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Targeting the PD-1 pathway in pediatric solid tumors and brain tumors

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Abstract: While remarkable advances have been made in the treatment of pediatric leukemia over the past decades, new therapies are needed for children with advanced solid tumors and high-grade brain tumors who fail standard chemotherapy regimens. Immunotherapy with immune checkpoint inhibitors acting through the programmed cell death-1 (PD-1) pathway has shown efficacy in some chemotherapy-resistant adult cancers, generating interest that these agents may also be helpful to treat certain refractory pediatric malignancies. In this manuscript we review current strategies for targeting the PD-1 pathway, highlighting putative biomarkers and the rationale for investigation of these drugs to treat common pediatric tumors such as sarcoma, neuroblastoma, and high-grade glioma. We summarize the completed and ongoing clinical trial data available, and suggest potential applications for further study.

Keywords: PD-1, nivolumab, pembrolizumab, pediatric, sarcoma, neuroblastoma, glioma

Introduction

Although the majority of children with newly diagnosed cancer are expected to be long-term survivors, cure remains elusive for patients with certain tumor types. For example, patients with high-risk neuroblastoma, advanced sarcoma, or high-grade glioma who relapse after initial therapy are rarely cured, and these diseases collectively account for over half of pediatric cancer deaths.1 Given that further increases or modifications in existing cytotoxic therapies are unlikely to provide substantial benefit, there is great interest in pursuing alternative approaches for these refractory cancers.

Targeting the immune system as a method for controlling tumor growth is intuitively appealing, as it represents an enabling of the body’s defenses instead of the usual weakening that is brought about by toxic conventional therapy. There is growing evidence that the tumor microenvironment and immune effector cells may help control proliferation of a variety of different pediatric tumors, prompting the investigation of tumor vaccines or other immunomodulating strategies to eradicate malignant cells, or at least restrain tumor growth.2–4

The most effective immunotherapy to date for pediatric solid tumors has been the chimeric monoclonal antibody ch14.18 (dinutuximab; Unituxin®), which targets the ganglioside GD2 that is ubiquitously present on the surface of neuroblastoma cells. Use of dinutuximab following autologous stem-cell transplantation improved the 2-year event-free survival for high-risk neuroblastoma patients from 46% to 66%,5 leading to US Food and Drug Administration (FDA) approval of this agent. This breakthrough study convincingly showed that, in certain contexts, immunotherapy can indeed improve the outcome for particular pediatric tumors. Given this success, and the recent expansion of immunotherapies for adult cancers detailed below, attention...
is now turning to whether targeting the programmed cell death-1 (PD-1) pathway will be beneficial for refractory pediatric solid tumors and brain tumors. While responses have been seen in adult cancers once thought intractable, these agents have not been efficacious in all clinical scenarios, and patient selection will be critical for success. In this review, we discuss the mechanisms and potential biomarkers for PD-1-targeted therapy, and outline how this may potentially be applied to pediatric solid tumors.

Overview of PD-1 pathway

In the last three decades, cancer therapy has increasingly focused on immunotherapy, based in part on observations that cancer patients may have better outcomes when tumor-infiltrating lymphocytes (TIL) are present. The premise is that these TIL are capable of recognizing and killing tumor cells, thus leading to prolonged patient survival. Cytotoxic T-cells are a key mediator of this immune-mediated antitumor effect, and there is now great interest in understanding how these cells are not only activated but also regulated.

As tumor cells die, dendritic cells present tumor-specific antigens through major histocompatibility complex (MHC) to T-cells, and provide additional costimulatory signals through surface receptors like CD28 (Figure 1). Once the T-cell becomes activated, other costimulatory molecules are expressed, such as 4.1BB, OX40, and CD40L. Activated T-cells then undergo clonal expansion and migrate to the site of tumor-related antigens, where they infiltrate the tumor and kill malignant cells through perforin and granzyme B. Shortly after activation, mechanisms for turning off the cells also appear, namely the expression of the checkpoint receptors CTLA-4 and PD-1. Collectively, these receptors control the quality, intensity, and duration of the immune response.

