[38] Teng and colleagues proposed that tumors could be divided into one of four types based upon the presence or absence of TILs and the PD-L1 status.[39] By using this model, we can construct a framework whereby immunotherapy can be most effective. In general NSCLC is thought to be immunogenic[40] and anti-PD-1/PD-L1 antibodies would be most effective in the presence of TILs and high PD-L1 expression. One of the potential phenotypes is the absence of TILs in the setting of PD-L1 positivity.[39] In this scenario, treatment with anti-PD-1/PD-L1 antibodies would be less effective, and would require a different approach to treatment such as by inducing immunogenic cell death to recruit TILs to the TME. In a different scenario, TILs can be present without PD-L1 expression. This suggests that alternative immunosuppressive mechanisms may be involved.[39] Outside the PD-1/PD-L1 axis there exists other immune regulators such as myeloid-derived suppressor cells (MDSCs), tumor-associated macrophages (TAMs), NK cells, dendritic cells, B-cells, and various chemokines/cytokines which likely play large roles in the TME.[42–44] Overall these factors underlie the complexity of the immune system outside of PD-1/PD-L1 alone.

These models provide a valuable framework to understand and develop treatment strategies. By using the cancer–immunity cycle, we can break down the current areas of clinical investigation into three parts: the release of cancer antigens, activation of the T-cell response, and regulation of the inhibitory immune response.

Promoting release of cancer antigens

Tumor vaccines

As demonstrated in the cancer–immunity cycle, a tumor-directed immune response first relies on the presence of tumor-specific antigens.[29] Tumor vaccines bridge this gap by introducing tumor antigens to prime the host immune system to produce antigen-specific effector and memory T-cell responses.[45] The currently studied vaccines can be divided broadly into those that target specific tumor antigens (antigen-specific) or numerous tumor cells (whole-cell). The aim of whole-cell vaccines is to broaden the exposure of tumor-associated antigens.

Results from completed phase III studies of vaccines targeting three different antigens have largely come with disappointing results. The melanoma-associated antigen-A3 (MAGE-A3) is expressed on cancer cells and found in normal testis and placental cells.[46] Despite being found in normal adult tissue, its presence is not immunogenic because it does not harness human leukocyte antigen (HLA) molecules. MAGE-A3 is overexpressed in nearly 40% of stage I–II NSCLCs.[47] The vaccine contains a recombinant form of MAGE-A3 with fusion protein D of *Haemophilus influenzae* along with an immune stimulant, AS02B. In a phase II study, patients with resected, MAGE-A3 positive, stage IB–II NSCLC, were randomized to adjuvant MAGE-A3 vaccinations or placebo.[48] Despite all patients who tested for immunogenicity having developed anti-MAGE-A3 antibodies, there was

no benefit with a disease-free interval, disease-free survival (DFS) or OS. The subsequent phase III study (MAGRIT) included 2312 patients with resected phase IB–IIIA MAGE-A3-positive NSCLC; this study allowed adjuvant chemotherapy. Similar to the phase II trial, there was no benefit of the MAGE-A3 vaccine over placebo among the primary endpoint of DFS in the overall population and in those who did not receive adjuvant chemotherapy; additionally there was no OS benefit.[49] Overall the treatment with the MAGE-A3 vaccine was well tolerated in both studies. Currently, a different MAGE-A3 vaccine is being studied in combination with pembrolizumab [ClinicalTrials.gov identifier: NCT02879760].

The mucin 1 (MUC-1) glycoprotein is another antigen found in NSCLC that pathologically promotes tumor cell growth *via* its interaction with cell surface receptors.[50] MUC-1 has been targeted in the development of two vaccines, tecemotide (L-BLP25) and TG4010 (MVA-MUC1-IL2). Tecemotide consists of a synthetic lipopeptide that proved to be well tolerated and immunogenic in the phase I study.[51] The phase III randomized clinical trial (START) compared tecemotide with placebo as a maintenance therapy in unresectable stage III NSCLC following chemoradiation.[52] There was no OS benefit seen except for a subgroup that received concurrent chemoradiation. Although this subgroup analysis sparked a subsequent trial in patients receiving concurrent chemoradiation, the sponsor ultimately terminated the trial. This decision was made as a result of the negative findings of the phase I/II Japanese study in unresectable stage III NSCLC patients, the majority of whom received concurrent chemoradiation.[53] There are no further studies with tecemotide at this time.

TG4010 is a constructed from the Modified Vaccinia Ankara that expresses both MUC-1 and interleukin (IL)-2.[54] The phase IIb/III randomized controlled trial (TIME) compared chemotherapy in combination with TG4010 with placebo for treatment-naïve metastatic NSCLC.[55] Their primary endpoint of median PFS was met; but there was only a 0.8 month absolute benefit [5.9 months *versus* 5.1 months, hazard ratio (HR) 0.74, 95% confidence interval (CI) 0.55–0.98, $p = 0.019$]. In addition, the study supported the use of a new biomarker, triple-positive activated lymphocytes (TrPAL), which is defined by the presence of low values of CD16, CD56, and CD69. These markers represent activated NK cells with the lowest values of TrPAL corresponding to the best response when combined with chemotherapy.[56] In the subgroup of patients with less than or equal to the third quartile (Q3) of TrPAL, there was a significant benefit of PFS (HR 0.59, 95% CI 0.40–0.87) and OS (HR 0.59, 95% CI 0.40–0.87) over placebo. Furthermore, the addition of TG4010 was well tolerated and is currently being explored with nivolumab in advanced NSCLC [ClinicalTrials.gov identifier: NCT02823990].

Lastly, belagenpumatucel-L, is a type of whole-cell vaccine consisting of four NSCLC cell lines with a transforming growth factor β (TGF-β) antisense gene modification.[57] This alteration improves the immunogenicity of the cancer cells to prime the host immune system.[58] The phase III randomized controlled trial (STOP) compared belagenpumatucel-L with placebo as a maintenance therapy for stage IIIA–IV NSCLC patients who had no disease progression following platinum-based chemotherapy.[59] The primary endpoint of OS was not met, however a prespecified analysis showed that patients who received chemoradiation prior to randomization demonstrated improved OS. This observation suggests the possible role of radiation therapy in the priming of the antitumor immune response. Currently other whole-cell vaccines, tergenpumatucel-L and viagenpumatucel-L (HS-110) are being studied in combination with immune checkpoint inhibitors [ClinicalTrials.gov identifiers: NCT02460367 and NCT02439450].

One of the perceived limitations to tumor vaccine monotherapy are the inhibitory signals of the TME, such as with Tregs, MDSCs, and other immune checkpoints.[60] Given the limited responses of current tumor vaccine therapies, the current strategy focuses on enhancing the antitumor response by combining it with other immune therapies. Preclinical studies provide evidence for combining PD-1/PD-L1 or CTLA-4 inhibitors to tumor vaccines. Binder and colleagues demonstrated that exhausted $CD8^+$ T-cells in a murine tumor model could be rescued minimally by increasing tumor-specific antigens *via Salmonella typhimurium* A1-R.[61] In contrast, by adding an anti-PD-L1 antibody in combination with antigen priming, there was an increase in antigen-specific T-cells and improved tumor rejection.

Duraiswamy and colleagues further established that combining a tumor vaccine (GVAX; a GM-CSF transduced whole-cell tumor) with anti-CTLA-4 and anti-PD-1/PD-L1 antibodies increased antigen-specific $CD8^+$ T-cells and enhanced tumor rejection when compared with dual antibody therapy without GVAX.[62]

Adoptive cell therapy (ACT)

In contrast with tumor vaccines that prime the effector and memory T-cell response with tumor antigens, ACT is the process whereby host lymphocytes are collected and modified, and then returned back to the patient. This process allows these engineered T-cells to directly target specific tumor-associated antigens for destruction. These cells can be modified with chimeric antigen receptors (CARs), TCRs, or with an expansion of TILs.

