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Indoleamine 2,3-dioxygenase (IDO) inhibitors and cancer immunotherapy

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ABSTRACT

Strategies for unlocking immunosuppression in the tumor microenvironment have been investigated to overcome resistance to first-generation immune checkpoint blockade with anti- programmed cell death protein 1 (PD-1)/programmed death-ligand 1 (PD-L1) and anti-cytotoxic *T*-lymphocyte associated protein 4 (CTLA-4) agents. Indoleamine 2,3-dioxygenase (IDO) 1, an enzyme catabolizing tryptophan to kynurenine, creates an immunosuppressive environment in preclinical studies. Early phase clinical trials investigating inhibition of IDO1, especially together with checkpoint blockade, provided promising results. Unfortunately, the phase 3 trial of the IDO1 inhibitor epacadostat combined with the PD-1 inhibitor pembrolizumab did not show clinical benefit when compared with pembrolizumab monotherapy in patients with advanced malignant melanoma, which dampened enthusiasm for IDO inhibitors. Even so, several molecules, such as the aryl hydrocarbon receptor and tryptophan 2,3-dioxygenase, were reported as additional potential targets for the modulation of the tryptophan pathway, which might enhance clinical effectiveness. Furthermore, the combination of IDO pathway blockade with agents inhibiting other signals, such as those generated by *PIK3CA* mutations that may accompany IDO1 upregulation, may be a novel way to enhance activity. Importantly, IDO1 expression level varies by tumor type and among patients with the same tumor type, suggesting that patient selection based on expression levels of IDO1 may be warranted in clinical trials.

Introduction

The development and approval of immune checkpoint (programmed cell death protein 1 [PD-1], programmed death-ligand 1 [PD-L1], cytotoxic *T*-lymphocyte associated protein 4 [CTLA-4], and lymphocyte-activation gene 3 [LAG-3]) inhibitors resulted in dramatic changes in the landscape of cancer therapy. Still, most patients treated with an immune checkpoint inhibitor, especially with a monotherapy approach, will demonstrate either primary or acquired resistance to these treatments, which has led to clinical research focusing on therapeutic options utilizing combination strategies with immune checkpoint inhibitors and other agents [1–4]. To date, multiple mechanisms of resistance have been proposed. In particular, tryptophan catabolism was suggested as having an important role in contributing to resistance to immunotherapy [5].

Tryptophan is essential for protein synthesis and cell survival. It is catabolized to its metabolites including kynurenine and kynurenic acid, which usually serve as neurotransmitters and molecules in cell signaling pathways [6]. Reports have also shown upregulation of tryptophan catabolism in response to the inflammatory status induced by autoimmune diseases [7,8]. These studies suggest that modulating the tryptophan pathway may be important for cancer immunotherapy. Still, to date, clinical studies with indoleamine 2,3-dioxygenase (IDO) inhibitors, have been disappointing, despite the crucial impact of IDO on tryptophan metabolism and on immunosuppression (Fig. 1 and Supplemental Table 1).

Here, we review the important role of tryptophan metabolism in the immune system orchestra, and the biological implications for optimizing the effectiveness of IDO inhibitors.

Biological role of tryptophan metabolism and indoleamine 2,3-dioxygenase (IDO)

Three enzymes–indoleamine 2,3-dioxygenase (IDO) 1, IDO2, and

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tryptophan 2,3-dioxygenase (TDO)– degrade tryptophan to its downstream metabolites, resulting in enhanced levels of immunosuppressive cells [9–22]. As a result, the role of IDO1 in cancer cells has been investigated as an attractive therapeutic target (Fig. 2).

Studies have revealed that IDO1 is an immunosuppressant in the tumor microenvironment and is related to tumor progression [10]. IDO1 regulates tryptophan metabolism by catabolizing tryptophan to kynurenine, the first step of tryptophan degradation. Reduced tryptophan levels are associated with poor clinical outcomes among multiple cancer types, consistent with the premise that regulation of tryptophan metabolism plays an important role in cancer survival or progression [11,12]. Decreased levels of tryptophan and increased expression of IDO1 correlate with an increase in the level of immunosuppressive cells such as regulatory T cells and myeloid-derived suppressor cells (MDSCs), a decreased level of tumor infiltration lymphocytes and NK cells, and upregulation of PD-1 in cytotoxic T cells [10,13,15,23]. Moreover, even with higher levels of tumor-infiltrating CD8 + T cells, the cancer genome atlas (TCGA) data analysis showed higher IDO1 expression was associated with worse clinical outcomes in colorectal cancer [16]. Several potential mechanisms mediating differentiation to regulatory T cells are through activation of the stress response kinase, general control nonderepressible 2 (GCN2), in the setting of tryptophan depletion, and activation of the aryl hydrocarbon receptor (AhR) by increased tryptophan metabolites in the tumor microenvironment [17–19]. Clinically, the increased expression of regulatory T cells was found in the context of increased expression of IDO1 in dendritic cells in patients with cervical cancer, and a high level of IDO1 in peripheral monocytes was associated with poorer outcomes in early-stage malignant melanoma [20,21]. These results suggest that higher levels of IDO1, not only in tumor cells but also inside the tumor microenvironment, contribute to the immune evasion by cancer cells.

Tryptophan catabolites also exert their immunosuppressive effect by activating the AhR in cancer cells and by suppressing the signaling pathway of cytotoxic lymphocytes, leading to decreased function of cytotoxic T cells [10,24]. Tryptophan metabolites, such as kynurenine, kynurenic acid, cinnabarinic acid, indole-3-pyruvic acid (I3P), indole-3-acetic acid, and indole-3-carboxaldehyde, have a role as ligands to the AhR [19,25–29]. The activated AhR induces the accumulation of tumor-associated macrophages and regulatory T cells, and tolerogenicity of MDSCs, making the tumor microenvironment more immunosuppressive and enabling the escape of cancer cells [22,30,31]. Moreover, differentiation to regulatory T cells via activation of AhR occurs in the environment where anti-inflammatory cytokines such as TGF- β and IL-10 are produced by dendritic cells with an immunosuppressive feature [22]. Conversely, knockdown of AhR in the oral cancer cell model leads to a decrease in the expression of PD-L1 positive tumor-infiltrating CD8 + T cells and an increase in the number of cytotoxic CD8 + T cells [32]. However, the AhR is also known to induce interleukin-6 (IL-6) in the tumor microenvironment synergistically [26,33]. IL-6 is one of the main cytokines observed around cancer cells and has a pro-inflammatory role leading to tumorigenesis, cell proliferation, angiogenesis, and invasiveness [34]. Upregulation of AhR increases the production of IL-6, resulting in the activation of STAT-3, which in turn leads to the generation of IDO1, creating an autocrine AhR-IL-6-STAT-3 signaling loop that maintains IDO1 expression in human cancer cells [35].

Taken together, ample evidence of the role of IDO1 as an immunosuppressive molecule in the tumor microenvironment supports therapeutic strategies to target the tryptophan-IDO1-kynurenine pathway, using IDO1 inhibitors, perhaps combined with other systemic therapies, such as cancer vaccines and or established checkpoint blockade agents [36].

Development of IDO inhibitors

Promising results in preclinical models and early phase clinical trials

IDO inhibitors, which generally suppress IDO1 or inhibit IDO1 and TDO concurrently, were applied in the clinic after IDO1 was found to exert immunosuppressive roles in the tumor microenvironment and to be associated with tumor progression in preclinical models [10,37].

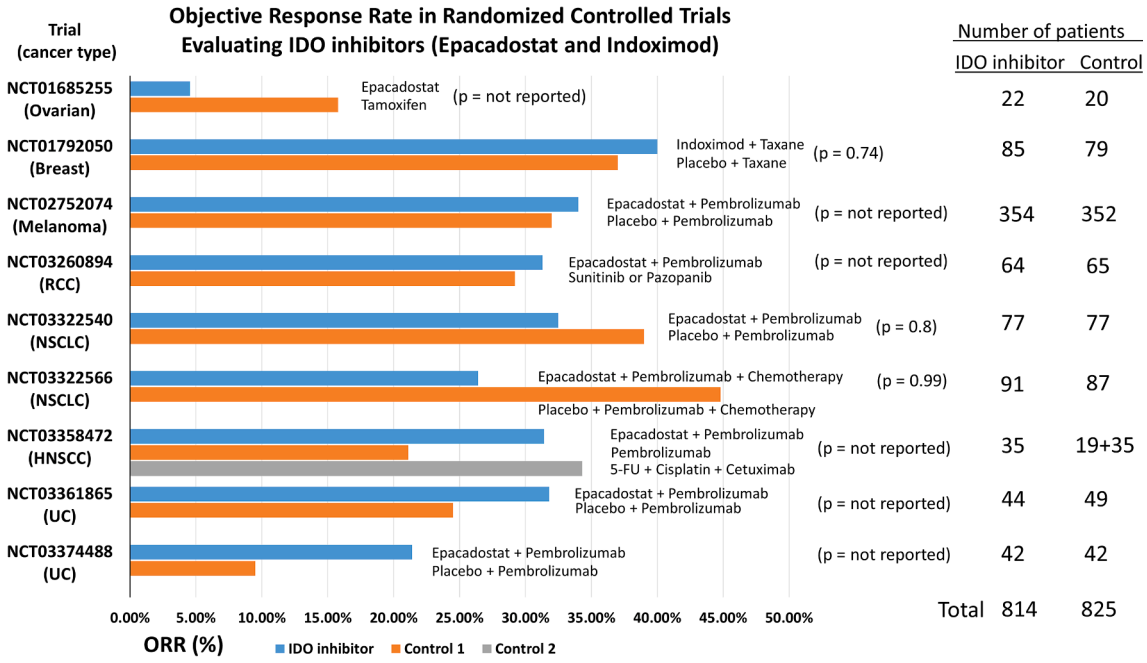

Fig. 1. Objective response rate (ORR) in selected randomized controlled trials evaluating epacadostat and indoximod. ORR was available from nine randomized controlled trials evaluating either epacadostat or indoximod. No study revealed significant differences in ORR. The vertical axis of the graph shows the National Clinical Trial number and cancer types. The horizontal axis of the graph shows the response rate (0–1). The blue bar illustrates the response rate of IDO inhibitors. The orange bar shows the response rate of the control treatment. The gray bar indicates the response rate of the additional control treatment if the study contains more than two treatment arms. **Abbreviations:** HNSCC, head and neck squamous cell carcinoma; IDO, indoleamine 2,3-dioxygenase: NSCLC, non-small cell lung carcinoma; OFP, ovarian, fallopian tube, and peritoneal; ORR, objective response rate; RCC, renal cell carcinoma; UC, urothelial carcinoma.