Augmenting clonal expansion of these cytotoxic T-cells has been accomplished with aldesleukin (interleukin 2), which is FDA approved for the treatment of metastatic renal cell carcinoma and melanoma. However, due to the high toxicity and relatively low response rates of aldesleukin, focus has shifted from augmenting expansion to prolonging the activation of cytotoxic T-cells by blocking checkpoint

Figure 1 Immune response to tumors.
Notes: (A) Dying tumor cells are taken up by antigen-presenting cells (eg, dendritic cells) and presented to T-cells (commonly in the lymph system) where they then undergo clonal expansion and trafficking into the tumor. (B) Activated cytotoxic T-cells proliferate, participate in generation of inflammatory and toxic cytokines, including fatal secretion of perforin and granzyme; following chronic stimulation checkpoint receptors on the T-cells are bound by their ligands and the T-cell response is terminated. Blocking the PD-1 and/or CTLA4 checkpoints with antibodies leads to activation/reactivation of T-cells so they generate an antitumor response.

Abbreviations: MHC, major histocompatibility complex; PD-1, programmed cell death-1; PD-L1, programmed death-ligand 1.
signals that can terminate the immune response. Although checkpoint signals are important to protect against autoimmune disease, they also protect the tumor from immune attack. The first target for checkpoint inhibition was CTLA-4, which competes with CD28 to bind the stimulatory molecules B7.1 and B7.2. CTLA-4 expression occurs upon T-cell activation, and once present CTLA-4 helps terminate T-cell activity. Ipilimumab is a monoclonal antibody against CTLA-4, and as such helps remove the brakes on the immune response and overcome tolerance by prolonging the period of T-cell activation. Ipilimumab has received FDA approval for the treatment of metastatic melanoma based on improved survival when compared to tumor vaccine; however, the overall response rate was only 11%. A pediatric phase I trial of 33 unselected patients with relapsed solid tumors treated with ipilimumab identified a maximum-tolerated dose of 5 mg/kg in patients <12 years old and 10 mg/kg in older patients. This compares to the FDA-approved dose of 3 mg/kg in adults. Unfortunately, no objective responses were seen, and focus has turned to second-generation checkpoint inhibitors targeting PD-1 with the hopes of further improving activity. In adult melanoma patients, pembrolizumab and nivolumab (PD-1 inhibitors) have proven to be superior to ipilimumab.

PD-1 is another checkpoint that is important in terminating the response of activated T-cells, and is upregulated by chronically activated T-cells. PD-1 is expressed on activated effector T-cells and other TIL such as natural killer cells, and when activated causes the T-cells to become unresponsive. This phenotype of PD-1$^+$ T-cells that is no longer cytotoxic is called T-cell exhaustion. Of note, mice deficient in PD-1 develop autoimmune diseases from unchecked immune activation, and blocking this pathway in PD-1-proficient mice with chronic viral infections restores antiviral immunity and reverses T-cell exhaustion. PD-1 signaling is induced following binding to either of its two ligands (PD-L1 or PD-L2), of which PD-L1 appears to be the more important in regulating T-cell antitumor function. PD-L1 is expressed in a variety of different tumors, and in dendritic cells, macrophages, and T-cells. Upregulation of PD-L1 expression by tumors is driven by inflammation when cytokines such as interferon gamma are expressed. Additionally, there is also a link between hypoxia, which can lead to infiltration of tumor-associated macrophages that express PD-L1. These immune-regulatory signals appear to be a mechanism tumors utilize to escape immune surveillance. Logically, it follows that tumors that express PD-L1 or contain macrophages that express PD-L1 might respond best to a PD-1 or PD-L1 inhibitor. This concept is depicted in Figure 2.