Both CAR T-cells and TCRs are genetically engineered to target a specific tumor-associated antigen (TAA).[63] Modified TCRs are high affinity receptors that target a specific MHC–peptide complex and are prone to formation of mixed TCR dimers with unknown specificities. Comparatively, CAR T-cells are MHC-independent and contain a single chain antibody with TAA specificity linked to an intracellular signaling domain. Following the success of CAR T-cell therapy in hematologic malignancies, researchers are trying to expand this role to solid tumors, including NSCLC.[64] The limitations in developing CAR T-cells and TCR in NSCLC are the selection of the ideal TAA with little to no expression in normal tissue. Some of these antigens being studied in early phase clinical trials include mesothelin (MSLN), MUC-1, carcinoembryonic antigen (CEA), glypican-3 (GPC3), human epidermal growth factor receptor 2 (HER2), and receptor tyrosine kinase like orphan receptor (ROR1). One of the main challenges in the development of CAR T-cell and TCR therapy is to limit off-tumor adverse effects. For example, off-tumor effects of treatment with MSLN immunotoxin, SS1P, can lead to the dose-limiting toxicity of pleuritis.[65] In developing CAR T-cells, safety switches such as with inducible caspase-9 gene or RNA electroporation, have been successful in addressing these issues.[66–68] In addition, the next hurdle for the CAR T-cell and TCR is to overcome the immune-tolerant state that the tumor microenvironment poses. PD-1 can similarly be upregulated in the setting of CAR T-cells and has shown to be effective when genetically engineered to the CAR T-cell itself.[69,70]

The utilization of ACT of TILs have shown success in previously treated metastatic melanoma with ORRs of around 40–50% and a minority with durable responses.[71,72] There have been attempts to expand this use to NSCLC. An earlier study evaluated the use of TILs as postoperative treatment for Stage II–III NSCLC.[73] Tissue samples were obtained from surgically resected primary lung lesions followed by the isolation of lymphocytes and cancer cells; these cells were expanded in a medium containing recombinant IL-2. Patients were stratified by stage and either received a TILs containing regimen or standard of care. The TILs were infused on day 0 along with daily subcutaneous injections of recombinant IL-2 until the maximum tolerated dose was achieved. Median OS favored the TIL arm *versus* standard of care treatment (22.4 months *versus* 14.1 months). The OS benefit was primarily seen in the most advanced disease with stage IIIB NSCLC patients receiving TILs with radiotherapy *versus* chemoradiation (23.9 months *versus* 73 months, $p < 0.01$). Widespread use of this therapy has been tempered by the ability to sufficiently produce enough TILs, not to mention the time it can take (up to 6–8 weeks) for this process. The application of a rapid expansion protocols that involves the stimulation of isolated TILs in culture with anti-CD3 antibody, irradiated peripheral blood mononuclear feeder cells, and IL-2, have been effective in melanoma.[74] Recently, preclinical creation and expansion of TILs from resected early stage primary lung cancers using a rapid expansion protocol were promising.[75] Despite these tumors having a small volume, sufficient TILs were available with this protocol after 2 weeks. Further clinical trials are anticipated and determining how it fits into the new wave of immunotherapy will be exciting.

Activating the T-cell response

Tumor necrosis factor receptor superfamily

The tumor necrosis factor receptor (TNFR) superfamily is a group of highly conserved type 1 transmembrane glycoproteins with cysteine-rich domains that possess both coinhibitory and costimulatory responses.[76] Herein, we will review five members of this class with stimulatory effects currently in clinical investigation [OX40, CD27, glucocorticoid-induced tumor necrosis factor

(GITR), 4-1BB, and CD40]. Table 2 lists the active trials in this category.

OX-40. OX-40 (CD134 or TNFRSF4) is expressed on activated T-cells and binds to the OX-40 ligand on activated APCs.[76] Activation of OX-40 results in expansion of both effector and memory $CD4^+$ T-cells, and to a lesser degree, $CD8^+$ T-cells.[77] The function of OX-40 was further confirmed in the evaluation of a patient with autosomal recessive mutation (R65C) resulting in the inability of OX-40L to bind to its receptor.[78] This patient developed early onset Kaposi's sarcoma, a human herpesvirus-8 (HHV-8) induced endothelial tumor that can be seen in states of dysfunctional or deficient $CD4^+$ T-cells, like human immunodeficiency virus (HIV).[79] The lack of functional OX-40 results in impaired $CD4^+$ T-cell responses to antigen exposure, decreasing memory $CD4^+$ T-cells and $CD8^+$ T-cells.

OX-40 is not only to be important with controlling infections but potentially beneficial in the antitumor response. In a phase I study of patients with refractory metastatic solid tumors, administration of a murine agonistic anti-human OX-40 monoclonal antibody resulted in an increased proliferation of $CD8^+$ and $CD4^+FoxP3^-$ T-cells (non-Tregs).[80] Despite no objective responses per Response Evaluation Criteria in Solid Tumors criteria, tumor shrinkage was seen in 12 of the 30 enrolled patients. Adverse events were mainly grade 1–2 with lymphopenia being a transient finding over 72 hours. Additional *in vivo* studies using a murine model showed that Tregs were inhibited with agonistic anti-OX-40 monoclonal antibodies, thus restoring dendritic cell and antitumor activity.[81,82] There are numerous anti-OX-40 monoclonal antibodies and one fusion protein undergoing clinical investigation as a single agent and in combination with other immune therapies. The fusion protein links the Fc portion of an immunoglobulin to OX-40L and has shown to be more potent than the monoclonal antibody counterpart in *in vivo* studies.[83] We await the results of these agents to evaluate if these benefits translate to human studies.

CD27. CD27 (TNFRSF7) differs from other members of the TNFRSF in that it is constitutively expressed on both naïve and activated effector T-cells.[84] Its ligand, CD70, is transiently expressed on activated dendritic cells, B-cells and T-cells. Their interaction results in $CD8^+$ T-cell effector and memory differentiation, B-cell synthesis, and NK cell activity.[85–87]

Varlilumab (CDX-1127) is the first-in-class humanized anti-CD27 monoclonal antibody currently under clinical investigation. The recent phase I study demonstrated that the agent was safe and well tolerated in patients with advanced, heavily pretreated melanoma, colorectal cancer and renal cell carcinoma.[88] The only dose-limiting toxicity was transient asymptomatic hyponatremia. Similar to preclinical studies, they observed increased active effector T-cells and decreased Tregs.[89,90] Responses were modest with two patients with renal cell carcinoma (RCC) showing long-term responses beyond 2 years. There is an ongoing phase II study to assess the combination of varlilumab with nivolumab in advanced solid tumors [ClinicalTrials.gov identifier: NCT02335918].