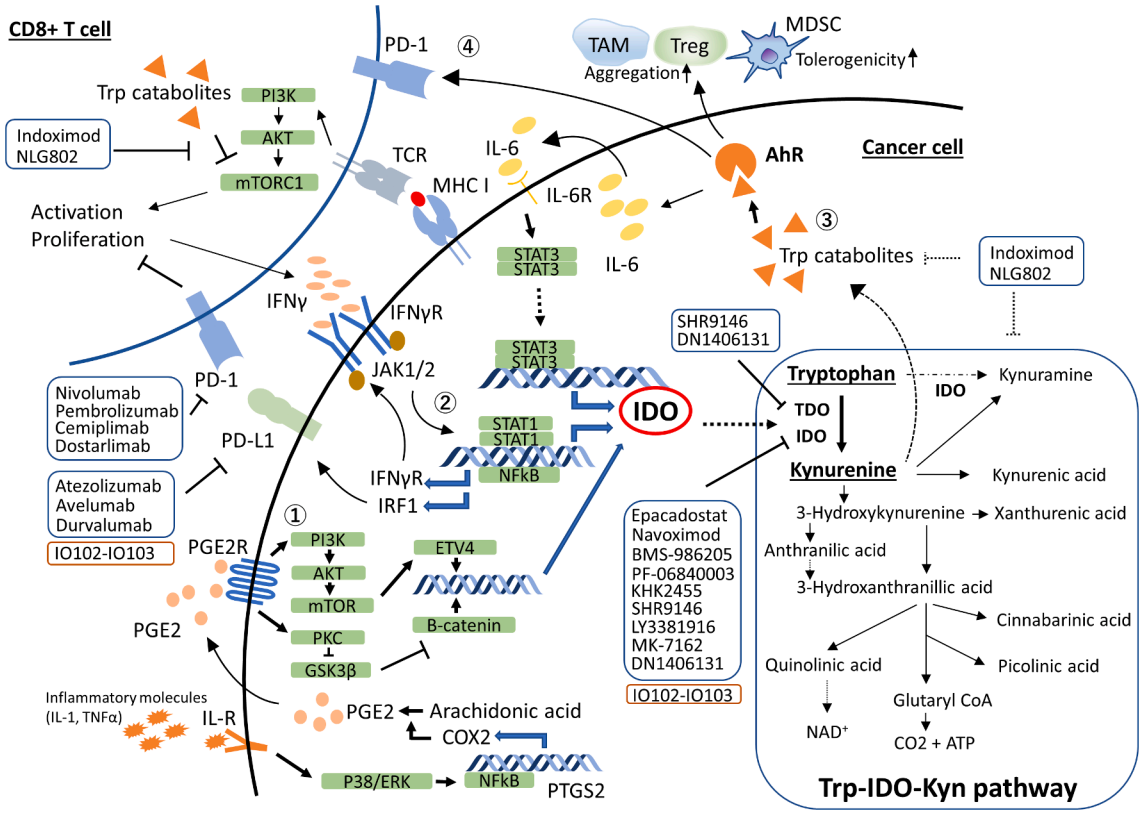

Fig. 2. Role of IDO in the tumor microenvironment. The expression of IDO is regulated by signaling pathways such as: (1) the PI3K-AKT-mTOR pathway; (2) the JAK-STAT pathway, which is typically upregulated by inflammatory molecules including PGE2, IFN γ, and IL-6; (3) tryptophan metabolites, which are catabolized from tryptophan by IDO or TDO activate the AhR pathway, leading to accumulation of TAM and Treg, and an increase in tolerogenicity of MDSCs around the tumor cells, making the tumor microenvironment immunosuppressive; (4) tryptophan catabolites, which also increase the expression of PD-1 on the surface of T cells and inhibit the cell signaling inside cytotoxic T cells, resulting in suppression of T cell function towards cancer cells. **Abbreviations**: AhR, aryl hydrocarbon receptor; AKT, protein kinase B; ATP, adenosine triphosphate; CoA, coenzyme A; COX2, cyclooxygenase 2; ERK, extracellular signal-regulated kinase 1/2; ETV4, ETS variant transcription factor 4; GSK3β, glycogen synthase kinase 3 beta; IDO, indoleamine 2,3-dioxygenase; IFN γ, interferon gamma; IFN γR, interferon gamma receptor; IL-1, interleukin 1; IL-6, interleukin 6; IL-6R, interleukin 6 receptor; IL-R, interleukin receptor; Kyn, kynurenine; MDSC, myeloid-derived-suppressor cell; MHC1, major histocompatibility complex 1; mTORC1, mammalian target of rapamycin complex 1; NAD+, nicotinamide adenine dinucleotide; NFkB, nuclear factor kappa B; PD-1, programed cell death 1; PD-L1, programmed death-ligand 1; PGE2, prostaglandin E2; PGE2R, prostaglandin E2 receptor; PI3K, phosphoinositide 3-kinase; PKC, protein kinase C; PTGS2, prostaglandin-endoperoxide synthase 2;STAT1, signal transducer and activator of transcription 1; STAT3, signal transducer and activator of transcription 3; TAM, tumor-associated macrophage; TCR, *T*-cell receptor; TDO, tryptophan-2,3-dioxygenase; TNFα, tumor necrosis factor alpha; Treg, regulatory T cell; Trp, tryptophan.

IDO1 deficiency was correlated with a decrease in the incidence and proliferation of hepatocellular carcinoma in mouse models, with suppressed invasion of regulatory T (Treg) cells in the liver [38]. In a mouse model of lung cancer, ablation of IDO1 resulted in a reduction in tumor burden, improvement in survival of MDSCs, and infiltration of PD-1 + CD8 + T cells in the tumor microenvironment [37]. Knockout of IDO1 in a mouse model of melanoma cells also revealed enhancement of therapeutic efficacy of PD-1/PD-L1 inhibitors and CTLA-4 inhibitors, suggesting synergistic efficacy of IDO1 inhibition with checkpoint inhibitors [5]. Through these preclinical studies, IDO1 inhibition gradually became an established target combined with other immunotherapeutic strategies [39,40].

As studies supported the strategy of targeting tryptophan catabolism mediated by IDO and TDO, various IDO1 and TDO inhibitors have been identified and entered into clinical trials (Supplementary Table 1) [6,41]. The IDO1 inhibitor epacadostat, which competes with tryptophan for IDO1 binding, was initially developed in the clinical setting after it was shown to boost antitumor effects by enhancing the function and proliferation of T- and NK-cells [42,43]. Unfortunately, epacadostat monotherapy was not impressive in regards to antitumor activity, but was well tolerated in a phase 1 study among patients with advanced cancer [44]. However, since synergistic effects with immune checkpoint inhibitors were observed in preclinical models [5,40], the combination of epacadostat with immune checkpoint inhibitors (anti-CTLA-4 inhibitor and anti-PD-L1 inhibitor) was investigated in early-phase clinical trials with promising results [39,45]. Subsequent phase 1/2 (ECHO-202/KEYNOTE-037) trial, an open-label and single-arm study with escalating doses of epacadostat, to evaluate epacadostat plus pembrolizumab (anti-PD1) in patients with advanced solid tumors, showed relatively high objective response rates (ORR = 40.3 %, n = 25/62), and adequate anti-tumor efficacy was seen, especially in patients with malignant melanoma (ORR = 61.9 %, n = 13/21) [46]. Unfortunately, phase 3 trials did not confirm the benefit (see next section) [47,48].

In addition to epacadostat, the IDO pathway modulator indoximod, and its prodrug NLG802, were developed. Although the precise mechanism of action remains controversial, these agents are known to modulate the IDO pathway, in contrast to IDO1 inhibitors, which directly inhibit the activity of IDO1 [49]. The combination of docetaxel and indoximod was well tolerated in patients with advanced solid tumors in a phase 1 trial [50]. Indoximod was subsequently evaluated with taxanes in patients with breast cancer in a randomized phase 2 trial, but it failed to meet its primary endpoint; the progression-free survival (PFS, 6.8 months in indoximod plus taxane vs 9.5 months in placebo plus taxane) [51]. BMS-986205 (Linrodostat), another IDO1 inhibitor, was the first agent to demonstrate potent reduction of plasma kynurenine level in a clinical trial; a subsequent clinical trial evaluating BMS-

986205 with nivolumab (anti-PD1) reported a promising ORR (34 %, n = 10/29 in an advanced bladder cancer cohort) [52,53].

Several IDO pathway inhibitors/modulators have been evaluated in clinical trials (summarized in Supplementary Table 1). Many of these trials showed disappointing results, either with the use of IDO inhibitor monotherapy or when combined with other agents in a randomized setting.

Failure in phase 3 KEYNOTE-252/ECHO-301 trial

Because of the encouraging results in early-phase trials such as the ECHO-202/KEYNOTE-037 phase 1/2 trial (epacadostat plus pembrolizumab in patients with advanced solid tumors) [46], the combination of epacadostat 100 mg twice daily with pembrolizumab 200 mg once every 3 weeks was compared with placebo plus pembrolizumab (anti-PD1) in a large phase 3, ECHO-301/KEYNOTE-252 trial, in advanced melanoma. However, this trial showed that epacadostat plus pembrolizumab did not improve PFS and overall survival when compared to pembrolizumab alone. Subgroup analysis based on the level of PD-L1 by immunohistochemistry (IHC) did not show differences in PFS between treatment groups [47]. Additionally, with a 1 % positivity threshold, ~ 90 % of tumors stained IDO1 positive, and IDO1 positivity did not correlate with the outcome; no other IDO1 positive thresholds were examined. This trial could not identify the right biomarker to predict the efficacy of the investigational treatment. Moreover, the prespecified endpoints such as pharmacokinetics and pharmacodynamics of epacadostat were not analyzed due to a lack of predictive factors or biomarkers, which made it difficult to address the reasons for the failure of epacadostat plus pembrolizumab in patients with advanced malignant melanoma in the ECHO-301/KEYNOTE-252 trial.