There are currently three FDA-approved antibodies targeting either PD-1 (nivolumab, pembrolizumab) or PD-L1 (aletuzumab), with several others in clinical trials. A summary is provided in Table 1. To date, there has been no published comparison of efficacy in patients treated with antibodies within a class (eg, nivolumab vs pembrolizumab), or between classes (PD-1 vs PD-L1). The toxicities of these
Table 1  Checkpoint inhibitors available in the USA and select inhibitors in advanced studies

<table>
<thead>
<tr>
<th>Drug</th>
<th>Target</th>
<th>Indication</th>
<th>Stage of development</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ipilimumab</td>
<td>CTLA4</td>
<td>Melanoma</td>
<td>FDA approved</td>
</tr>
<tr>
<td>Tremelimumab</td>
<td>CTLA4</td>
<td>Head and neck</td>
<td>Phase III – NCT02369874</td>
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<tr>
<td></td>
<td></td>
<td>Mesothelioma</td>
<td>Phase III – NCT01843374</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non-small-cell lung cancer</td>
<td>Phase III – NCT02542293</td>
</tr>
<tr>
<td>Pembrolizumab</td>
<td>PD-1</td>
<td>Non-small-cell lung cancer</td>
<td>FDA approved</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Melanoma</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Head and neck cancer</td>
<td></td>
</tr>
<tr>
<td>Nivolumab</td>
<td>PD-1</td>
<td>Non-small-cell lung cancer</td>
<td>FDA approved</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Melanoma</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Renal cell cancer</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Head and neck cancer</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hodgkin lymphoma</td>
<td></td>
</tr>
<tr>
<td>Pidilizumab</td>
<td>PD-1</td>
<td>Diffuse large B-cell lymphoma</td>
<td>Phase II – NCT02530125</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Multiple myeloma</td>
<td>Phase II – NCT02077959</td>
</tr>
<tr>
<td>PDR001</td>
<td>PD-1</td>
<td>Neuroendocrine tumors</td>
<td>Phase II – NCT02955069</td>
</tr>
<tr>
<td>Atezolizumab</td>
<td>PD-L1</td>
<td>Non-small-cell lung cancer</td>
<td>FDA approved</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bladder cancer</td>
<td>Phase III – NCT02369874</td>
</tr>
<tr>
<td>Durvalumab</td>
<td>PD-L1</td>
<td>Head and neck cancer</td>
<td>Phase III – NCT02453282</td>
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<tr>
<td></td>
<td></td>
<td>Non-small-cell lung cancer</td>
<td>Phase III – NCT02576574</td>
</tr>
<tr>
<td>Avelumab</td>
<td>PD-L1</td>
<td>Non-small-cell lung cancer</td>
<td>Phase III – NCT02926196</td>
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<td></td>
<td></td>
<td>Breast cancer</td>
<td>Phase III – NCT02580058</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ovarian cancer</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: FDA, Food and Drug Administration; PD-1, programmed cell death-1; PD-L1, programmed death-ligand 1.

Putative biomarkers and mechanisms of resistance for PD-1-targeted therapy

At present, there is no single biomarker that accurately predicts response to anti-PD-1 therapy. Based on the current understanding of the immune system’s antitumor response, there are several key elements that can explain how tumors escape immune surveillance and grow. Tumors that are not immunogenic will not be recognized by the immune system. Immunogenic tumors can avoid immune surveillance by preventing inflammation and lymphocyte penetration into the tumor, or they can avoid immune surveillance by terminating the immune response through expressed checkpoint ligands.

Intuitively, tumors that have escaped immune surveillance and express PD-L1 on the cell surface should benefit from either anti-PD-1 or anti-PD-L1 therapy. However, clinical trial experience shows that this is not always the case. Key areas of investigation include how expression of PD-L1 is assessed, what threshold is linked to clinical benefit from these agents, and whether PD-L1 expression is required for therapeutic success. As seen in Table 2, PD-L1 is most commonly assessed by immunohistochemistry (IHC), although a variety of different antibodies, different tissues (fresh, frozen, paraffin embedded, primary vs metastatic), and different thresholds for positivity have been used (reviewed in Hutarew). Despite these limitations, most trials involving lung cancer and melanoma patients show a general association between outcome and PD-L1 expression, although it is not necessarily required for therapeutic benefit. In contrast, PD-L1 expression in urothelial cancer or renal cell cancer seems even less predictive of response to nivolumab or pembrolizumab, as some patients clearly benefit despite little or no expression. These results suggest that the utility of PD-L1 as a biomarker is limited and may not be broadly applicable across all tumor types.