GITR. GITR (TNFRSF18) is expressed on naïve $CD4^+$ and $CD8^+$ T-cells in addition to B-cells and NK cells. It is also constitutively expressed on Tregs.[76,91] When GITR binds to its ligand (GITRL) on APCs, this results in increased expression of $CD4^+$ and $CD8^+$ T-cells, and maturation of Tregs.[92] GITR has been shown in murine models to increase $CD4^+$ Th9 T-cells that activate tumor-infiltrating dendritic cells, resulting in cytotoxic cell killing.[93] In addition, agonistic anti-GITR antibodies has also been shown to reverse the negative effects of Tregs by causing *in vivo* Treg depletion and decreased suppressive activity on effector T-cells.[94,95] However the effects of GITR-GITRL can also vary by cell type; for instance in NK cells, GITR is thought to have a negative role in NK cell activation.[92]

Overall, GITR is an attractive target because of its increased cytotoxic effects and diminished suppressive actions on Tregs. The effects of GITR were further enhanced when combined with PD-1 and CTLA-4 inhibitors. In a murine ovarian cancer model, combination of an agonistic anti-GITR monoclonal antibody with anti-PD-1 therapy combination demonstrated significant tumor shrinkage with a minority of mice having long-term effects. Furthermore, they also noted an increase in the presence of effector T-cells as compared with Tregs, thus overcoming the immune-tolerant state.[96] In addition, a similar synergistic effect was also seen in combination with anti-CTLA4 antibodies in increasing $CD8^+$

Table 2. Select immune activating agents in clinical trial.

Class	Drug	Sponsor	Regimen	Indication	NCT	Phase/ status
TNF receptor superfamily						
OX-40	INCAGN01949 (mAb)	Incyte Corp	Monotherapy	Advanced solid tumor	NCT02923349	Phase I/II recruiting
			Combination with Nivo, Ipi, or Nivo/ Ipi		NCT03241173	Phase I/II recruiting
	GSK3174998 (mAb)	Glaxo Smith Kline	Monotherapy, Combination with Pembro	Advanced solid tumor	NCT02528357	Phase I recruiting
	MEDI0562 (mAb)	Med-Immune Inc.	Monotherapy	Advanced solid tumors	NCT02318394	Phase I completed
			Combination with Durva or Tremi		NCT02705482	Phase I recruiting
	MEDI6383 (fusion protein)		Monotherapy and in combination with Durva	Advanced solid tumors	NCT02221960	Phase I active, not recruiting
	MOXR0916 (mAb)	Genentech	Combination with Atezo	Advanced solid tumors	NCT02410512	Phase I active, not recruiting
CD27	Varlilumab (CDX-1127) (mAb)	Celldex Therapeutics	Combination with Nivo	Advanced solid tumors	NCT02335918	Phase I/II active, not recruiting
			Monotherapy		NCT01460134	Phase I completed
GITR	BMS-986156	Bristol-Myers Squibb	Monotherapy, Combination with Nivo	Advanced solid tumors	NCT02598960	Phase I/II active, not recruiting
	GWN323	Novartis	Monotherapy and in combination with PDR 001 (anti-PD-1 mAb)	Advanced solid tumors, lymphoma	NCT02740270	Phase I/II recruiting
	INCAGN01876 (mAb)	Incyte	Monotherapy	Advanced solid tumors	NCT02697591	Phase I/II recruiting
			Combination with Nivo, Ipi, Nivo/Ipi	Advanced solid tumors	NCT03126110	Phase I/II recruiting
	MEDI1873 (fusion protein)	Med-Immune LLC	Monotherapy	Advanced solid tumors	NCT02583165	Phase I active, not recruiting
	OMP-336B11 (engineered human protein)	Onco-Med Pharma	Monotherapy	Advanced solid tumors	NCT03295942	Phase I Recruiting
	TRX518 (mAb)	Leap Therapeutics, Inc.	Monotherapy	Advanced solid tumors	NCT01239134	Phase I Recruiting

(Continued)

Table 2. (Continued)

Class	Drug	Sponsor	Regimen	Indication	NCT	Phase/ status
4-1BB	Urelumab (BMS-663513) (mAb)	Bristol-Myers Squibb	Combination with Nivo	Advanced solid tumors	NCT02534506	Phase I recruiting
			Combination with nivolumab	Advanced solid tumors, NHL	NCT02253992	Phase I/II recruiting
			Monotherapy	Advanced solid tumors, NHL	NCT01471210	Phase I completed
	Utomilumab (PF-05082566) (mAb)	Pfizer	Monotherapy in patients with advanced cancer. Combination with rituximab for NHL	Advanced solid tumors	NCT01307267	Phase I active, not recruiting
			Monotherapy, Combination with PF-05082566 (4-1BB/CD137) agonist	Advanced solid tumors	NCT02315066	Phase I recruiting
			Combination with avelumab (A), avelumab and PF-0418600 (OX40 agonist mAb)	Advanced solid tumors	NCT02554812	Phase Ib/II recruiting
			Combination with MK-3475 (PD-1 inhibitor)	Advanced solid tumors	NCT02179918	Phase Ib completed
CD40	ADC-1013 (mAb)	Alligator Bioscience AB	Monotherapy intratumoral and IV	Advanced solid tumors	NCT02379741	Phase I completed
	APX005M (mAb)	Apexigen, Inc.	Combination with Nivo	NSCLC, melanoma	NCT03123783	Phase I/II recruiting
			Combination with anti-CSFR-1 mAb (FPA008), combination with FPA008 and Nivo	NSCLC, melanoma, RCC	NCT03502330	Phase I not yet recruiting
	JNJ-64457107 (mAb)	Janssen	Monotherapy	Advanced solid tumors	NCT02829099	Phase I/II recruiting
	RO7009789 (mAb)	Hoffmann-La Roche	Combination with Atezo	Advanced solid tumors	NCT02304393	Phase I recruiting
	SEA-CD40 (mAb)	Seattle Genetics, Inc.	Combination with Pembro	Advanced solid tumors, HL, DLBCL, indolent lymphoma	NCT02376699	Phase I recruiting

Atezo, atezolizumab; DLBCL, diffuse large B-cell lymphoma; Durva, durvalumab; GITR, glucocorticoid-induced tumor necrosis factor; HL, Hodgkin's lymphoma; Ipi, Ipilimumab; IV, intravenous; mAb, monoclonal antibody; NCT, ClinicalTrials.gov; NHL, non-Hodgkin's lymphoma; Nivo, nivolumab; NSCLC, non-small cell lung cancer; PD-1, programmed death protein-1; Pembro, pembrolizumab; RCC, renal cell carcinoma; TNF, tumor necrosis factor.

TILs and reducing the negative effects from Tregs.[97] Currently there are numerous anti-GITR antibodies in clinical trials as monotherapy and in combination with PD-1 and CTLA-4 antibodies.

4-1BB. Similar to OX-40 and GITR, 4-1BB (CD137 or TNFRSF9) is a costimulatory receptor found on activated T-cells and myeloid cells that are important in maintaining memory T-cells and expansion of antigen-specific CD8+ T-cells.[98,99] Agonistic effects of 4-1BB results in a novel T-cell population with direct cytotoxic activity *via* granzyme, perforin and Fas ligand pathways.[100] There are currently two agonistic anti-4-1BB monoclonal antibodies currently studied in clinical trials (utomilumab or PF-05082566; urelumab or BMS-663513). The initial monotherapy studies were complicated by severe potentially fatal hepatitis that resulted in the termination of some studies. These toxicities were thought to be dose-related and are currently being studied with lower doses in combination with other cancer therapies such as checkpoint inhibitors.[101]

Similar to other costimulatory receptors discussed, the rationale behind combining these agents with immune checkpoint inhibitors is appealing; by releasing the immune-suppressing signals of the tumor microenvironment and augmenting the recruitment of cytotoxic effector T-cells, this would hope to synergize the desired effect. Both anti-CTLA-4 and anti-PD-1 monoclonal antibodies are being tested in combination with anti-4-1BB demonstrating preclinical success.[101] The combination of anti-CTLA-4 and anti-4-1BB antibodies resulted in long-lasting tumor eradication via $CD8^+$ T-cells when compared with either agent alone.[102] In addition, as noted in clinical studies, anti-4-1BB resulted in severe autoimmune hepatotoxicity that was also confirmed in this study. Interestingly, the addition of anti-CTLA-4 antibodies in combination mitigated this autoimmune effect. Similar findings of superior tumor eradication in combination with anti-PD-1 antibodies were also demonstrated in a murine model of squamous cell carcinoma of the lung.[103] Clinical studies with these two monoclonal antibodies are ongoing. It should also be noted that 4-1BB is also being studied to enhance the effector T-cell response with other therapies such as adoptive T-cell and vaccine models. When combined with adoptive cytotoxic T-cell transfer into a murine melanoma model, there was prolonged survival of intratumoral effector T-cells resulting in tumor eradication.[104]