Current status of IDO inhibitors

Multiple negative phase 3 trials

Along with the ECHO-301/KEYNOTE-252 trial, several phase 3 trials were conducted to evaluate the efficacy of the combination of epacadostat and pembrolizumab for a variety of cancer types. However, these trials were halted or underwent a setback to phase 2 trials after the failure of the ECHO-301/KEYNOTE-252 trial. The partial or full results of these trials were reported and ORR in each trial is summarized in Fig. 1. Although ORR with IDO1 inhibitor use was relatively higher in patients with cisplatin-ineligible urothelial carcinoma (ORR = 31.8 % in epacadostat plus pembrolizumab, 24.5 % in placebo plus pembrolizumab) or recurrent advanced urothelial carcinoma (ORR = 21.4 % in epacadostat plus pembrolizumab, 9.5 % in placebo plus pembrolizumab), no apparent clinical benefit was observed in patients treated with the combination of IDO1 inhibition and an immune checkpoint inhibitor or other agents in similar or other types of cancer (NCT03260894, NCT03322540, NCT03322566, NCT03358472, NCT03361865, NCT03374488) (Fig. 1 and Supplemental Table 1) [51,54]. Phase 3 trials evaluating another IDO1 inhibitor, BMS-986205, with the anti-PD1 nivolumab in patients with malignant melanoma, head and neck cancer, and non-small cell lung cancer were subsequently halted (NCT03329846) (NCT03386838) (NCT03417037). One phase 3 study, which evaluates the combination of BMS-986205 with or without nivolumab in patients with muscle-invasive bladder cancer is ongoing (NCT03329846).

Current trials re-evaluating IDO inhibitors

While larger combination IDO1/immune checkpoint inhibitor trials did not demonstrate efficacy, phase 1 and 2 trials are ongoing to uncover efficacy for patients with advanced malignancies. Epacadostat, for example, is being evaluated in the preoperative setting in combination with chemoradiation for rectal cancer (NCT03516708), PD-1 inhibition (retifanlimab), radiation, and bevacizumab for recurrent glioma (NCT03532295), and with retifanlimab or other therapies in advanced endometrial cancer (NCT04463771). Studies assessing indoximod (IDO pathway modulator) and BMS-986205 (IDO1 inhibitor) are ongoing and further evaluation is pending (Table 1).

Future perspectives: How can we optimize IDO inhibitors in the cancer immunotherapy era?

The negative result of the ECHO-301/KEYNOTE-252 trial raised questions about the usefulness of targeting IDO metabolism in cancer immunotherapy. Previously, several possible causes of the disappointing observations were proposed: insufficient inhibition of IDO1, no selection of patients based on IDO1 expression, lack of consideration for expression of other molecules including TDO2, and inadequate blockade of the IDO1 downstream pathway [41]. Here, we discuss possible reasons for failure in previous clinical trials, and suggest potential new tactics for targeting tryptophan catabolism in cancer immunotherapy.

Ensuring adequate blockade of tryptophan catabolism in the tumor microenvironment

In the ECHO-301/KEYNOTE-252 trial, the dose of epacadostat was set at 100 mg twice daily. This dosing was based on several phase 1 studies evaluating epacadostat as monotherapy or as part of the combination with ipilimumab (anti-CTLA4) or pembrolizumab (anti-PD1). In a phase 1 study assessing epacadostat as monotherapy, sufficient inhibition of IDO1 was achieved when epacadostat was dosed at 100 mg or more, twice daily [45]. The dose of epacadostat combined with ipilimumab was evaluated at 25–300 mg twice daily in a phase 1/2 trial for patients with advanced melanoma [55]. A dose of 100 mg twice daily was chosen when combined with pembrolizumab in a phase 2 trial but dose-dependent efficacy was not evaluated in these early phase trials officially [46]. Although clinical activity was seen in different doses of epacadostat in these trials and the ECHO-301/KEYNOTE-252 trial selected 100 mg twice daily dose based on the result of the phase 2 trial, there is a question if 100 mg twice daily is the best dose or not [46]. Indeed, CTLA-4 inhibitors, PD-1/PD-L1 inhibitors, and cancer vaccine therapy induced an increase in IDO1 expression and metabolic activity, implying that a higher dose of IDO1 inhibitors might be needed when combined with immunotherapy [56–58].

Another question is whether IDO1 inhibitors actually block the activity of IDO1 and change tryptophan and kynurenine levels in cancer cells. Pharmacokinetics and pharmacodynamics analyses in the phase 1/2 ECHO-202/KEYNOTE-037 trial showed $\geq$ 50 % inhibition of IDO1 when epacadostat was given at 100 mg twice daily [46]. However, this trial and the phase 3 ECHO-301/KEYNOTE-252 trial did not measure intratumoral or serum tryptophan and kynurenine levels before and during the treatment. One study revealed an association between an increased tryptophan level with the activation of CD8 + T cells in a mouse model, suggesting the importance of periodic measurement of tryptophan metabolites before and during treatments [59]. Additionally, IDO1 blockade might be insufficient to suppress the production of tryptophan derivatives that are ligands of AhR. Activation of AhR suppresses anti-tumor immunity and induces tumor progression, and thus, tryptophan metabolites need to be fully reduced to exert the efficacy of IDO pathway inhibitors. However, a recent study revealed interleukin-4-induced-1 (IL4I1) as a stronger activator of AhR than IDO1 and TDO2 [28]. Through the production of metabolites such as I3P, IL4I1 activates AhR, leads to an increase in Tregs and MDSCs, and suppresses the anti-tumor immunity. It was also shown in this study that immune checkpoint blockade induced both IDO1 and IL4I1, suggesting that the presence of IL4I1 weakens the degradation of tryptophan metabolites through IDO1 blockade and explains the failure of the ECHO-301/KEYNOTE-252 trial [28].

Table 1
Current status of development of agents targeting the IDO pathway: Study examples (see also **Supplemental** Table 1) (data search as of February 27th, 2022 (PubMed and Clinicaltrials.gov)).

Drug	Target	Company	Number of clinical trials registered in NCT (clinicaltrias.gov)	References
Epacadostat (INCB024360)	IDO1	Incyte	**61** 7: Active, not recruiting 19: Completed 8: Active, recruiting 13: Terminated 13: Withdrawn 1: Unknown status	[45–47,54,55,98–103]
Indoximod (NLG-8189)	IDO pathway	Lumos Pharma (Previously NewLink)	**15** 1: Active, not recruiting 10: Completed 2: Active, recruiting 2: Terminated	[49–51,67,104–109]
Navoximod (GDC-0919)	IDO1	Genentech	**2** 2: Completed	[65,68]
Linrodostat (BMS-986205)	IDO1	Bristol-Myers Squibb	**20** 5: Active, not recruiting 5: Completed 6: Active, recruiting 1: Terminated 3: Withdrawn	[52,53,110,111]
PF-06840003	IDO1	iTeos Therapeutics (Previously Pfizer)	**1** 1: Terminated	[112]
NLG802	IDO pathway	Lumos Pharma (Previously NewLink)	**1** 1: Completed	[49]
KHK2455	IDO1	Kyowa Hakko Kirin	**3** 1: Completed 1: No longer available 1: Active, not recruiting	[113]
SHR9146 (HTI-1090)	IDO1 and TDO	Jiangsu Hengrui Medicine Co., ltd	**2** 1: Unknown status 1: Completed	[114]
MK-7162	IDO1	Merck	**1** 1: Completed	[115]
LY3381916	IDO1	Eli Lilly	**1** 1: Terminated	[69]
DN1406131	IDO1 and TDO2	Shanghai De Novo Pharmatech	**1** 1: Unknown	NCT03641794
IDO vaccine	IDO	Copenhagen University Hospital at Herlev	**2** 1: Completed 1: Terminated	[116,117]
IO102-IO103 (vaccine)	IDO and PD-L1	IO Biotech	**3** 1: Completed 1: Not yet recruiting 1: Active, recruiting	[97]

Abbreviations: IDO, indoleamine-2,3-dioxygenase; NCT, National Clinical Trial; PD-L1, programmed death-ligand 1; TDO, tryptophan-2,3-dioxygenase.

In the ECHO-301/KEYNOTE-252 trial, patients treated with adjuvant ipilimumab (7–10 %) and previous BRAF inhibitors (12 %) were included. BRAF inhibitors have a role as an agonist binding directly to AhR, resulting in stimulation of its nuclear translocation. The use of BRAF inhibitors is associated with an increase in the AhR-activated and BRAF inhibitor-persister cells in the malignant melanoma xenograft model [60]. Activation of AhR can lead to an increase in PD-L1-expressing CD8 + T cells and an induction of IDO1 [32,35]. The AhR pathway can also potentially activate IDO2 and TDO2, which may decrease the efficacy of IDO1 inhibitors [31,61]. Thus, the ECHO-301/KEYNOTE-252 trial may have included a subpopulation of patients more resistant to IDO1 inhibition. These insights indicate that inadequate suppression of tryptophan catabolism can be one of the reasons for the primary resistance to IDO1 blockade combined with immune checkpoint inhibitors, and the dynamic interrogation of intracellular tryptophan catabolites may be useful in predicting the outcome of IDO1 inhibitors and developing novel therapeutic strategies.

Selecting patients based on high IDO1 expression in their cancer

The presence of IDO1 expression in tumor cells or other cells in the tumor microenvironment may be important when using IDO1 inhibitors. However, the expression pattern of IDO1 varies across tumor types and even within the same tumor type. In the ECHO-301/KEYNOTE-252 trial, IDO1 status was positive in 62 % of patients treated with epacadostat plus pembrolizumab and in 66 % of those treated with pembrolizumab alone, when IDO1 positivity was defined as a tumor or intra-tumoral immune cell expression higher than 1 % of cells [47]. Assessment of IDO1 expression by IHC in common solid tumors revealed various positive rates in cervical cancer (52–100 %), endometrial cancer (18–94 %), urothelial carcinoma (94 %), ovarian cancer (57–66 %), colorectal cancer (13–90 %), renal cell carcinoma (44–81 %), breast cancer (37 %-46 %), pancreatic carcinoma (37 %), and glioblastoma (8 %) [62]. This heterogeneity of IDO1 positivity is likely due to different methods to determine the expression of IDO1, such as IHC and reverse transcription–polymerase chain reaction, and various definitions of positivity such as positivity only in cancer cells or in tumor-infiltrating lymphocytes.