PD-L1 expression is induced by inflammatory cytokines such as interferon gamma, and the expression of this cytokine may mark the mechanism the tumor has utilized to escape immune surveillance and consequently be a biomarker for PD-1 inhibitor activity. For example, in a preliminary report describing the treatment of patients with non-small-cell lung cancer with the anti-PD-L1 antibody durvalumab, patients whose tumors coexpressed interferon gamma and PD-L1 had improved survival (hazard ratio [HR] 0.4, \( P=0.016 \)) compared with those expressing PD-L1 alone (HR 0.64,
These findings suggest that some type of panel of biomarkers may be most efficacious for patient selection.

Another putative biomarker for response to anti-PD-1 therapy is the total mutational burden, with studies showing improved response rates in patients with >100 mutations in tumor tissue. Somatic mutations have the potential to encode “non-self” immunogenic antigens (also called neoantigens), which may make the tumor more visible to the immune system. Mutations may be induced by exposure, such as sunlight or cigarette smoke, and perhaps this may be one reason why PD-1 agents have been successful in melanoma and lung cancer. Alternatively, mutations also may be dramatically increased in tumors demonstrating mismatch repair (MMR) deficiency, and this can result in microsatellite instability (MSI) and sensitivity to PD-1 inhibition. For example, patients treated with pembrolizumab for colon cancer showed response rates as high as 40% in patients whose tumors showed MMR deficiency, compared with 0% in MMR-proficient tumors. Whole-exome sequencing demonstrated a mean of 1,782 mutations per tumor in the

Table 2 Review of select biomarker studies and their ability to enrich responding patient populations

<table>
<thead>
<tr>
<th>Biomarker</th>
<th>Drug</th>
<th>Disease/setting</th>
<th>Cutoff</th>
<th>Outcome</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tumor PD-L1</td>
<td>Pembrolizumab&lt;sup&gt;59&lt;/sup&gt;</td>
<td>NSCLC</td>
<td>Mostly second line</td>
<td>1%–24%</td>
<td>OS – 10 mo</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>25%–49%</td>
<td>OS – 10 mo</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50%–74%</td>
<td>OS – 16 mo</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>75%+</td>
<td>OS – 17 mo</td>
<td></td>
</tr>
<tr>
<td>Nivolumab&lt;sup&gt;60&lt;/sup&gt;</td>
<td>NSCLC</td>
<td>second line (nonsquamous histology)</td>
<td>&lt;5%</td>
<td>OS – 10 mo</td>
<td>IHC assay with antibody 28-8</td>
</tr>
<tr>
<td>Atezolizumab&lt;sup&gt;61&lt;/sup&gt;</td>
<td>NSCLC</td>
<td>Second line</td>
<td>&lt;1%</td>
<td>OS – 13 mo</td>
<td>SP142 assay</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&gt;1%</td>
<td>OS – 16 mo</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&gt;5%</td>
<td>OS – 16 mo</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&gt;50%</td>
<td>OS – 21 mo</td>
<td></td>
</tr>
<tr>
<td>Nivolumab&lt;sup&gt;62&lt;/sup&gt;</td>
<td>Melanoma</td>
<td>First line</td>
<td>&lt;5%</td>
<td>PFS – 5 mo</td>
<td>IHC assay with antibody 28-8</td>
</tr>
<tr>
<td>Pembrolizumab&lt;sup&gt;63&lt;/sup&gt;</td>
<td>Melanoma</td>
<td>Prior treatment</td>
<td>&lt;1%</td>
<td>PFS – 3 mo</td>
<td>IHC assay with antibody 22C3</td>
</tr>
<tr>
<td>Pembrolizumab&lt;sup&gt;64&lt;/sup&gt;</td>
<td>Head and neck cancer</td>
<td></td>
<td>Positive predictive value</td>
<td>40%</td>
<td>Interferon gamma genes: CXCL9, CXCL10</td>
</tr>
<tr>
<td>Atezolizumab&lt;sup&gt;65&lt;/sup&gt;</td>
<td>NSCLC</td>
<td>Second line</td>
<td>Negative predictive value</td>
<td>95%</td>
<td>IDO1, INF gamma, HLA-DRA, and STAT1</td>
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<tr>
<td>Pembrolizumab&lt;sup&gt;66&lt;/sup&gt;</td>
<td>NSCLC</td>
<td>High (above median)</td>
<td>T&lt;sub&gt;eff&lt;/sub&gt;/INF high</td>
<td>ORR – 59%</td>
<td>Nonsynonymous</td>
</tr>
<tr>
<td>Pembrolizumab&lt;sup&gt;67&lt;/sup&gt;</td>
<td>NSCLC</td>
<td>Prior treatment</td>
<td>Low (below median)</td>
<td>ORR – 12</td>
<td>Exom sequencing with 9049 nonsynonymous, coding point mutations considered</td>
</tr>
<tr>
<td>Pembrolizumab&lt;sup&gt;66&lt;/sup&gt;</td>
<td>NSCLC</td>
<td>High (above median)</td>
<td>Prior treatment</td>
<td>PFS – 14.5 mo</td>
<td>Total exonic mutations</td>
</tr>
<tr>
<td>Pembrolizumab&lt;sup&gt;68&lt;/sup&gt;</td>
<td>Colorectal cancer</td>
<td>Second line</td>
<td>Mismatch repair deficient</td>
<td>ORR – 40%</td>
<td>Microsatellite instability analysis using an assay from Promega</td>
</tr>
<tr>
<td>Angiopoietin 2 PD-1 inhibitor&lt;sup&gt;25&lt;/sup&gt;</td>
<td>Melanoma</td>
<td>Second line</td>
<td>Mismatch repair proficient</td>
<td>ORR – 0%</td>
<td>Serum-based assay</td>
</tr>
</tbody>
</table>