CD40. Lastly, CD40 and its ligand CD40L (CD154) are expressed on a broad range of different cell types including APCs, B-cells, platelets and even nonhematopoietic cells like endothelial cells and smooth muscle cells.[105] Their interaction is important in priming of dendritic cells to activate cytotoxic $CD8^+$ T-cells in the antitumor response.[106–108]

Currently, there are six agonistic anti-CD40 monoclonal antibodies currently in early phase studies for advanced solid tumors. The first among the group was CP-870,893; in the phase I study, the most common adverse effect was grade 1–2 cytokine release syndrome marked by fever, rigors, rash, nausea, vomiting and myalgias that occurred minutes to hours after infusion. In addition, there were dose-related and transient hematologic and liver toxicities. Of the 29 patients studied (5 of which had NSCLC), objective responses were seen in 14%.[109] Unfortunately, there are no active trials in advanced NSCLC for CP-870,893 at this time. One potential solution to reduce the dose-limiting immune toxicities is through direct tumor injection to stimulate systemic immune responses. This concept has been studied with ADC-1013; in preclinical murine models, there was successful generation of tumor-specific cytotoxic T-cell activity.[110] The current clinical trial [ClinicalTrials.gov identifier: NCT02379741] is completed and pending results. Owing to the limitations with monotherapy and dose-limiting immune toxicities, other strategies are currently being explored such as combining these agents with chemotherapy or immune checkpoint inhibitors.[105]

Reversing inhibitory signals

Immunoglobulin superfamily

The immunoglobulin superfamily (IgSF) is an ever-growing list of additional immune checkpoints that are being studied in clinical trials. We review here, the current members of the IgSF for which there are active clinical trials; these include lymphocyte-activation gene 3 (LAG-3), T-cell immunoglobulin mucin 3 (TIM-3), T-cell immunoglobulin and ITIM domain (TIGIT), killer immunoglobulin-like receptor (KIR), and V-domain immunoglobulin

suppressor of T-cell activation (VISTA). Table 3 lists the active trials in this category.

LAG-3. LAG-3 (CD223) is important cell surface molecule that can be found on both Tregs and effector $CD8^+$ T-cells.[111,112] Tregs maintain immune tolerance by inhibiting effector T-cells. LAG-3 is a $CD4^+$ T-cell homolog that binds to MHC class II molecules, facilitating their suppressive function.[113] In the setting of effector T-cell activation, LAG-3 is upregulated. *In vitro* studies of knockout mice ($LAG\text{-}3^{-/-}$) showed diminished control of Treg expression.[112] Furthermore, inhibition of LAG-3 was found to reverse the state of $CD8^+$ T-cell immune tolerance.[111]

In addition to its role on Tregs, LAG-3 is also found in low levels on effector T-cells.[114] Upon their activation, LAG-3 expression on effector T-cells is increased, thus ensuring T-cell homeostasis. Inhibition by antibodies against LAG-3 resulted in the expansion and activity of effector T-cells *in vivo* and *in vitro*.[111,115] In murine models, the recruitment of TILs by antitumor vaccines in combination with LAG-3 antibodies further augmented the cytotoxic tumor response.[111]

In the setting of immune-tolerant environments such as in cancer, TILs can coexpress both LAG-3 and PD-1, which is thought to work synergistically.[116,117] Murine knockout models for both LAG-3 and PD-1 ($LAG\text{-}3^{-/-}PDCD\text{-}1^{-/-}$) developed early, fatal multiorgan autoimmune disease as compared with mice containing only a single knockout gene. Furthermore, treatment with dual antibodies against both LAG-3 and PD-1 resulted in significant tumor shrinkage due to the increased recruitment of tumor-specific $CD8^+$ T-cells as compared with monotherapy.[117] A similar synergistic effect was also seen with chronic viral infections; in a murine model of chronic lymphocytic choriomeningitis virus infection, dual blockade of LAG-3 and PD-1 increased antigen-specific $CD8^+$ T-cells and decreased viral load compared with untreated controls.[118] Preclinical studies have also demonstrated the presence of LAG-3 expression on the TILs of other cancers such as melanoma,[119] hepatocellular carcinoma,[120] gastric cancer,[121] and NSCLC.[122] The synergistic effects of LAG-3 and PD-1 are currently being explored in multiple clinical trials. Dual blockade with anti-LAG-3 antibodies and currently approved PD-1 inhibitors, is an exciting novel combination which may have less toxicity compared with CTLA-4 combinations given that LAG-3 and PD-1 expression are primarily limited to TILs.[117,123]

Lastly, it should also be noted that soluble LAG3 (sLAG-3), in contrast with LAG-3, when bound to MHC class II, results in dendritic cell maturation and migration to lymph nodes.[124] It was also shown to induce tumor-specific $CD8^+$ T-cell responses.[125] An injectable, recombinant soluble LAG-3Ig fusion protein has shown to be safe in early phase studies involving metastatic breast cancer and RCC.[126,127] There are ongoing studies assessing the benefit of this recombinant soluble LAG-3Ig fusion protein in addition to monoclonal antibodies against LAG-3.

TIM-3. TIM-3 is a membrane protein found on T helper 1 cells (Th1), a subset of $CD4^+$ T-cells which are important for cell-mediated immunity. It also found on $CD8^+$ T-cells, Tregs, and cells of the innate immune system. TIM-3 binds to its ligand, galectin-9, a carbohydrate-binding protein that can be found on lymphocytes.[128] When bound together, the combination acts as an inhibitory signal, regulating Th1 responses and induction of peripheral tolerance.[129,130] In naïve immune states, galectin-9 is expressed in high levels within numerous tissues such as in lymph nodes and the spleen. In the setting of immune activation, galactin-9 mRNA expression is downregulated to allow for the expansion of Th1 cells and promoting the inflammatory response. This response is balanced by the induction of galactin-9 expression by the resultant production of inflammatory cytokines, interferon-gamma (INF-γ) and IL-1β.[128] Of note, TIM-3 has other receptors HMGB1 and Ceacam-1, which are important in maintaining its inhibitory function and may have a role as future checkpoint targets.[131]

Similar to LAG-3, TIM-3 expression correlates with chronic viral infections and cancer.[132,133] In addition, when PD-1 is coexpressed with TIM-3 on TILs, this produces a state of T-cell exhaustion whereby there is a lack of inflammatory cytokines in response to antigen exposure. Dual inhibition with antibodies against PD-1 and TIM-3 has a synergistic effect at restoring antitumor immunity and causing tumor regression as compared with monotherapy alone.[133,134] TIM-3

Table 3. Selected immune checkpoint inhibitors in clinical trials.