To illustrate the IDO1 expression across diverse cancer types, we performed a comprehensive analysis of IDO1 RNA expression across diverse solid tumor types in 514 patients diagnosed with advanced cancer at the Moores Cancer Center at the University of California San Diego (Fig. 3). The percentile of the IDO1 expression based on transcript level in each patient was ranked on a scale of 1 to 100 as previously

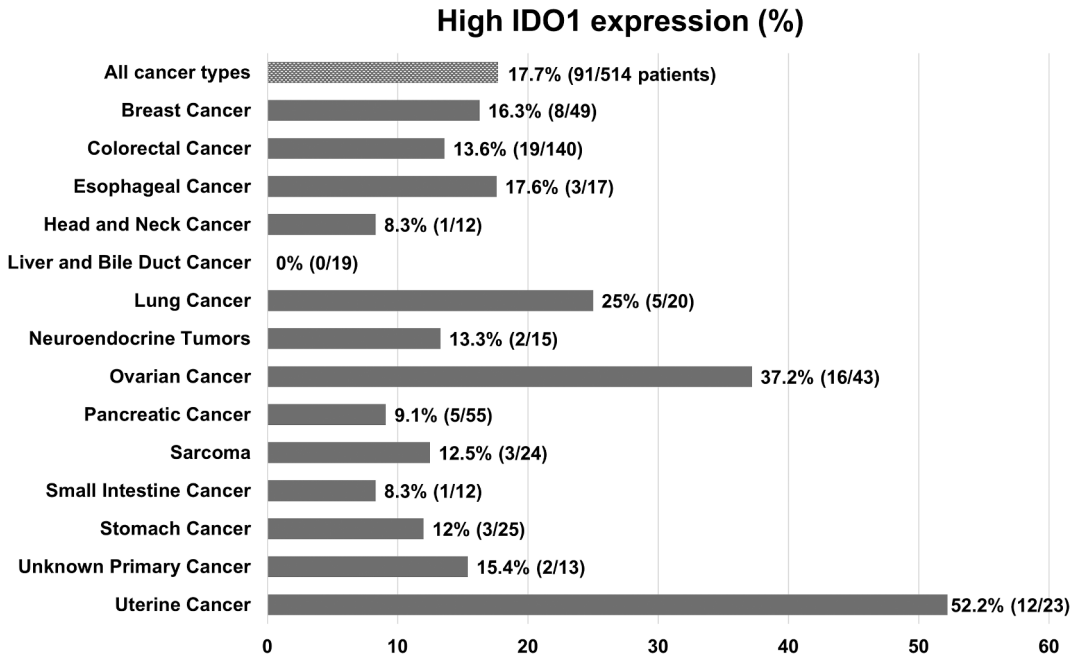

Fig. 3. High IDO1 RNA (≥75 percentile rank) expression rate across cancer types. Different patterns of IDO1 RNA expression based on the primary site of cancer are shown (n = 514). Transcriptomic sequencing was used to evaluate the expression of IDO1 based on RNA transcript abundance normalized to internal housekeeping gene profiles and ranked (0–100 percentile) in a standardized manner to a reference population of 735 tumors spanning 35 histologies. The expression profiles were stratified by rank values into "Low" (0–74), and "High" (75–100) as previously described [63]. The percentage of the population with high expression is shown in this graph. Among diverse types of cancer, RNA expression of IDO1 was highest in patients with uterine cancer (52.2 %, 12/23 patients) followed by ovarian cancer (37.2 %, 16/43), lung cancer (25 %, 5/20), and esophageal cancer (17.6 %, 3/17). **Abbreviations**: IDO1, Indoleamine 2,3-dioxygenase 1; RNA, Ribonucleic acid.

described [63] (normalized to the reference population of 735 tumors spanning 35 histologies), and classified into low (0–24), moderate (25–74), and high (75–100). The percentage of high IDO1 expression was 17.7 % (91/514 patients) in all cancer types, and was highest in patients with uterine cancer (52.2 %, 12/23), followed by ovarian cancer (37.2 %, 16/43), lung cancer (25 %, 5/20), and esophageal cancer (17.6 %, 3/17). There was high variability of IDO1 RNA expression between and within tumor types.

However, the positivity of IDO1 expression was not set as one of the inclusion criteria in most clinical trials using IDO inhibitors. Subgroup analysis based on IDO1 expression in the ECHO-1/KEYNOTE-252 trial did not show a survival difference between each group (HR = 0.99, 95 % CI: 0.69–1.42), but a threshold of the positivity of IDO1 was set as more than 1 %, and most patients were categorized as positive IDO1 expression. Moreover, information on the PD-L1 expression ratio in patients with positive IDO1 expression was lacking. IDO1 expression was retrospectively analyzed and was not set as a stratification factor before enrolling patients in this trial; therefore, it is unknown if the clinical characteristics of patients with IDO1 expression in each group were equally distributed. Although recent development of molecular-targeted therapy led to biomarker-driven cancer treatments with improved outcomes, the majority of immunotherapy trials are still conducted without setting prespecified biomarkers, which potentially miss the identification of good responders [64]. It is plausible that the selection of patients based on their tumor's expression of IDO is needed in order to optimize IDO inhibitor responsiveness.

Choosing the most suitable IDO1 inhibitor

Although mechanisms of action are broadly categorized as IDO1 inhibitors/modulators, available agents might have a different impact on IDO1 inhibition, tryptophan catabolism, and other molecular pathways in the tumor microenvironment. For example, indoximod and navoximod are regarded as IDO pathway modulators, since they are not the actual inhibitors of the IDO1 enzyme, but can exert their effect as a substance mimicking tryptophan [49,65]. This results in iDO-mediated tryptophan deprivation, leading to a revitalization of mTOR signals necessary for the antitumor T cell activity [66]. Therefore, indoximod or navoximod might be able to exert better anti-cancer immunity, especially when combined with T cell-targeting immunotherapy theoretically. The combination of indoximod plus an immune checkpoint inhibitor demonstrated an ORR of 55.7 % among patients with advanced melanoma in a phase 2 trial [67]. However, a phase 1 trial evaluating the combination of navoximod and atezolizumab for patients with advanced solid tumors only showed little clinical benefit (ORR = 9 %, n = 6/66 in the dose-escalation population, ORR = 11 %, n = 10/91 in the dose-expansion cohort) [68].

Another factor that needs to be considered is the actual pharmacodynamics of the IDO1 inhibitors/modulators. Reduction in intratumoral kynurenine levels or changes in intra-tumoral tryptophan/kynurenine ratio might differ in each IDO1 inhibitor. Epacadostat monotherapy inhibits more than 90 % of the plasma kynurenine level when dosed with 100 mg or more twice daily, but pharmacodynamics analysis regarding intratumoral levels of tryptophan metabolites remains scarce [45]. BMS-986205, one of the other IDO1 inhibitors, was associated with a reduction of the intratumoral kynurenine level of up to 90 % when administered either as monotherapy or combined with nivolumab for patients with advanced cancer [52]. Another IDO1 inhibitor, PF-0684003 demonstrated an 80 % reduction of the intratumoral kynurenine level in a mouse model [57]. Recently, LY338196 also showed a 76 % and 67 % decrease in the kynurenine level in plasma and cancer cells when dosed as monotherapy or in combination with a PD-L1 inhibitor (LY3300054) for advanced cancer [69]. In contrast, indoximod and navoximod were not associated with a significant reduction in the intratumoral kynurenine level in phase 1 trials [50,65]. Further studies are needed to elucidate the association between clinical efficacy and changes in levels of intratumoral tryptophan metabolites.

Targeting TDO2 or IDO2

Other enzymes in addition to IDO1, including IDO2 and TDO2, are potentially important regulators of tryptophan catabolism in the tumor microenvironment. Although BMS-986205, an IDO1 inhibitor, demonstrated a sufficient reduction in plasma kynurenine level and T cell proliferation without having activities against IDO2 and TDO2 in preclinical models, several reports revealed the association of TDO2 or IDO2 with cancer immunity and clinical phenomena [70]. TDO2 is seen in multiple cancer types as an immunosuppressive molecule and catabolic enzyme of tryptophan, leading to tumor progression [25,71]. Tryptophan degradation through TDO2 leads to the production of immunosuppressive kynurenine, resulting in the AhR activation and inhibition of T cells [25]. TDO2 is also associated with epithelial-to-mesenchymal transition through activation of the AhR pathway, leading to invasion and metastasis of hepatic cellular carcinoma in a cell model [72]. In IDO/TDO-overexpressing tumors, the active AHR pathway through kynurenine is observed, leading to the promotion of Treg and tumor-associated macrophages, and creating an immunosuppressive environment and resistance to immune checkpoint inhibitors [73]. In addition, TDO2, rather than IDO1, is clinically correlated with a poorer outcome in patients with renal cell carcinoma treated with an immune checkpoint inhibitor [74]. Blockade of TDO2 improved antitumor T cell activity and dendritic cell function, leading to regression of tumor nodules in a mouse model [75]. Therefore, inhibition of TDO2 could be a promising strategy for cancer immunotherapy.

Targeting IDO2 would be another option to augment the efficacy of the IDO1 blockade. IFNγ is the major cytokine to induce IDO1 through the JAK-STAT pathway but it also induces IDO2 [76]. If IDO1 was blocked, the signal from IFNγ would potentially increase the level of IDO2 in a cancer cell, probably resulting in a diminishment of the effect of IDO1 inhibitors. Therefore, IDO2 inhibition would be a meaningful way to revoke the resistance to IDO1 blockade; however, inhibition of IDO2 has not been established because of the difficulty in purifying molecules to inhibit IDO2 physiologically [77]. In addition, the efficacy of the tryptophan metabolizing process by IDO2 is presumably less than that by IDO1 and, thus, it is uncertain if inhibition of IDO2 opens avenues to overcome the resistance to IDO1 blockade [78]. Currently, inhibition of both IDO1 and TDO2 is evaluated in phase 1 clinical trials. One study reported the development of pan- and IDO1/TDO2 inhibition in mouse and human cell models [79]. A recent preclinical study evaluating a dual IDO1/TDO inhibitor showed effective blockade of the kynurenine pathway and kynurenine-AhR signaling, resulting in a reduction in migration and invasion of pancreatic carcinoma cells in mice [80]. A phase 1 study assessing M4112, the first dual inhibitor of IDO1 and TDO2 evaluated in the clinical setting, reported safety in patients with advanced cancer but this agent was not associated with a reduction in plasma kynurenine level, resulting in termination of the trial [81]. A recent study explored the compounds which can potentially block both IDO1 and TDO2 and 10 compounds were confirmed to inhibit IDO1 and TDO2 [82]. Only a few agents are undergoing evaluation in phase trials, but these results could expedite the developmental process of dual IDO1 and TDO2 inhibitors in the future.