<sup>Abbreviations</sup>: INF, interferon; IHC, immunohistochemistry; mo, months; NSCLC, non-small-cell lung cancer; OS, overall survival; PD-1, programmed cell death-1; PD-L1, programmed death-ligand 1; PFS, progression-free survival.
MMR-deficient cohort, compared to 73 in the proficient group. Assessing for mutational burden and MSI can now be done by commercial assays, and may be another potentially important factor to consider regarding patient selection.

Finally, there is some recent information suggesting that angiopoietin-2 (Ang2) may also be a biomarker for PD-1-targeted therapy, and importantly one that can be assessed by peripheral blood at various time points. Ang2 is a critical regulator of tumor-associated blood vessel maturation, and is involved with the recruitment of monocytes/macrophages into the tumor microenvironment and induction of PD-L1 expression in M2-polarized macrophages. Wu et al found that for 43 melanoma patients treated with PD-1 blockade, those with high circulating levels of Ang2 (defined as >3,175 pg/mL) or rising levels during treatment had reduced overall survival, suggesting that Ang2 may mediate resistance to checkpoint inhibitors, and could be used to select and follow patients. Although pediatric data are limited, one study of 35 various pediatric solid tumor or brain tumor patients showed that the median circulating Ang2 level at diagnosis would be considered low at 2,482 pg/mL, suggesting potential sensitivity to PD-1 inhibition according to this parameter. A list of biomarkers used in key clinical trials is provided in Table 2.

There are several proposed mechanisms of resistance to PD-1 blockade, and include interruptions of any step along the pathway of T-cell cytotoxicity. Some tumors such as prostate cancer have very little PD-L1 expression despite the presence of TIL, and so may be resistant for this reason. Mutations in tumor can account for downregulation of MHC and decreased immunogenicity, or altered dendritic cell migration. In addition, involvement of other PD-1-independent pathways may help tumor cells evade T-cell destruction. Some tumor cells are induced by interferon gamma to express indoleamine 2,3-dioxygenase, which can render experimental models of melanoma resistant to PD-1 blockade. Other complex mechanisms such as extreme T-cell exhaustion or impaired development of effective T-cell memory may also contribute to resistance (reviewed in O’Donnell et al).