Class	Drug	Sponsor	Regimen	Indication	NCT	Phase/ status
Immunoglobulin superfamily						
TIM3	LY3321367 (mAb)	Eli Lilly and Company	Monotherapy, combination with anti-PD-L1 mAb (LY3300054)	Advanced solid tumors	NCT03099109	Phase I recruiting
	MBG453 (mAb)	Novartis	Monotherapy, combination with anti-PD-1 mAb (PDR001)	Advanced solid tumors	NCT02608268	Phase I recruiting
	TSR-022 (mAb)	Tesaro	Monotherapy, combination with anti-PD-L1 mAb	Advanced solid tumors	NCT02817633	Phase I recruiting
LAG 3	BMS-986016 (mAb)	Bristol Myers	Monotherapy and in combination with nivolumab	First/second-line NSCLC with PD on/after anti-PD1/PDL1	NCT01968109	Phase I/II recruiting
	LAG525 (mAb)	Novartis	Monotherapy, combination with anti-PD-1 mAb (PDR001)	Advanced solid tumors	NCT02460224	Phase I/II recruiting
	MGD013 (mAb)	Macro-genics	Monotherapy	Advanced solid tumors, hematologic neoplasms	NCT03219268	Phase I recruiting
	REGN3767 (mAb)	Regeneron Pharma	Monotherapy, combination with anti-PD-1 mAb (REGN2810)	Advanced solid tumors	NCT03005782	Phase I recruiting
	TSR-033 (mAb)	Tesaro	Monotherapy, combination with anti-PD-1 mAb	Advanced solid tumors	NCT03250832	Phase I recruiting
	INCAGN022385 (mAb)	Incyte Corp	Monotherapy	Advanced malignancies	NCT03538028	Phase I recruiting
TIGIT	OMP-313M32 (mAb)	OncoMed Pharma	Monotherapy	Advanced solid tumors	NCT03119428	Phase I recruiting
KIR	BMS-986015 (mAb)	Bristol-Myers Squibb	Combination with Ipi monotherapy, combination with Nivo, Nivo/Ipi	Advanced solid tumors	NCT01750580 NCT01714739	Phase I completed Phase I active, not recruiting
VISTA	CA-170 (SM)	Curis, Inc	Monotherapy	Advanced solid tumors, lymphoma	NCT02812875	Phase I recruiting
Metabolites and myeloid cell factors						
IDO	Epacadostat (INCB 24360) (IDOi)	Incyte Corp	Epacadostat combination with azacitadine and Pembro	Advanced solid tumors	NCT02959437	Phase I/II active, not recruiting
			Epacadostat combination with anti-PD-1 mAb and chemotherapy		NCT03085914	Phase I/II recruiting
			Epacadostat combination with Pembro		NCT02178722	Phase I/II active, not recruiting
			Epacadostat combination with Nivo and PD *versus* PD *versus* Nivo and PD	First line stage IV or recurrent NSCLC	NCT03348904	Phase III active not recruiting

(Continued)

Table 3. (Continued)

Class	Drug	Sponsor	Regimen	Indication	NCT	Phase/ status
			Epacadostat combination with Pembro *versus* Pembro	First line stage IV NSCLC with PD-L1 ⩾50%	NCT03322540	Phase III recruiting
			Epacadostat combination with Pembro and PD chemotherapy *versus* Pembro and PD	First line stage IV NSCLC	NCT03322566	Phase II recruiting
			Epacadostat combination with Nivo/Ipi *versus* epacadostat combination with Nivo and BMS-986015 (anti-KIR mAb)	Advanced solid tumors	NCT03347123	Phase I/II recruiting
	Indoximod (NLG0401) (IDOi)	NewLink Genetics Corp	Indoximod combination with docetaxel, tergenpumatucel-L	NSCLC, at least one prior platinum-doublet chemotherapy	NCT02460367	Phase I/II Unknown
Adenosine CD73	CPI-444 (A2aR antagonist)	Corvus Pharma, Inc.	Monotherapy, combination with anti-PD-L1 mAb (Atezo)	Advanced solid tumors	NCT02655822	Phase I recruiting
	CPI-006 (anti-CD73 mAb)		Monotherapy, combination with CPI-144 (A2aR antagonist), combination with CPI-144 and Pembro	Advanced solid tumors	NCT03454451	Phase I/Ib
	PBF-509 (A2aR antagonist)	Paobiofarma SL	Monotherapy, combination with anti-PD-L1 antibody (PDR001)	Advanced NSCLC, one prior line of therapy	NCT02403193	Phase I/II recruiting
	PBF-1129 (A2aR antagonist)		Monotherapy	Advanced NSCLC	NCT03274479	Phase I not yet recruiting
	NIR178 (A2aR antagonist)	Novartis	Combination with anti-PD-L1 antibody (PDR001)	Advanced solid tumors, NHL	NCT03207867	Phase II recruiting
	NZV930 (anti-CD73 mAb)		Monotherapy, combination with anti-PD-L1 antibody (PDR001), combination with NIR178 (A2aR antagonist), combination with PDR001 and NIR178	Advanced malignancies	NCT03549000	Phase I/IIb Not yet recruiting
	MEDI9447 (anti-CD73 mAb)	MedImmune LLC	Monotherapy, combination with Durva	Advanced solid tumors	NCT02503774	Phase I recruiting
Arginase	INCB001158	Incyte Corp	Monotherapy, combination with Pembro	Advanced solid tumors	NCT02903914	Phase I/II recruiting
			Combination with epacadostat ± Pembro	Advanced solid tumors	NCT03361228	Phase I/II recruiting
IL-10	AM0010 (recombinant pegylated IL-10)	ARMO Bio Sciences	Monotherapy, combination with standard of care therapy	Advanced solid tumors	NCT02009449	Phase I, active not recruiting
CSFR-1	FPA008 (mAb)	Five Prime Therapeutics, Inc., Bristol-Myers Squibb	Combination with Nivo	Advanced solid tumors	NCT02526017	Phase I recruiting

Atezo, atezolizumab; Durva, durvalumab; IDOi, IDO inhibitor; IL, interleukin; IP, intraperitoneal; Ipi, ipilimumab; mAb, monoclonal antibody; NCT, ClinicalTrials.gov; Nivo, nivolumab; NHL, non-Hodgkin's lymphoma; NSCLC, non-small cell lung cancer; PD, platinum doublet; PD-L1, programmed death ligand-1; Pembro, pembrolizumab; SM, small molecule; SubQ, subcutaneous.

is found in on both $CD4^+$ and $CD8^+$ TILs of many solid and hematologic malignancies, including NSCLC.[135] Gao and colleagues evaluated 51 tissue specimens of patients with pathologically confirmed NSCLC and compared their TIM-3 expression with normal lung tissue. TIM-3 expression was found on the majority of $Foxp3^+$ Tregs and were associated with more advanced disease.[136] In addition, TIM-3 expression on NK cells was also shown to be associated with stage III/VI disease and a decreased OS in NSCLC.[137,138] Based upon preclinical studies suggesting a synergistic effect with combination anti-PD-1 antibodies, anti-TIM-3 antibodies are currently being studied as monotherapy and in combination for NSCLC.

TIGIT. TIGIT is expressed on NK cells, effector/memory T-cells and Tregs.[139,140] It has two ligands, CD155 (poliovirus receptor or PVR) and CD112, which are expressed on tumor cells, in addition to APCs and T-cells.[131] TIGIT binds with a higher affinity to CD155 but must also compete with binding of CD155 to stimulatory (CD226) and inhibitory (CD96) signals.[141–143] Binding of TIGIT to its receptor results in the inhibition of IL-12, shifting T-cell production away from the cell-mediated Th1, pathway, resulting in an immune-tolerant state.[140,144] The resultant downstream cell signaling response also decreases NK-mediated cytokine release and cell killing.[139] One hypothesis is that activation of the stimulatory signal, CD226, promotes cell-mediated killing that is balanced by the inhibitory signal, TIGIT, which competes for binding of CD155 with CD226.[141,142] TIGIT remains an additional checkpoint important in the regulation of T-cell responses.