Blocking the aryl hydrocarbon receptor (AhR) pathway

The AhR is a ligand-dependent transcription factor that mediates many of the biological and toxicological actions of a variety of hydrophobic natural and synthetic chemicals. Tryptophan catabolites are known ligands of AhR, and the AhR pathway is associated with the accumulation and proliferation of immunosuppressive cells in the tumor microenvironment. Activation of the AhR pathway is related to viability, migration, and proliferation of cancer cells, and antagonists of AhR lead to a reduction in tumor aggressiveness [83]. AhR is also associated with the induction of IDO2 and TDO2, which might result in mitigation of the efficacy of IDO1 inhibition [61,84]. Therefore, although the AhR pathway is downstream of iDO-kynurenine signaling, blockade of the AhR can theoretically augment the efficacy of IDO1 inhibition. Interestingly, a recent study reported that activated AhR through IDO1-kynurenine signaling induced PD-1 expression on CD8 + T cells in the tumor microenvironment of the ovarian cancer model [85]. This suggests an association of inhibitory checkpoint signaling with the activation of the iDO-AhR pathway, and the AhR inhibition with immune checkpoint blockade might be a better synergistic therapeutic option.

Several companies have developed AhR inhibitors and shown their efficacy in the reduction of activity of immunosuppressive cells and induction of pro-inflammatory response toward tumor cells in preclinical models [86,87]. Phase 1 trials to evaluate AhR inhibitors, such as IK-175 as monotherapy or in combination with nivolumab, and BAY2416964 as monotherapy or in combination with pembrolizumab, have started and are recruiting patients with advanced solid tumor or urothelial carcinoma (NCT04069026) (NCT04200963) (NCT04999202).

Targeting other pathways or molecules to augment the efficacy of IDO1

IDO1 can be induced by the activation of several cell signaling pathways such as the prostaglandin E2 (PGE2) pathway. The expression of cyclooxygenase-2 drives the expression of IDO1 and TDO2 in tumor cells through the activation of E prostanoid receptor and protein kinase C and phosphoinositide 3-kinase (PI3K) pathways (Fig. 2) [88,89]. Hence, regulation of the PGE2 pathway and its related molecules can probably improve the efficacy of IDO1 inhibitors.

A recent study investigating the relationship between the expression of immunoregulatory molecules and mutations in “targetable” molecules showed significant upregulation of IDO1 expression in the presence of phosphatidylinositol-4,5-bisphosphate 3-kinase catalytic subunit alpha (*PIK3CA*) mutations (E545K and R88Q) [90]. This could be due to the activation of IDO1 transcription through the EP receptor-PI3K pathway, and suggests that targeting PIK3CA with a combined regimen utilizing a PIK3CA inhibitor and an IDO1 inhibitor may be a reasonable strategy for patients with high IDO1 expression accompanied by *PIK3CA* alterations in order to unlock the immunosuppressive microenvironment [88]. An association between downregulation of IDO1 expression and *BRAF V600E* mutations was also observed, suggesting that there might be less efficacy of IDO1 inhibitors in tumors bearing *BRAF V600E* mutations [90]. Upregulation of IDO1 expression in melanomas resistant to BRAF inhibitors has also been reported [91]. Further investigation is necessary to better understand the complexity of the interaction between the MAPK pathway and tryptophan metabolism.

Another potential strategy to enhance the efficacy of IDO1 inhibitors would be the combination with angiogenesis inhibitors. IDO1-expressing cells are related to an increase in neovascularization and genetic loss of IDO1 is associated with reduction of IL-6 and neovascularization [92,93]. Although clinical trials combining IDO1 inhibitors with vascular endothelial growth factor (VEGF) inhibitors have not been conducted, a phase 2 trial evaluating nivolumab plus the IDO1 inhibitor, BMS986205, will assess changes in inflammatory markers including VEGF before and after the treatment, and give an insight into the clinical effect of IDO1 inhibition on angiogenesis (NCT03854032).

Additionally, the non-enzymic function of IDO1 decreased the survival of animal models with glioblastoma through an increase in complement factor H and its isoform, factor H like protein, independent of tryptophan catabolism [94]. This observation suggests an association between the non-enzymic function of IDO1 and the survival of cancer cells.

Combining drugs to optimize checkpoint blockade

IDO1 inhibitors have been mainly evaluated as monotherapy or in combination with PD-1 or PD-L1 inhibitors in clinical trials. Combinations of IDO inhibitors with a CTLA-4 checkpoint inhibitor or a cancer

vaccine therapy are under evaluation. Two clinical trials assessed the combination of an IDO1 inhibitor with a CTLA-4 inhibitor, but clinical efficacy was limited. A phase 2 trial that assessed epacadostat with ipilimumab (anti-CTLA4) showed limited clinical activity in patients with malignant melanoma (ORR = 25.6 %, n = 10/39 in immunotherapy-naïve patients; ORR = 0 %, n = 0/11, in patients previously treated with immunotherapy) [55]. In contrast, a phase 2 trial evaluating indoximod with either pembrolizumab, nivolumab, or ipilimumab for advanced melanoma showed promising efficacy (ORR = 55.7 %, n = 39/70) [67]. To augment the efficacy of IDO1 inhibition with checkpoint blockade, the identification of checkpoints and other immune molecules associated with higher IDO1 expression by utilizing an immunogram technique may be in future research [95]. Additionally, a phase 1 study that assessed the safety of ipilimumab with a peptide vaccine derived from IDO demonstrated the safety but the efficacy of this combination did not exceed that of ipilimumab monotherapy [96]. A recent phase 1/2 trial of an immune-modulatory vaccine against IDO and PD-L1 (IO102-IO103) in combination with nivolumab in metastatic malignant melanoma demonstrated ORR of 80 % (n = 24/30) with a median PFS of 26 months [97]. A phase 2 study evaluating pembrolizumab plus IO102-IO103 for patients with metastatic NSCLC, head and neck cancer, and urothelial bladder cancer has just begun (NCT05077709). Larger studies are warranted to confirm the efficacy of vaccine therapy against IDO combined with a systemic immune checkpoint inhibitor (NCT05155254).

Conclusions: Potential strategies for future clinical trials

Immuno-oncology is a rapidly expanding field with multiple successes in the treatment of advanced malignancies. Immune checkpoint blockade re-activates the immune system suppressed by the tumor and allows immune cells to perform their function of eradicating cancer cells. Checkpoint blockade with anti-PD-1/PD-L1/CTLA-4 agents produces remarkable responses in a variety of neoplasms. However, many patients do not respond, possibly because of the activation of alternate immunosuppressive pathways. In this regard, it has been recognized that IDO1 and the tryptophan-kynurenine pathway are crucial to immune evasion. As a result, a multitude of IDO1 inhibiting tryptophan analogs, including small-molecule inhibitors and peptide vaccines, are currently being assessed in clinical trials. However, some of these trials have shown disappointing efficacy results. Future optimization of this important area requires ensuring sufficient pharmacologic inhibition of IDO1 by agents used in the clinic, stratifying patients based on IDO1 expression, co-targeting important molecular pathways (such as the PI3K/mTOR signals) that may play a co-dependent role, and suppression of compensatory mechanisms mediated through molecules such as IDO2 or TDO.

Declaration of Competing Interest.

YF does not have known competing financial interests or personal relationships that could affect the work reported in this paper.

MKN, SP, JMC, and PD are all employees of Omniseq, Inc., a division of Labcorp Oncology, and hold restricted stock in LabCorp.

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Appendix A. Supplementary material

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References

[1] Sharma P, Hu-Lieskovan S, Wargo JA, Ribas A. Primary, adaptive, and acquired resistance to cancer immunotherapy. Cell 2017;168:707–23.
[2] Sicklick JK, Kato S, Okamura R, Schwaederle M, Hahn ME, Williams CB, et al. Molecular profiling of cancer patients enables personalized combination therapy: the I-PREDICT study. Nat Med 2019;25:744–50.
[3] Kato S, Kim KH, Lim HJ, Boichard A, Nikanjam M, Weihe E, et al. Real-world data from a molecular tumor board demonstrates improved outcomes with a precision N-of-One strategy. Nat Commun 2020;11:4965.
[4] Sicklick JK, Kato S, Okamura R, Patel H, Nikanjam M, Fanta PT, et al. Molecular profiling of advanced malignancies guides first-line N-of-1 treatments in the I-PREDICT treatment-naïve study. Genome Med 2021;13:155.
[5] Holmgaard RB, Zamarin D, Munn DH, Wolchok JD, Allison JP. Indoleamine 2,3-dioxygenase is a critical resistance mechanism in antitumor T cell immunotherapy targeting CTLA-4. J Exp Med 2013;210:1389–402.
[6] Platten M, Nollen EAA, Röhrig UF, Fallarino F, Opitz CA. Tryptophan metabolism as a common therapeutic target in cancer, neurodegeneration and beyond. Nat Rev Drug Discov 2019;18:379–401.
[7] Maria NI, van Helden-Meeuwsen CG, Brkic Z, Paulissen SM, Steenwijk EC, Dalm VA, et al. Association of Increased Treg Cell Levels With Elevated Indoleamine 2,3-Dioxygenase Activity and an Imbalanced Kynurenine Pathway in Interferon-Positive Primary Sjögren's Syndrome. Arthritis Rheumatol 2016;68:1688–99.
[8] Mancuso R, Hernis A, Agostini S, Rovaris M, Caputo D, Fuchs D, et al. Indoleamine 2,3 dioxygenase (IDO) expression and activity in relapsing-remitting multiple sclerosis. PLoS ONE 2015;10:e0130715.
[9] Opitz CA, Somarribas Patterson LF, Mohapatra SR, Dewi DL, Sadik A, Platten M, et al. The therapeutic potential of targeting tryptophan catabolism in cancer. Br J Cancer 2020;122:30–44.
[10] Brandacher G, Perathoner A, Ladurner R, Schneeberger S, Obrist P, Winkler C, et al. Prognostic value of indoleamine 2,3-dioxygenase expression in colorectal cancer: effect on tumor-infiltrating T cells. Clin Cancer Res 2006;12:1144–51.
[11] Weinlich G, Murr C, Richardsen L, Winkler C, Fuchs D. Decreased serum tryptophan concentration predicts poor prognosis in malignant melanoma patients. Dermatology 2007;214:8–14.
[12] Suzuki Y, Suda T, Furuhashi K, Suzuki M, Fujie M, Hahimoto D, et al. Increased serum kynurenine/tryptophan ratio correlates with disease progression in lung cancer. Lung Cancer 2010;67:361–5.
[13] Witkiewicz A, Williams TK, Cozzitorto J, Durkan B, Showalter SL, Yeo CJ, et al. Expression of indoleamine 2,3-dioxygenase in metastatic pancreatic ductal