**Preclinical testing in pediatric cancers**

In considering whether PD-1 targeting would be appropriate for pediatric cancers, a key issue is whether potential biomarkers suggested by adult studies are present in childhood tumors as well. Although limited, there is a growing body of evidence about PD-L1 expression, mutational burden, and MSI in important childhood cancers such as bone and soft tissue sarcoma, neuroblastoma, and high-grade glioma.

**Pediatric sarcoma**

In two of the larger studies to date of osteosarcoma, IHC analysis showed PD-L1 expression in 25%–47% of primary tumor samples, and tumors expressing PD-L1 were significantly more likely to have infiltrating immune cells, which often expressed PD-1. Importantly, PD-L1 expression correlated with worse event-free survival, and these findings are consistent with the concept that PD-L1 in tumor cells may interact with PD-1-expressing cells in the microenvironment to help evade immune rejection by the host. Interestingly, PD-L1 expression has been reported to be more common in metastatic lesions than in primary tumors, which is relevant considering that metastases are more likely than primary tumors to cause death in this disease. Further, osteosarcoma has a greater inherent genomic instability and higher mutational burden than many other pediatric solid tumors, which may also predispose to benefit from PD-1-targeted therapy. Finally, use of the immune adjuvant mifamurtide has previously shown benefit in osteosarcoma and is approved by the European Medicines Agency, further demonstrating the potential role of immunotherapy for this disease.

PD-L1 expression has been less well studied in Ewing sarcoma, another important pediatric sarcoma that may originate either in bone or soft tissue. One study demonstrated expression in 8 (57%) of 14 primary bone tumor samples, while 8 (38%) of 21 soft tissue primaries have reported PD-L1 expression in other studies. For rhabdomyosarcoma, the most common pediatric soft tissue sarcoma, data are limited but Chowdhury et al have reported expression in 13 (86%) of 15 alveolar rhabdomyosarcoma and 8 (50%) of 16 embryonal rhabdomyosarcoma patient samples. More robust analysis of the tumor microenvironment is not yet available, although infiltrating PD-1 CD8 lymphocytes are present in a subset of these tumors.

**Neuroblastoma**

Neuroblastoma is the most common extracranial solid tumor in children, and high-risk disease accounts for up to 15% of pediatric cancer deaths. An early study did not identify PD-L1 expression in any of the 18 tested samples from neuroblastoma patients. In contrast, Chowdhury et al reported PD-L1 surface expression in 31 (72%) of 43 patient tumor samples, with lower survival in patients expressing PD-L1. Dondero et al confirmed that PD-1 expression is present in lymphocytes obtained from metastatic bone marrow samples, and that PD-L1 expression in tumor cells is inducible with interferon gamma. Interestingly, the production of cytokines such as interferon is particularly high in patients following treatment with the recently approved...
monoclonal antibody dinutuximab, suggesting potential benefit for combination therapy.

High-grade glioma
PD-L1 expression has been identified in 6 (30%) of 20 pediatric high-grade glioma samples, and larger studies in adults showed expression in 68% of 62 glioblastoma samples, with a strong trend for worse outcome in these patients. In addition, a subset of pediatric high-grade glioma tumors has evidence of MSI, which reflects the increased mutational status of the tumor and the potential greater number of neoantigens that could induce a host immune response. Viana-Pereira et al have reported MSI to be present in 14 (19%) of 71 high-grade glioma samples, significantly higher than that seen with adult tumors. While some of those patients may have had the rare congenital MMR deficiency syndrome (MMRDS, previously called Turcot syndrome), MSI may also arise independently outside of this defined cancer predisposition. The potential benefit for using anti-PD-1 antibodies to treat these hypermutated tumors was shown by Bouffet et al, who reported sustained responses in two siblings with pediatric glioblastoma and MMRDS who were treated with single-agent nivolumab. Taken together, these findings support further investigation of PD-1-targeted drugs for this disease.