TIGIT is highly expressed in TILs within the tumor microenvironment. Along with PD-1, LAG-3, and TIM-3, the expression of TIGIT on $CD8^+$ TILs resulted in a dysfunctional effector T-cell incapable for antitumor activity.[145] The previous theme of synergistic activity with PD-1 inhibition in reversing the state of effector T-cell exhaustion also persists when combined with a TIGIT inhibitor.[145,146] Interestingly there is evidence of synergistic activity with blockade of TIM-3 in the IgSF, thus potentially leading the way for future clinical trials combining the novel checkpoint inhibitors.[144] Currently, there is one anti-TIGIT antibody in a phase I study for locally advanced and metastatic solid tumors. It remains to be seen if TIGIT will be combined with other immune checkpoint inhibitors or with alterations of its coinhibitory/stimulatory signals.

KIR. KIRs are a family of regulatory cell surface receptors that are responsible for maintaining the balance of NK-mediated cell killing against foreign cells and limiting autoimmune attack.[147] KIRs are found on NK cells and $CD8^+$ T-cells. NK cells are a part of the innate immune system that makes up roughly 10% of circulating human lymphocytes.[43] Their role in protecting against infections and cancer is rooted in its ability to identify cells not expressing MHC class I molecules.[148] In certain cancers such as in lung cancer, MHC class I molecules are downregulated to escape immune attack.[149] The KIR and NKG2A/CD94 receptors are two NK cell inhibitory receptors that bind to HLA class I molecules. The downstream effects of KIRs vary depending on the extracellular domain. The presence of a long cytoplasmic tail (KIR2DL, KIR3DL) results NK cell inhibition while the short cytoplasmic tail (KIR3DS, KIR3DS) results in NK cell activation.[148]

Tumor cells can also escape immune destruction by increasing the inhibitory subset of KIRs to escape cytotoxic T-cell killing.[150] In NSCLC, NK cells were noted to be in decreased numbers and have reduced NK activation as compared with areas of the lung without cancer.[151,152] The reduction in NK cells may also be related to the increase in Tregs found in the tumor microenvironment. Unfortunately, even NK cells that infiltrate the tumor have an impaired cytotoxic ability.[153] Among the KIRs detected in NSCLC tumor cells or TILs, expressing KIR 2D (L1, L3, L4, S4) and KIR 3DL1 were poor prognostic indicators associated with decreased survival.[154] It remains to be seen to what role KIRs are involved in this process.

Anti-KIR monoclonal antibodies, 1-7F9 and lirilumab (BMS-986015), are currently being studied in hematologic malignancies and solid tumors. In the preclinical study for 1-7F9, a humanized monoclonal antibody against KIR2DL1, KIR2DL2, and KIR2DL3 receptors, there was increased NK cell-mediated lysis of acute myeloid leukemia (AML) blasts.[155] Lirilumab is the recombinant version with a stabilized hinge, which was also shown to be effective in lymphoma in combination with the anti-CD20 monoclonal antibody, rituximab.[156] Currently lirilumab is being studied

in combination with PD-1 and CTLA-4 inhibitors in advanced solid tumors.

Lastly, it should also be noted that the other NK cell checkpoint, NKG2A-CD94, has also shown to be a potential target in cancer cells.[157] Anti-NKG2A-CD94 monoclonal antibody, monalizumab (IPH2201), is currently being combined with the anti-PD-L1 antibody, durvalumab, for advanced solid tumors. NKG2A-CD94 is a heterodimer that binds to a nonclassical HLA class I molecule, HLA-E.[158] NKG2A-CD94 possesses similar regulatory properties on NK cells as with KIR and is dependent on binding to HLA-E. HLA-E has been noted in various hematologic malignancies and solid tumors, including NSCLC. However, high expressions of HLA-E in NSCLC were associated with a worsened OS.[159] Studies demonstrate the lack of NK cell-mediated tumor activity within NSCLC; hopefully the monoclonal antibodies targeting the interactions of NKG2A-HLA-E and KIR-HLA class I molecules are able to reverse this process.

VISTA. VISTA is a member of the B7 family that shares similarities to immune checkpoints, PD-1 and CTLA-4.[160] It is a very conserved protein that is found predominantly on hematopoietic cells in the myeloid lineage such as macrophages, dendritic cells, MDSCs, and neutrophils; they are also noted on Tregs.[161] VISTA acts as both a ligand and receptor, and is noted to be upregulated within the TME. Preclinical studies have demonstrated that in murine models of solid tumors, overexpression of VISTA is associated with T-cell exhaustion and inhibition through monoclonal antibodies reverses this effect.[162,163] It was also demonstrated that both PD-1 and VISTA are nonredundant checkpoint inhibitors that show synergistic activity with dual inhibition.[164]

As a result, targeting VISTA in combination with other immune checkpoints is an area of interest. Unfortunately, the phase I study of a novel humanized IgG1 monoclonal antibody against VISTA (JNJ-61610588) was terminated by the pharmaceutical sponsor [ClinicalTrials.gov identifier: NCT02671955]. However, a novel agent, CA-170, is a small molecule inhibitor of PD-1, PD-L1/2, and VISTA-PD-1H that is currently undergoing phase I study. Initial results are promising without any dose-limiting toxicities and showing peripheral T-cell expansion.[165]

Metabolites and myeloid cell factors

In addition to targeting additional immune checkpoint inhibitors of the TME, immunosuppressing metabolites have also become an area of interest. There are currently soluble inhibitors in trial for indoleamine 2,3-dioxygenase (IDO), adenosine, arginase, and other myeloid factors. Table 3 lists the active trials in this category.

IDO. IDO is an enzyme ubiquitously expressed on TILs and myeloid cells in various tissues sites including the lung.[166] It functions in the catabolism of the amino acid tryptophan (Try), to kynurenine (Kyn) and its metabolites.[167] Depletion of tryptophan results in an increase of a stress-response kinase called GCN2 that causes a decrease in T-cell activation.[168] Furthermore, Kyn binds to the aryl hydrocarbon receptor, causing the production of Tregs.[169]

NSCLC is among the solid tumors showing a high expression of IDO and was predominantly represented within the TME.[166] IDO expression is mediated by a number of inflammatory signals including IFN-γ.[170,171] Numerous studies attempt to indirectly measure IDO activity by calculating the ratio of Kyn to Try (Kyn/Try).[167] A higher Kyn/Try ratio was seen not only in patients with NSCLC compared with healthy controls but also in more advanced *versus* early stage disease.[172] In addition, in patients with stage III NSCLC who underwent induction chemotherapy followed by concurrent chemoradiation, elevated Kyn/Try ratios after induction chemotherapy were associated with decreased OS.[173] These studies demonstrate that IDO expression plays an active role in maintaining the immune-tolerant environment in NSCLC and is a potential therapeutic target.

There have been two main IDO inhibitors (epacadostat and indoximod) evaluated in clinical studies and one IDO peptide vaccine.[167] Epacadostat (INCB024360) is a small molecule inhibitor of IDO1. Preclinical studies have shown *in vitro* and *in vivo* increases in T-cell, NK cell, and DC cell proliferation with reductions in Tregs, and suppression of tumor growth in murine models, respectively.[174] In the phase I study, epacadostat was well tolerated with the most common side effects being fatigue, nausea, decreased appetite and vomiting; the recommended phase II dose achieved >90% IDO1 activity inhibition.[175] Overall ORR was limited at 34.6% with the best response being stable

disease. The lack of response may be due to need for combination therapy due to the presence of other immune checkpoints.[176] Combination therapy trials with epacadostat are ongoing. Preliminary data on the phase I/II study combining epacadostat with pembrolizumab in the NSCLC cohort [ClinicalTrials.gov identifier: NCT02178722] showed a disease control rate of 57% (4/7) and 53% (9/17) for patients with a PD-L1 TPS $\geqslant$50% *versus* $<$50%, respectively.[177] Side effects were similar to the phase I study. Results from the phase III study of epacadostat in combination with pembrolizumab in unresectable advanced stage melanoma showed no PFS or OS benefit over pembrolizumab alone [ClinicalTrials.gov identifier: NCT02752074].[178] We will await the results in NSCLC but should temper our expectations about this combination.