adenocarcinoma recruits regulatory T cells to avoid immune detection. J Am Coll Surg. 2008;206:849-54; discussion 54-6.
[14] Ino K, Yoshida N, Kajiyama H, Shibata K, Yamamoto E, Kidokoro K, et al. Indoleamine 2,3-dioxygenase is a novel prognostic indicator for endometrial cancer. Br J Cancer 2006;95:1555–61.
[15] Liu Y, Liang X, Dong W, Fang Y, Lv J, Zhang T, et al. Tumor-Repopulating Cells Induce PD-1 Expression in CD8(+) T Cells by Transferring Kynurenine and AhR Activation. Cancer Cell. 2018;33:480-94.e7.
[16] Zhang R, Li T, Wang W, Gan W, Lv S, Zeng Z, et al. Indoleamine 2, 3-Dioxygenase 1 and CD8 Expression Profiling Revealed an Immunological Subtype of Colon Cancer With a Poor Prognosis. Front Oncol 2020;10:594098.
[17] Munn DH, Sharma MD, Baban B, Harding HP, Zhang Y, Ron D, et al. GCN2 kinase in T cells mediates proliferative arrest and anergy induction in response to indoleamine 2,3-dioxygenase. Immunity 2005;22:633–42.
[18] Rodriguez PC, Quiceno DG, Ochoa AC. L-arginine availability regulates T-lymphocyte cell-cycle progression. Blood 2007;109:1568–73.
[19] Mezrich JD, Fechner JH, Zhang X, Johnson BP, Burlingham WJ, Bradfield CA. An interaction between kynurenine and the aryl hydrocarbon receptor can generate regulatory T cells. J Immunol 2010;185:3190–8.
[20] Nakamura T, Shima T, Saeki A, Hidaka T, Nakashima A, Takikawa O, et al. Expression of indoleamine 2, 3-dioxygenase and the recruitment of Foxp3-expressing regulatory T cells in the development and progression of uterine cervical cancer. Cancer Sci 2007;98:874–81.
[21] Meireson A, Ferdinande L, Haspeslagh M, Hennart B, Allorge D, Ost P, et al. Clinical relevance of serum Kyn/Trp ratio and basal and IFNγ-upregulated IDO1 expression in peripheral monocytes in early stage melanoma. Front Immunol 2021;12:736498.
[22] Quintana FJ, Murugaiyan G, Farez MF, Mitsdoerffer M, Tukpah AM, Burns EJ, et al. An endogenous aryl hydrocarbon receptor ligand acts on dendritic cells and T cells to suppress experimental autoimmune encephalomyelitis. Proc Natl Acad Sci USA 2010;107:20768–73.
[23] Ino K, Yamamoto E, Shibata K, Kajiyama H, Yoshida N, Terauchi M, et al. Inverse correlation between tumoral indoleamine 2,3-dioxygenase expression and tumor-infiltrating lymphocytes in endometrial cancer: its association with disease progression and survival. Clin Cancer Res 2008;14:2310–7.
[24] Greene LI, Bruno TC, Christenson JL, D'Alessandro A, Culp-Hill R, Torkko K, et al. A role for tryptophan-2,3-dioxygenase in CD8 T-cell suppression and evidence of tryptophan catabolism in breast cancer patient plasma. Mol Cancer Res 2019;17:131–9.
[25] Opitz CA, Litzenburger UM, Sahm F, Ott M, Tritschler I, Trump S, et al. An endogenous tumour-promoting ligand of the human aryl hydrocarbon receptor. Nature 2011;478:197–203.
[26] DiNatale BC, Murray IA, Schroeder JC, Flaveny CA, Lahoti TS, Laurenzana EM, et al. Kynurenic acid is a potent endogenous aryl hydrocarbon receptor ligand that synergistically induces interleukin-6 in the presence of inflammatory signaling. Toxicol Sci 2010;115:89–97.
[27] Lowe MM, Mold JE, Kanwar B, Huang Y, Louie A, Pollastri MP, et al. Identification of cinnabarinic acid as a novel endogenous aryl hydrocarbon receptor ligand that drives IL-22 production. PLoS ONE 2014;9:e87877.
[28] Sadik A, Somarribas Patterson LF, Öztürk S, Mohapatra SR, Panitz V, Secker PF, et al. IL4I1 Is a Metabolic Immune Checkpoint that Activates the AHR and Promotes Tumor Progression. Cell. 2020;182:1252-70.e34.
[29] Zhang X, Gan M, Li J, Li H, Su M, Tan D, et al. Endogenous indole pyruvate pathway for tryptophan metabolism mediated by IL4I1. J Agric Food Chem 2020;68:10678–84.
[30] Li Q, Harden JL, Anderson CD, Egilmez NK. Tolerogenic phenotype of IFN-γ-induced IDO+ dendritic cells is maintained via an autocrine IDO-kynurenine/AhR-IDO Loop. J Immunol 2016;197:962–70.
[31] Nguyen NT, Kimura A, Nakahama T, Chinen I, Masuda K, Nohara K, et al. Aryl hydrocarbon receptor negatively regulates dendritic cell immunogenicity via a kynurenine-dependent mechanism. Proc Natl Acad Sci U S A 2010;107:19961–6.
[32] Kenison JE, Wang Z, Yang K, Snyder M, Quintana FJ, Sherr DH. The aryl hydrocarbon receptor suppresses immunity to oral squamous cell carcinoma through immune checkpoint regulation. Proc Natl Acad Sci USA 2021;118.
[33] Hollingshead BD, Beischlag TV, Dinatale BC, Ramadoss P, Perdew GH. Inflammatory signaling and aryl hydrocarbon receptor mediate synergistic induction of interleukin 6 in MCF-7 cells. Cancer Res 2008;68:3609–17.
[34] Kumari N, Dwarakanath BS, Das A, Bhatt AN. Role of interleukin-6 in cancer progression and therapeutic resistance. Tumour Biol 2016;37:11553–72.
[35] Litzenburger UM, Opitz CA, Sahm F, Rauschenbach KJ, Trump S, Winter M, et al. Constitutive IDO expression in human cancer is sustained by an autocrine signaling loop involving IL-6, STAT3 and the AHR. Oncotarget 2014;5:1038–51.
[36] Uyttenhove C, Pilotte L, Théate I, Stroobant V, Colau D, Parmentier N, et al. Evidence for a tumoral immune resistance mechanism based on tryptophan degradation by indoleamine 2,3-dioxygenase. Nat Med 2003;9:1269–74.
[37] Schafer CC, Wang Y, Hough KP, Sawant A, Grant SC, Thannickal VJ, et al. Indoleamine 2,3-dioxygenase regulates anti-tumor immunity in lung cancer by metabolic reprogramming of immune cells in the tumor microenvironment. Oncotarget 2016;7:75407–24.
[38] Shibata Y, Hara T, Nagano J, Nakamura N, Ohno T, Ninomiya S, et al. The role of indoleamine 2,3-dioxygenase in diethylnitrosamine-induced liver carcinogenesis. PLoS ONE 2016;11:e0146279.
[39] Spranger S, Koblish HK, Horton B, Scherle PA, Newton R, Gajewski TF. Mechanism of tumor rejection with doublets of CTLA-4, PD-1/PD-L1, or IDO blockade involves restored IL-2 production and proliferation of CD8(+) T cells directly within the tumor microenvironment. J Immunother Cancer 2014;2:3.
[40] Wainwright DA, Chang AL, Dey M, Balyasnikova IV, Kim CK, Tobias A, et al. Durable therapeutic efficacy utilizing combinatorial blockade against IDO, CTLA-4, and PD-L1 in mice with brain tumors. Clin Cancer Res 2014;20:5290–301.
[41] Van den Eynde BJ, van Baren N, Baurain J-F. Is there a clinical future for IDO1 inhibitors after the failure of epacadostat in melanoma? Ann Rev Cancer Biol 2020;4:241–56.
[42] Liu X, Shin N, Koblish HK, Yang G, Wang Q, Wang K, et al. Selective inhibition of IDO1 effectively regulates mediators of antitumor immunity. Blood 2010;115:3520–30.
[43] Sieviläinen M, Saavalainen J, Adnan-Awad S, Salo T, Al-Samadi A. IDO1 inhibition reduces immune cell exclusion through inducing cell migration While PD-1 blockage increases IL-6 and -8 secretion from T cells in head and neck cancer. Front Immunol 2022;13:812822.
[44] Beatty GL, O'Dwyer PJ, Clark J, Shi JG, Newton RC, Schaub R, et al. Phase I study of the safety, pharmacokinetics (PK), and pharmacodynamics (PD) of the oral inhibitor of indoleamine 2,3-dioxygenase (IDO1) INCB024360 in patients (pts) with advanced malignancies. Journal of Clinical Oncology. 2013;31:15_suppl, 3025-3025.
[45] Beatty GL, O'Dwyer PJ, Clark J, Shi JG, Bowman KJ, Scherle PA, et al. First-in-Human Phase I Study of the Oral Inhibitor of Indoleamine 2,3-Dioxygenase-1 Epacadostat (INCB024360) in Patients with Advanced Solid Malignancies. Clin Cancer Res 2017;23:3269–76.
[46] Mitchell TC, Hamid O, Smith DC, Bauer TM, Wasser JS, Olszanski AJ, et al. Epacadostat plus pembrolizumab in patients with advanced solid tumors: Phase I results from a multicenter, open-label phase I/II trial (ECHO-202/KEYNOTE-037). J Clin Oncol 2018;36:3223–30.
[47] Long GV, Dummer R, Hamid O, Gajewski TF, Caglevic C, Dalle S, et al. Epacadostat plus pembrolizumab versus placebo plus pembrolizumab in patients with unresectable or metastatic melanoma (ECHO-301/KEYNOTE-252): a phase 3, randomised, double-blind study. Lancet Oncol 2019;20:1083–97.
[48] https://ClinicalTrials.gov/show/NCT03322540. Pembrolizumab Plus Epacadostat vs Pembrolizumab Plus Placebo in Metastatic Non-Small Cell Lung Cancer (KEYNOTE-654-05/ECHO-305-05). Accessed on Feb 27th, 2022.
[49] Kumar S, Jaipuri FA, Waldo JP, Potturi H, Marcinowicz A, Adams J, et al. Discovery of indoximod prodrugs and characterization of clinical candidate NLG802. Eur J Med Chem 2020;198:112373.
[50] Soliman HH, Jackson E, Neuger T, Dees EC, Harvey RD, Han H, et al. A first in man phase I trial of the oral immunomodulator, indoximod, combined with docetaxel in patients with metastatic solid tumors. Oncotarget 2014;5:8136–46.
[51] Mariotti V, Han H, Ismail-Khan R, Tang SC, Dillon P, Montero AJ, et al. Effect of taxane chemotherapy with or without indoximod in metastatic breast cancer: a randomized clinical trial. JAMA Oncol 2021;7:61–9.
[52] Siu LL, Gelmon K, Chu Q, Pachynski R, Alese O, Basciano P, et al. Abstract CT116: BMS-986205, an optimized indoleamine 2,3-dioxygenase 1 (IDO1) inhibitor, is well tolerated with potent pharmacodynamic (PD) activity, alone and in combination with nivolumab (nivo) in advanced cancers in a phase 1/2a trial. Cancer Research. 2017;77:CT116.
[53] Tabernero J, Luke JJ, Joshua AM, Varga AI, Moreno V, Desai J, et al. BMS-986205, an indoleamine 2,3-dioxygenase 1 inhibitor (IDO1i), in combination with nivolumab (NIVO): Updated safety across all tumor cohorts and efficacy in pts with advanced bladder cancer (advBC). Journal of Clinical Oncology. 2018;36:15_suppl, 4512-4512.
[54] Kristeleit R, Davidenko I, Shirinkin V, El-Khouly F, Bondarenko I, Goodheart MJ, et al. A randomised, open-label, phase 2 study of the IDO1 inhibitor epacadostat (INCB024360) versus tamoxifen as therapy for biochemically recurrent (CA-125 relapse)-only epithelial ovarian cancer, primary peritoneal carcinoma, or fallopian tube cancer. Gynecol Oncol 2017;146:484–90.
[55] Gibney GT, Hamid O, Lutzky J, Olszanski AJ, Mitchell TC, Gajewski TF, et al. Phase 1/2 study of epacadostat in combination with ipilimumab in patients with unresectable or metastatic melanoma. J Immunother Cancer 2019;7:80.
[56] Brown ZJ, Yu SJ, Heinrich B, Ma C, Fu Q, Sandhu M, et al. Indoleamine 2,3-dioxygenase provides adaptive resistance to immune checkpoint inhibitors in hepatocellular carcinoma. Cancer Immunol Immunother 2018;67:1305–15.
[57] Gomes B, Driessens G, Bartlett D, Cai D, Cauwenberghs S, Crosignani S, et al. Characterization of the selective indoleamine 2,3-dioxygenase-1 (IDO1) catalytic inhibitor EOS200271/PF-06840003 supports IDO1 as a critical resistance mechanism to PD-(L)1 blockade therapy. Mol Cancer Ther 2018;17:2530–42.
[58] Zahm CD, Johnson LE, McNeel DG. Increased indoleamine 2,3-dioxygenase activity and expression in prostate cancer following targeted immunotherapy. Cancer Immunol Immunother 2019;68:1661–9.
[59] Qin R, Zhao C, Wang CJ, Xu W, Zhao JY, Lin Y, et al. Tryptophan potentiates CD8(+) T cells against cancer cells by TRIP12 tryptophanylation and surface PD-1 downregulation. J Immunother Cancer 2021;9:e002840.
[60] Corre S, Tardif N, Mouchet N, Leclair HM, Boussemart L, Gautron A, et al. Sustained activation of the Aryl hydrocarbon Receptor transcription factor promotes resistance to BRAF-inhibitors in melanoma. Nat Commun 2018;9:4775.
[61] Vogel CF, Goth SR, Dong B, Pessah IN, Matsumura F. Aryl hydrocarbon receptor signaling mediates expression of indoleamine 2,3-dioxygenase. Biochem Biophys Res Commun 2008;375:331–5.
[62] Godin-Ethier J, Hanafi LA, Piccirillo CA, Lapointe R. Indoleamine 2,3-dioxygenase expression in human cancers: clinical and immunologic perspectives. Clin Cancer Res 2011;17:6985–91.
[63] Conroy JM, Pabla S, Glenn ST, Burgher B, Nesline M, Papanicolau-Sengos A, et al. Analytical validation of a next-generation sequencing assay to monitor immune responses in solid tumors. J Mol Diagn 2018;20:95–109.