Completed and upcoming clinical trials with PD-1 agents to treat pediatric cancers
To date, there have been only a few reports of treatment of pediatric cancer patients with agents targeting the PD-1 pathway. Apart from the glioma patients with MMR deficiency treated with pembrolizumab as above, all other reports involve genetically unselected patients. Blumenthal et al retrospectively described outcomes in 22 patients with MSI, which reflects the increased mutational status of the tumor and the potential greater number of neoantigens that could induce a host immune response. Viana-Pereira et al have reported MSI to be present in 14 (19%) of 71 high-grade glioma samples, significantly higher than that seen with adult tumors. While some of those patients may have had the rare congenital MMR deficiency syndrome (MMRDS, previously called Turcot syndrome), MSI may also arise independently outside of this defined cancer predisposition. The potential benefit for using anti-PD-1 antibodies to treat these hypermutated tumors was shown by Bouffet et al, who reported sustained responses in two siblings with pediatric glioblastoma and MMRDS who were treated with single-agent nivolumab. Taken together, these findings support further investigation of PD-1-targeted drugs for this disease.

Table 3 Ongoing trials of agents targeting the PD-1 or PD-L1 pathway for treatment of pediatric cancer

<table>
<thead>
<tr>
<th>ClinicalTrials.gov identifier</th>
<th>Population</th>
<th>Agent</th>
<th>Other drugs</th>
<th>Design</th>
<th>Sponsor/comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCT02304458</td>
<td>Relapsed solid tumors</td>
<td>Nivolumab</td>
<td>+/-ipilimumab</td>
<td>Phase I/II</td>
<td>COG</td>
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<tr>
<td>NCT02332668</td>
<td>Melanoma, PD-L1 positive</td>
<td>Pembrolizumab</td>
<td>–</td>
<td>Phase I/II</td>
<td>35 institutions</td>
</tr>
<tr>
<td>NCT02022695</td>
<td>Recurrent high-grade glioma</td>
<td>Pembrolizumab</td>
<td>–</td>
<td>Phase I/II</td>
<td>PBTC</td>
</tr>
<tr>
<td>NCT02813135</td>
<td>Recurrent solid tumors</td>
<td>Pembrolizumab</td>
<td>Cyclophosphamide</td>
<td>Basket trial</td>
<td>European study</td>
</tr>
<tr>
<td>NCT02541604</td>
<td>Recurrent solid tumors</td>
<td>Atezolizumab</td>
<td>–</td>
<td>Phase I/II</td>
<td>Hoffmann-LaRoche</td>
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<tr>
<td>NCT03000684</td>
<td>Recurrent osteosarcoma</td>
<td>Avelumab</td>
<td>–</td>
<td>Phase I/II</td>
<td>St Jude</td>
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Abbreviations: COG, Children’s Oncology Group; PBTC, Pediatric Brain Tumor Consortium; PD-L1, programmed death-ligand 1; PD-1, programmed cell death-1.
for that tumor type. This expansive trial includes many cor-
relative studies and should help better define the role of PD-1 in-
inhibition in treating pediatric tumors.

Other ongoing studies include a Pediatric Brain Tumor
Consortium phase I/II study in which pembrolizumab is
being evaluated for treatment of recurrent high-grade glioma
or other hypermutated brain tumors (NCT02359565). Pem-
brolizumab is also being studied in a pediatric phase I/II
trial as single-agent treatment for recurrent melanoma or
PD-L1-positive tumors (NCT02332668). In addition, anti-
PD-1 antibodies are also being included in so-called “basket
trials” for recurrent pediatric solid tumors, in which patients
are stratified based on molecular characteristics of the
tumor rather than the histiotype (NCT02813135). In regard
to PD-L1 antibodies, a phase I/II study of atezolizumab is
now open for patients <30 years with recurrent solid tumors
(NCT02541604), and a phase II study of avelumab is open
for patients with recurrent osteosarcoma (NCT03006848).

Safety and response considerations
As opposed to the myelosuppression usually seen with
conventional chemotherapy, the toxicity of anti-PD-1 anti-
odies has often been immune-related such as pneumonitis,
colitis, hepatitis, hypophysitis, and thyroiditis. In gen-
eral, the occurrence of these toxicities has correlated with
antitumor effects, consistent with the mechanism of action
of these agents. In the limited number of pediatric patients
studied to date, the severity and scope of adverse events
seem similar to adults. The development of pneumonitis and
pleural effusions is of particular concern in pediatric sarcoma
patients, who commonly have bulky lung or pleural metas-
tases that may be associated with effusions. Such patients
being treated with anti-PD-1 antibodies should be monitored
carefully, and be considered for drainage or other medical
management that could include steroids.