Indoximod (NLG-8189) is a second oral IDO inhibitor that has also shown to be well tolerated along with similar minimal responses as a single agent.[179] Preclinical studies support tumor regression when indoximod is combined with cytotoxic chemotherapy, suggesting the importance of TILs in optimizing the tumor response to IDO inhibitors.[180] The subsequent phase I study combining indoximod with docetaxel in advanced solid tumors (34% were NSCLC) was overall well tolerated and showed comparable disease control rates to epacadostat.[181] Building upon these early data, there is an ongoing phase I/II study combining indoximod and docetaxel with tergenpumatucel-L [ClinicalTrials.gov identifier: NCT02460367]. Tergenpumatucel-L is a vaccine consisting of allogeneic lung cancer cells that express alpha-1,3-galactosyltransferase (α[1,3] Gal), a carbohydrate for which we have established innate immune response against.[182] In a phase II study with advanced NSCLC, 56% (9/16) of patients who progressed on the vaccine and subsequently received chemotherapy achieved a response.[183] This study suggested that tergenpumatucel-L might sensitize patients to chemotherapy, hence the rationale of its addition to indoximod and docetaxel combination. It should also be noted that another IDO peptide vaccine from Denmark was shown to be well tolerated and effective for advanced NSCLC with remarkable long-term disease response.[184] Overall, IDO remains a promising target that likely requires additional immune checkpoint inhibition or augmentation of TILs to the TME to maximize antitumor response.

Adenosine. Adenosine is a molecule that is produced as a byproduct of tumor cell killing and proinflammatory mediators such as hypoxia.[185] Adenosine triphosphate (ATP) released is converted to adenosine monophosphate (AMP) by the enzyme CD39, and AMP is then converted to adenosine by the rate-limiting enzyme CD73. Adenosine then interacts with one of four G-protein coupled receptors (A1, A_{2A}, A_{2B}, A3). Adenosine receptors A_{2A} and A_{2B} have immune-suppressing properties, likely acting as a physiologic break to excess inflammation.

Tumor cells manipulate this process to promote an immune-tolerant environment.[186] The ischemic tumor environment is associated with an upregulation of CD39, CD73, and Tregs to promote an adenosine-mediated immune-suppressing state.[187,188] In many tumors including NSCLC, CD73 expression is a poor prognostic indicator.[189] Preclinical studies show that tumors produce higher levels of adenosine than in normal tissue[190] and reduce the activity of NK cells and effector T-cells.[185] Inhibition of the A_{2A} receptor was shown to decrease tumor cell growth in both *in vitro* and *in vivo* NSCLC models.[191] Hence, CD73 and adenosine receptors (mainly A_{2A}) have garnered interest as potential therapeutic targets.[192] Anti-CD73 monoclonal antibodies are being tested as monotherapy and in combination with a PD-L1 inhibitor for advanced solid tumors [ClinicalTrials.gov identifiers: NCT02503774, NCT03549000, NCT03454451].[193] There are at least three adenosine A_{2A} receptor monoclonal antibodies in clinical trials [ClinicalTrials.gov identifiers: NCT02403193, NCT02655822, NCT03207867]. Like with other checkpoint inhibitors, a synergistic antitumor effect can be seen when combined with anti-CD73 and anti-A_{2A} receptor blockade and is being evaluated in the current studies.[193–195] Lastly, in NSCLC, CD73 and A_{2A} receptor expression was primarily seen in adenocarcinoma histology with epidermal growth factor receptor mutations, potentially warranting further investigation in combination with current targeted therapies for selected patients.[189]

Arginase and other myeloid cell factors. L-Arginine is an important amino acid for the growth of T-cells and a pathway that is manipulated by tumor cells.[42,196] Arginase-1 (ARG1) is an enzyme constitutively expressed on granulocytes and upregulated by MDSCs and TAMs. MDSCs are

derived from immature myeloid cells and promote an immunosuppressive state in the TME. One of the mechanisms by which MDSCs maintain this environment is through the depletion of L-arginine by upregulating ARG1, resulting in apoptosis of tumor-antigen specific effector T-cells. Similar to depletion of Try, the depletion of extracellular L-arginine downregulates T-cell activity though the loss of expression of TCR CD3 zeta chain.[197] Elevated ARG1 expression has been documented in NSCLC as compared with healthy controls. *In vivo* inhibition of ARG1 in a lung cancer murine model reduced tumor growth but was unsuccessful in mice that genetically lacked of functional T and B-cells.[198] This finding highlights the importance of the need for TILs in addition to inhibition of ARG1. Currently, a single arginase inhibitor is being studied as monotherapy and in combination with nivolumab [ClinicalTrials.gov identifier: NCT02903914].

The TAMs are another subset of myeloid cells that can promote tumorigenesis in a similar fashion to MDSCs.[42] They share features with M2 macrophages, which express high levels of IL-10, decreasing the production of effector T-cells and promoting tumor survival. The effects of TAMs include increased angiogenesis and metastases, tumor invasion, and resistance to apoptosis.[199] TAMs also express PD-L1 and therefore an attractable target in combination with agents targeting tumorigenesis within the myeloid lineage.[200] Chemokines (i.e. CCL2) and cytokines (i.e. CSF1R, IL-10, Tie2) involved in this dysfunctional process are under investigation. Agents targeting IL-10 and colony stimulating factor 1 receptor (CSF1R) are currently being studied in clinical trials.

IL-10 has the potential to express contrasting responses; at low levels it can produce an immunosuppressive response but at high concentrations, it can promote the proliferation of $CD8^+$ T-cells.[201,202] Reversal of its immunosuppressive response with an anti-IL-10 antibody resulted in increased IL-12 expression and cytotoxic T-cell activity in a breast cancer murine model. Alternatively, in a phase I study of patients with advanced solid tumors, pegylated recombinant IL-10 (AM0010) is being evaluated for its ability to stimulate the expansion of $CD8^+$ TILs [ClinicalTrials.gov identifier: NCT02009449]. As a single agent, it was well tolerated but responses were limited; the experimental phase in combination with chemotherapy or immunotherapy is ongoing.[203]

CSF1R binding to its ligand CSF1 is important to allow for continued immune-suppressing actions of TAMs and other myeloid cells.[204] Inhibition of CSF1R not only reduces the amount of TAMs, but also increases $CD8^+$ T-cells.[205] Numerous CSF1R inhibitors (small molecules and monoclonal antibodies) are currently being studied in clinical trials as monotherapy and in combination with both chemotherapy and immunotherapy. Overall, these agents are well tolerated with common side effects including fatigue, transaminitis, and facial/peripheral edema. NSCLC has demonstrated increased TAMs as noted by an increase of M2 macrophages in all histologies except large cell carcinoma.[206] In addition, high levels of IL-10 expression in TAMs were associated with more advanced NSCLC stage and poor histologic differentiation.[207] Therefore, given the increase of TAMs in NSCLC, the potential role for CSF1R inhibitors is promising.