[64] Adashek JJ, Goloubev A, Kato S, Kurzrock R. Missing the target in cancer therapy. Nat Cancer 2021;2:369–71.
[65] Nayak-Kapoor A, Hao Z, Sadek R, Dobbins R, Marshall L, Vahanian NN, et al. Phase Ia study of the indoleamine 2,3-dioxygenase 1 (IDO1) inhibitor navoximod (GDC-0919) in patients with recurrent advanced solid tumors. J Immunother Cancer 2018;6:61.
[66] Prendergast GC, Metz R. A perspective on new immune adjuvant principles: Reprogramming inflammatory states to permit clearance of cancer cells and other age-associated cellular pathologies. Oncoimmunology 2012;1:924–9.
[67] Zakharia Y, Rixe O, Ward JH, Drabick JJ, Shaheen MF, Milhem MM, et al. Phase 2 trial of the IDO pathway inhibitor indoximod plus checkpoint inhibition for the treatment of patients with advanced melanoma. Journal of Clinical Oncology. 2018;36:5_suppl, 9512-9512.
[68] Jung KH, LoRusso P, Burris H, Gordon M, Bang YJ, Hellmann MD, et al. Phase I Study of the Indoleamine 2,3-Dioxygenase 1 (IDO1) Inhibitor Navoximod (GDC-0919) Administered with PD-L1 Inhibitor (Atezolizumab) in Advanced Solid Tumors. Clin Cancer Res 2019;25:3220–8.
[69] Kotecki N, Vuagnat P, O'Neil BH, Jalal S, Rottey S, Prenen H, et al. A Phase I Study of an IDO-1 Inhibitor (LY3381916) as Monotherapy and in Combination With an Anti-PD-L1 Antibody (LY3300054) in Patients With Advanced Cancer. J Immunother 2021;44:264–75.
[70] Balog A, Lin TA, Maley D, Gullo-Brown J, Kandoussi EH, Zeng J, et al. Preclinical characterization of linrodostat mesylate, a novel, potent, and selective oral indoleamine 2,3-dioxygenase 1 inhibitor. Mol Cancer Ther 2021;20:467–76.
[71] D'Amato NC, Rogers TJ, Gordon MA, Greene LI, Cochrane DR, Spoelstra NS, et al. A TDO2-AhR signaling axis facilitates anoikis resistance and metastasis in triple-negative breast cancer. Cancer Res 2015;75:4651–64.
[72] Li L, Wang T, Li S, Chen Z, Wu J, Cao W, et al. TDO2 promotes the EMT of hepatocellular carcinoma through Kyn-AhR pathway. Front Oncol 2020;10:562823.
[73] Campesato LF, Budhu S, Tchaicha J, Weng CH, Gigoux M, Cohen IJ, et al. Blockade of the AHR restricts a Treg-macrophage suppressive axis induced by L-Kynurenine. Nat Commun 2020;11:4011.
[74] Sumitomo M, Takahara K, Zennami K, Nagakawa T, Maeda Y, Shiogama K, et al. Tryptophan 2,3-dioxygenase in tumor cells is associated with resistance to immunotherapy in renal cell carcinoma. Cancer Sci 2021;112:1038–47.
[75] Hsu YL, Hung JY, Chiang SY, Jian SF, Wu CY, Lin YS, et al. Lung cancer-derived galectin-1 contributes to cancer associated fibroblast-mediated cancer progression and immune suppression through TDO2/kynurenine axis. Oncotarget 2016;7:27584–98.
[76] Witkiewicz AK, Costantino CL, Metz R, Muller AJ, Prendergast GC, Yeo CJ, et al. Genotyping and expression analysis of IDO2 in human pancreatic cancer: a novel, active target. J Am Coll Surg. 2009;208:781-7; discussion 7-9.
[77] Röhrig UF, Majjigapu SR, Caldelari D, Dilek N, Reichenbach P, Ascencao K, et al. 1,2,3-Triazoles as inhibitors of indoleamine 2,3-dioxygenase 2 (IDO2). Bioorg Med Chem Lett 2016;26:4330–3.
[78] Pantouris G, Serys M, Yuasa HJ, Ball HJ, Mowat CG. Human indoleamine 2,3-dioxygenase-2 has substrate specificity and inhibition characteristics distinct from those of indoleamine 2,3-dioxygenase-1. Amino Acids 2014;46:2155–63.
[79] Winters M, DuHadaway JB, Pham KN, Lewis-Ballester A, Badir S, Wai J, et al. Diaryl hydroxylamines as pan or dual inhibitors of indoleamine 2,3-dioxygenase-1, indoleamine 2,3-dioxygenase-2 and tryptophan dioxygenase. Eur J Med Chem 2019;162:455–64.
[80] Liang H, Li T, Fang X, Xing Z, Zhang S, Shi L, et al. IDO1/TDO dual inhibitor RY103 targets Kyn-AhR pathway and exhibits preclinical efficacy on pancreatic cancer. Cancer Lett 2021;522:32–43.
[81] Naing A, Eder JP, Piha-Paul SA, Gimmi C, Hussey E, Zhang S, et al. Preclinical investigations and a first-in-human phase I trial of M4112, the first dual inhibitor of indoleamine 2,3-dioxygenase 1 and tryptophan 2,3-dioxygenase 2, in patients with advanced solid tumors. J Immunother Cancer 2020;8:e000870.
[82] Capochiani de Iudicibus R, Tomek P, Palmer BD, Tijono SM, Flanagan JU, Ching LM. Parallel discovery of selective and dual inhibitors of tryptophan dioxygenases IDO1 and TDO2 with a newly-modified enzymatic assay. Bioorg Med Chem. 2021;39:116160.
[83] DiNatale BC, Smith K, John K, Krishnegowda G, Amin SG, Perdew GH. Ah receptor antagonism represses head and neck tumor cell aggressive phenotype. Mol Cancer Res 2012;10:1369–79.
[84] Yamamoto T, Hatabayashi K, Arita M, Yajima N, Takenaka C, Suzuki T, et al. Kynurenine signaling through the aryl hydrocarbon receptor maintains the undifferentiated state of human embryonic stem cells. Sci Signal 2019;12:eaaw3306.
[85] Amobi-McCloud A, Muthuswamy R, Battaglia S, Yu H, Liu T, Wang J, et al. IDO1 expression in ovarian cancer induces PD-1 in T cells via aryl hydrocarbon receptor activation. Front Immunol 2021;12:678999.
[86] Vogel CFA, Lazennec G, Kado SY, Dahlem C, He Y, Castaneda A, et al. Targeting the aryl hydrocarbon receptor signaling pathway in breast cancer development. Front Immunol 2021;12:625346.
[87] Gutcher I, Kober C, Roese L, Roewe J, Schmees N, Prinz F, et al. Abstract 1288: Blocking tumor-associated immune suppression with BAY-218, a novel, selective aryl hydrocarbon receptor (AhR) inhibitor. Cancer Res 2019;79:1288.
[88] Hennequart M, Pilotte L, Cane S, Hoffmann D, Stroobant V, Plaen E, et al. Constitutive IDO1 expression in human tumors is driven by cyclooxygenase-2 and mediates intrinsic immune resistance. Cancer Immunol Res 2017;5:695–709.
[89] Ochs K, Ott M, Rauschenbach KJ, Deumelandt K, Sahm F, Opitz CA, et al. Tryptophan-2,3-dioxygenase is regulated by prostaglandin E2 in malignant glioma via a positive signaling loop involving prostaglandin E receptor-4. J Neurochem 2016;136:1142–54.
[90] Szeto CW, Kurzrock R, Kato S, Goloubev A, Veerapaneni S, Preble A, et al. Association of differential expression of immunoregulatory molecules and presence of targetable mutations may inform rational design of clinical trials. ESMO Open 2022;7:100396.
[91] Sandri S, Watanabe LRM, Oliveira EA, Faião-Flores F, Migliorini S, Tiago M, et al. Indoleamine 2,3-dioxygenase in melanoma progression and BRAF inhibitor resistance. Pharmacol Res 2020;159:104998.
[92] Dey S, Mondal A, DuHadaway JB, Sutanto-Ward E, Laury-Kleintop LD, Thomas S, et al. IDO1 signaling through GCN2 in a subpopulation of Gr-1(+) cells shifts the IFNγ/IL6 balance to promote neovascularization. Cancer Immunol Res 2021;9:514–28.
[93] Mondal A, Smith C, DuHadaway JB, Sutanto-Ward E, Prendergast GC, Bravo-Nuevo A, et al. IDO1 is an integral mediator of inflammatory neovascularization. EBioMedicine 2016;14:74–82.
[94] Zhai L, Bell A, Ladomersky E, Lauing KL, Bollu L, Nguyen B, et al. Tumor cell IDO enhances immune suppression and decreases survival independent of tryptophan metabolism in glioblastoma. Clin Cancer Res 2021;27:6514–28.
[95] Kato S, Okamura R, Kumaki Y, Ikeda S, Nikanjam M, Eskander R, et al. Expression of TIM3/VISTA checkpoints and the CD68 macrophage-associated marker correlates with anti-PD1/PDL1 resistance: implications of immunogram heterogeneity. Oncoimmunology 2020;9:1708065.
[96] Bjoern J, Iversen TZ, Nitschke NJ, Andersen MH, Svane IM. Safety, immune and clinical responses in metastatic melanoma patients vaccinated with a long peptide derived from indoleamine 2,3-dioxygenase in combination with ipilimumab. Cytotherapy 2016;18:1043–55.
[97] Kjeldsen JW, Lorentzen CL, Martinenaite E, Ellebaek E, Donia M, Holmstroem RB, et al. A phase 1/2 trial of an immune-modulatory vaccine against IDO/PD-L1 in combination with nivolumab in metastatic melanoma. Nat Med 2021;27:2212–23.
[98] Naing A, Powderly JD, Falchook G, Creelan B, Nemunaitis J, Lutzky J, et al. Abstract CT177: Epacadostat plus durvalumab in patients with advanced solid tumors: preliminary results of the ongoing, open-label, phase I/II ECHO-203 study. Cancer Research. 2018;78:CT177.
[99] Daud A, Saleh MN, Hu J, Bleeker JS, Riese MJ, Meier R, et al. Epacadostat plus nivolumab for advanced melanoma: Updated phase 2 results of the ECHO-204 study. Journal of Clinical Oncology. 2018;36:15_suppl, 9511-9511.
[100] Kelly CM, Chi P, Dickson MA, Gounder MM, Keohan ML, Qin L-X, et al. A phase II study of epacadostat and pembrolizumab in patients with advanced sarcoma. Journal of Clinical Oncology. 2019;37:15_suppl, 11049-11049.
[101] Tanyi JL, Dorigo O, Oza AM, Strauss JF, Pejovic T, Ghamande SA, et al. DPX-Survivac and intermittent low-dose cyclophosphamide (CPA) with or without epacadostat (E) in the treatment of subjects with advanced recurrent epithelial ovarian cancer (DeCidE1 trial): T cell responses and tumor infiltration correlate with tumor regression. Journal of Clinical Oncology. 2019;37:15_suppl, 5576-5576.
[102] Hellmann MD, Gettinger S, Chow LQM, Gordon M, Awad MM, Cha E, et al. Phase 1 study of epacadostat in combination with atezolizumab for patients with previously treated advanced nonsmall cell lung cancer. Int J Cancer 2020;147:1963–9.
[103] Doi T, Fujiwara Y, Shitara K, Shimizu T, Yonemori K, Matsubara N, et al. The safety and tolerability of epacadostat alone and in combination with pembrolizumab in patients with advanced solid tumors: results from a first-in-Japanese phase I study (KEYNOTE-434). Invest New Drugs. 2021;39:152-62.
[104] Jackson E, Dees EC, Kauh JS, Harvey RD, Neuger A, Lush R, et al. A phase I study of indoximod in combination with docetaxel in metastatic solid tumors. Journal of Clinical Oncology. 2013;31:15_suppl, 3026-3026.
[105] Colman H, Mott F, Spira AI, Johnson TS, Zakharia Y, Vahanian NN, et al. A phase 1b/2 study of the combination of the IDO pathway inhibitor indoximod and temozolomide for adult patients with temozolomide-refractory primary malignant brain tumors: Safety analysis and preliminary efficacy of the phase 1b component. Journal of Clinical Oncology. 2015;33:15_suppl, 2070-2070.
[106] Jha GG, Gupta S, Tagawa ST, Koopmeiners JS, Vivek S, Dudek AZ, et al. A phase II randomized, double-blind study of sipuleucel-T followed by IDO pathway inhibitor, indoximod, or placebo in the treatment of patients with metastatic castration resistant prostate cancer (mCRPC). Journal of Clinical Oncology. 2017;35:15_suppl, 3066-3066.
[107] Emadi A, Duong VH, Pantin J, Imran M, Koka R, Singh Z, et al. Indoximod Combined with Standard Induction Chemotherapy Is Well Tolerated and Induces a High Rate of Complete Remission with MRD-Negativity in Patients with Newly Diagnosed AML: Results from a Phase 1 Trial. Blood 2018;132(Supplement 1):332.
[108] Bahary N, Wang-Gillam A, Haraldsdottir S, Somer BG, Lee JS, O'Rourke MA, et al. Phase 2 trial of the IDO pathway inhibitor indoximod plus gemcitabine / nab-paclitaxel for the treatment of patients with metastatic pancreas cancer. Journal of Clinical Oncology. 2018;36:15_suppl, 4015-4015.
[109] Soliman H, Khambati F, Han HS, Ismail-Khan R, Bui MM, Sullivan DM, et al. A phase-1/2 study of adenovirus-p53 transduced dendritic cell vaccine in combination with indoximod in metastatic solid tumors and invasive breast cancer. Oncotarget 2018;9:10110–7.
[110] Luke JJ, Gelmon K, Pachynski RK, Desai J, Moreno V, Tabernero JM, et al. O41 Preliminary antitumor and immunomodulatory activity of BMS-986205, an optimized indoleamine 2,3-dioxygenase 1 (IDO1) inhibitor, in combination with nivolumab in patients with advanced cancers. 32nd Annual Meeting and Pre-