Another characteristic of PD-1-targeted therapy is the po-
tential for the temporary increase in size of lesions as a
consequence of therapy-related inflammation. This effect is
termed pseudoprogression, and has led to the development
of a modified response assessment system called immune-
related response criteria that are now used in trials of these
agents. This revised system allows for more interval growth
of tumor to occur before the determination of progressive
disease is made, based on past observations of patients going
on to have prolonged disease stability despite some initial
growth of tumor. The concept of tumor pseudoprogression
may have the greatest clinical implications in the treatment
of brain tumors, as at least one death has now been reported
in a pediatric patient with recurrent glioblastoma who was
treated with nivolumab and developed fatal cerebral edema
despite operative intervention.

Combination therapies
Given the common tendency of cancers to develop resistance
to monotherapies, it is likely that some patients may benefit
only when PD-1 agents are combined with other drugs that
may be synergistic. The only FDA-approved combination is
nivolumab together with the CTLA-4 inhibitor ipilimumab
for the treatment of metastatic melanoma. While this intui-
tively appealing strategy of double checkpoint inhibition
increases the response rate and overall survival, the rate
of grade 3–4 toxicity is also increased when compared to
nivolumab alone, emphasizing that toxicity considerations
will be important when planning combination therapies.

Some conventional chemotherapy drugs such as cyclo-
phosphamide, platinum analogs, and taxanes can elicit
immunogenicity by recruiting immune cells to the microen-
vironment, stimulating natural killer-dependent antitumor
immunity and T-cell responses, and disrupting immune
suppressor mechanisms by depleting regulatory T-cells and
myeloid-derived suppressor cells. These immunomodula-
tory effects may be optimized by using lower or more pro-
tracted dosing, and this strategy is being utilized in an
ongoing pediatric study combining pembrolizumab with
low-dose oral cyclophosphamide (NCT02813135).

The ability of radiotherapy to induce immune responses
is only now beginning to be understood. Preclinical studies
suggest that the combination of a PD-1 antibody with radia-
tion can be synergistic, and combination phase III studies
are now underway for glioblastoma (NCT02617589) and
lung cancer (NCT027768558). If this strategy is successful in
adults, it is likely that pediatric trials combining radiotherapy
and anti-PD-1 antibodies will soon follow. Other possible
combinations include targeted agents such as dabrafenib
or trametinib together with anti-PD-1 therapy, or even
tumor vaccines or oncolytic viruses such as tailmogene
laherparepvecm, which produces GM-CSF and is being
evaluated together with pembrolizumab in a phase III trial
for melanoma patients (NCT02263508).

Conclusions and future directions
The use of PD-1-targeted agents has revolutionized the
treatment of certain adult cancers, generating excitement in
part because some of the most responsive tumors have been
previously refractory to conventional therapies. Still emer-
ging is the identification of a reliable biomarker or panel of

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characteristics that can allow appropriate patient selection. Available information to date suggests that PD-L1 expression on tumor cells, a strong lymphocytic presence in the tumor microenvironment, and an increased mutational burden are important but not yet definitive markers that suggest efficacy. These features are variably present in some high-risk pediatric tumors, and support further investigation of PD-1-targeted therapy. However, data from adult studies clearly show that the presence or absence of these putative biomarkers does not guarantee the success or failure of this therapeutic strategy. Although off-label use is tempting for patients with multiply recurrent tumors, caution should be taken in light of the still unproven benefit of these agents for pediatric cancers, and the potential for organ toxicity related to immune effects. Trials are underway, which will better define the role these drugs may play for treating pediatric cancers, either as single agents or in combination with chemotherapy, radiation, or other molecularly targeted or biologic therapies.

Disclosure
The authors report no conflicts of interest in this work.

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