Tumor biomarkers

Immunotherapy in advanced NSCLC is being moved towards the front-line setting either as monotherapy or in combination with systemic chemotherapy.[11,14,15,17] We must be cognizant of the fact that not all patients benefit equally from immunotherapy. Few patients have durable responses as noted by the plateau in the Kaplan–Meier PFS curves, but some patients have inferior responses when compared with chemotherapy as suggested by the initial crossing of PFS curves.[13,20] How to best predict which patients will benefit the most from immunotherapy is an important question that remains unanswered. PD-L1 is the tumor biomarker most often used but it does have its limitations. PD-L1 expression does not always predict response to PD-1 and PD-L1 inhibitors.[28] In phase III studies of previously treated advanced NSCLC, nivolumab and atezolizumab, even patients with PD-L1 $<1\%$ expression had OS and PFS benefit over docetaxel.[8,24] Despite this, higher PD-L1 expression is generally associated with a comparatively greater response to immunotherapy.[7,24] Moreover, the tumor heterogeneity of PD-L1 expression and availability of numerous PD-L1 assays used for the various immune checkpoint inhibitors caution

the reliance of PD-L1 alone at predicting response to immunotherapy.[208,209]

Attempts at identifying additional tumor biomarkers have been explored. The heterogeneity of somatic mutations among various tumor types has been previously reported, with NSCLC demonstrating a range of mutations (0.1–100 somatic mutations per Mb) but is particularly highest in smokers *versus* never-smokers[33,210] It is proposed that a high TMB is associated with increased neoantigen exposure to APCs, thereby activating the tumor immune response.[32] Rizvi and colleagues evaluated TMB through whole exome sequencing to determine the amount of somatic nonsynonymous mutations in patients with NSCLC who were treated with pembrolizumab.[32] In tumors with >178 nonsynonymous mutations per tumor, labeled as high TMB, there was an improved response to pembrolizumab as compared with tumors with low TMB. They also reported improved ORR and PFS in patients harboring a molecular smoking signature marked by C-to-A transversions. The utility of TMB was also explored in a nonprespecified analysis of the Checkmate 026 phase III study that compared nivolumab monotherapy with chemotherapy in treatment-naïve advanced NSCLC patients.[13] Whole exome sequencing was used to determine TMB, with >242 mutations per tumor being considered as high TMB. As this was an exploratory analysis, patient with tumors of high TMB were unbalanced (30% in the nivolumab arm, 39% in the chemotherapy arm). Interestingly, ORR in the high TMB group was numerically higher with nivolumab over chemotherapy (47% *versus* 28%) along with the PFS (9.7 months *versus* 5.8 months). There was no association between the level of PD-L1 and TMB status. Patients with both PD-L1 expression of >50% and high TMB were found to have an ORR of 75% *versus* 25% in patients treated with nivolumab (n = 16) *versus* chemotherapy (n = 32), respectively. The *post-hoc* nature of these results limits our adoption of TMB until more prospective studies are completed. Recently published results from the multipart phase III trial, Checkmate 227, met its coprimary endpoint of PFS among patients with high TMB (⩾10 mu/Mb) in advanced, treatment-naïve NSCLC, regardless of PD-L1 status, who were treated with combination nivolumab and ipilimumab *versus* chemotherapy.[20] Patients with high *versus* low TMB had significantly greater median and 12-month PFS (42.6% *versus* 13.2%, HR 0.58, 95% CI 0.41–0.81, $p < 0.0001$). Responses were also durable at 12-months (68% *versus* 25%). Among patients with high TMB, the 12-month PFS rate was similarly improved over chemotherapy among the PD-L1 ⩾1% *versus* <1% (42% *versus* 16% and 45% *versus* 8%, respectively). The trial also included treatment with nivolumab monotherapy for patients with PD-L1 ⩾ 1%; there was no improvement in PFS regardless of TMB status. Although OS data is immature, this study supports TMB as a useful biomarker outside of PD-L1 in identifying patients who may benefit from combination immunotherapy.

Lastly, Teff gene signature expression is another biomarker that has gained interest. It was introduced in the phase II POPLAR study comparing atezolizumab monotherapy to docetaxel for previously treated advanced NSCLC.[7] It initially included the expression of eight genes (CD8A, GZMA, GZMB, IFNγ, EOMES, CXCL9, CXCL10, and TBX21) believed to be associated with pre-existing immunity and PD-L1 expression on immune cells. The Teff-high *versus* low cohort was based upon gene expression at or above the median level *versus* below the median level, respectively. The Teff gene signature was refined to include the expression of three messenger RNAs (PD-L1, CXCL9, and INF-γ) and applied to the subsequent phase III OAK trial that compared atezolizumab with docetaxel in previously treated advanced NSCLC patients.[8] The biomarker was found to be a more sensitive indicator for PFS compared with PD-L1 expression.[211] The recent phase III IMPower 150 trial evaluating first-line atezolizumab with carboplatin, paclitaxel, and bevacizumab to carboplatin, paclitaxel and bevacizumab included PFS benefit in the Teff-high population as one of its coprimary endpoints.[17] The PFS was significantly longer in the atezolizumab-containing arm and this benefit persisted for the Teff-high (11.3 months *versus* 6.8 months, HR 0.51, 95% CI, 0.38–0.68, $p < 0.0001$) and Teff-low cohorts (7.3 months *versus* 7.0 months, HR 0.76, 95% CI, 0.60–0.96). Prolonged PFS was seen regardless of PD-L1 status; responses of the Teff-high and Teff-low were comparable with tumor cell (TC) or immune cell (IC) 1/2/3 (PD-L1 ⩾ 1% of tumor cells or tumor-infiltrating immune cells) and TC or IC 0 (PD-L1 < 1% of tumor cells or

tumor-infiltrating immune cells), respectively. Given the similar benefit of Teff-high and PD-L1 $\geqslant$ 1%, the exact utility of Teff in addition to PD-L1 warrants further investigation. Identifying a consistent and predictable biomarker will become crucial in the new era of immunotherapeutic combinations. Although PD-L1 expression continues to be the gold standard at this time, I suspect that a combination of tumor biomarkers will be needed in deciding the proper therapeutic approach.

Conclusion

The immune system plays an important role in not only eradicating disease but also promoting long-lasting immunity. As we better understand how the immune system responds to cancer, we can specifically target the mechanisms whereby TCs evade destruction beyond PD-1/PDL-1 and CTLA-4. We now have a surplus of clinical trials evaluating the role of new immune checkpoints, immune-suppressing cytokines and metabolites, and costimulatory signals. In addition to focusing on shifting the cancer-immune set point towards T-cell stimulation, we also understand the importance of TILs in the antitumor response. Tumor vaccines are now being studied in combination with immune checkpoint inhibitors to improve tumor-associated T-cell activity that appeared to be lacking with monotherapy. Building upon the success of ACT in hematologic malignancies, the development of CAR T-cells for solid tumors like NSCLC are promising, especially in tumors lacking appropriate TILs. Models of the interactions between the host immune system and cancer help to provide an excellent framework to understand this complex process and allow us to understand that we cannot adopt a 'one size fits all' approach when it comes to immunotherapy. We described therapies in development that target three main areas of active research: the release of cancer antigens, activation of the T-cell response, and regulation of the inhibitory immune response. Based on preclinical studies and ongoing clinical trials with novel agents, it appears that we must adopt a combination approach. However, determining the most efficacious combination (i.e. two immune checkpoint inhibitors, costimulatory and checkpoint inhibitors, tumor vaccine and immune checkpoint inhibitors) while minimizing immune-related and financial toxicities will be the next hurdles. In addition, understanding how to personalize this treatment as proposed by Teng and colleagues will also be a challenge.[39] Despite these unanswered questions, there is no doubt that the era of immunotherapy has been met with great success and growing optimism. We must work to further understand of this complex system if we hope to build on the current early success of immunotherapy.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Conflict of interest statement

NV has no conflicting interests. LB has participated in advisory boards for Takeda, Astra Zeneca, Novartis, Genentech.

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