Conference Programs of the Society for Immunotherapy of Cancer (SITC 2017): Late-Breaking Abstracts. Journal for ImmunoTherapy of Cancer. 2017;5:89.
[111] Luke JJ, Tabernero J, Joshua A, Desai J, Varga AI, Moreno V, et al. BMS-986205, an indoleamine 2, 3-dioxygenase 1 inhibitor (IDO1i), in combination with nivolumab (nivo): Updated safety across all tumor cohorts and efficacy in advanced bladder cancer (advBC). Journal of Clinical Oncology. 2019;37:7_suppl, 358-358.
[112] Reardon DA, Desjardins A, Rixe O, Cloughesy T, Alekar S, Williams JH, et al. A phase 1 study of PF-06840003, an oral indoleamine 2,3-dioxygenase 1 (IDO1) inhibitor in patients with recurrent malignant glioma. Invest New Drugs 2020;38:1784–95.
[113] Desai P, Rao S, Ikawa Y, Kapelan B, Efuni S, Latek R, et al. Abstract CT238: An open-label, phase 1 study of IDO inhibitor KHK2455 in combination with avelumab in adult subjects with locally advanced or metastatic urothelial carcinoma. Cancer Research. 2020;80:CT238.
[114] Cheng Y, Liu Y, Xu J, Zhu J, Wang Y, Xin Y, et al. A phase I study of an IDO inhibitor (SHR9146) plus camrelizumab and in combination with/without apatinib in patients with advanced solid tumors: Safety and efficacy analysis. Journal of Clinical Oncology 2021;39. 3101–3101.
[115] https://ClinicalTrials.gov/show/NCT03364049. Study of MK-7162 in Combination With Pembrolizumab (MK-3475) in Adult Participants With Advanced Solid Tumors (MK-7162-002). Accessed on Feb 27th, 2022.
[116] Iversen TZ, Engell-Noerregaard L, Ellebaek E, Andersen R, Larsen SK, Bjoern J, et al. Long-lasting disease stabilization in the absence of toxicity in metastatic lung cancer patients vaccinated with an epitope derived from indoleamine 2,3 dioxygenase. Clin Cancer Res 2014;20:221–32.
[117] Kjeldsen JW, Iversen TZ, Engell-Noerregaard L, Mellemgaard A, Andersen MH, Svane IM. Durable clinical responses and long-term follow-up of stage III-IV non-small-cell lung cancer (NSCLC) patients treated with IDO peptide vaccine in a phase I study-a brief research report. Front Immunol 2018;9:2145.