Nanomedicine and cancer immunotherapy: focus on indoleamine 2,3-dioxygenase inhibitors

Abstract: Nanomedicine application in cancer immunotherapy is currently one of the most challenging areas in cancer therapeutic intervention. Innovative solutions have been provided by nanotechnology to deliver cytotoxic agents to the cancer cells partially affecting the healthy cells of the body during the process. Nanoparticle-based drug delivery is an emerging approach to stimulate the immune responses against cancer. The inhibition of indoleamine 2,3-dioxygenase (IDO) is a pivotal area of research in cancer immunotherapy. IDO is a heme-containing immunosuppressive enzyme, which is responsible for the degradation of tryptophan while increasing the concentration of kynurenine metabolites. Various preclinical studies showed that IDO inhibition in certain diseases may result in significant therapeutic effects. Here, we provide a review of the natural and synthetic inhibitors of IDO. These inhibitors are classified according to their source, inhibitory concentrations, the chemical structure, and the mechanism of action. Tumor-targeted chemotherapy is an advanced technique and has more advantages as compared to the conventional chemotherapy. Search for more efficient and less toxic nanoparticles in conjunction with compounds to inhibit IDO is still an area of interest for several research groups worldwide, especially revealing to be an extensive and a promising area in cancer therapeutic innovations.

Keywords: indoleamine 2,3-dioxygenase, natural inhibitors of IDO, synthetic inhibitors of IDO, nanomedicine, cancer therapeutics

Introduction

Medicine has evolved dramatically in recent years. New strategies have emerged for the diagnosis and treatment of various diseases, leading to a better prognosis and improved quality of life in patients. Within this new environment that combines technology and medicine, it seems that the next rung on the ladder of technological advances is primarily focused on nanomedicine, especially in the area of cancer biology. In conventional chemotherapy, drugs generally exhibit high toxicity for both cancer and healthy cells.1 Nanomedicine offers the possibility of a direct effect of drugs on diseased cells without harming the healthy cells in the body,2 preventing the high toxicity associated with chemotherapy. This leads to a therapeutic advantage that only affects the tumor and preserves the structure and function of the healthy tissue.

Nanoparticles are gradually being used as a carrier for delivering molecular drugs to the sites of tumor growth. Nanoparticles not only increase the circulation time of the molecular cargo but also protects it from biodegradation.3 Liposomes,4 hydrogels,5 nanofibers,6 metallic nanoparticles7 and nanodiamonds8 are examples of nanomaterials that have been widely tested as transporters for specific drugs for the treatment of cancers. The first polymeric vector for small interfering RNA delivery entered a phase I trial in 2008. It was termed as CALAA-01 and was prepared using...
such as gadolinium or superparamagnetic iron oxide, so achieved by encapsulating nanoparticles in contrast to media quality by making use of imaging methods, such as computed auxiliary agents for obtaining diagnostic images of better immunostimulatory cascade, which can work against the actively take in antigen-loaded nanocarriers by initiating an Nanoparticles have also been used to formulate vaccines paclitaxel indicated for the treatment of various cancers. 2005, formulated with a nanoparticle containing albumin and example is the drug Abraxane doxorubicin formulation exhibited decreased cardiotoxicity compared with Gold nanoparticles are used preferentially for drug delivering, diagnosis and treatment of cancer.29

The implementation of nanomedicine in the treatment and diagnosis of cancer has acquired great value and drugs combined with nanoparticles are already in various stages of preclinical and clinical trials for the treatment of breast, lung, melanoma, pancreatic and gastroesophageal cancers (Tables 1 and 2).

Novel therapies utilizing nanomedicine can result in superior treatments as compared to the current regimens. The goal to achieve increased efficacy and reduced toxicity has been achieved by overcoming the drug delivery challenges using nanomedicine to detect and treat pancreatic ductal adenocarcinoma, colorectal cancer (CRC), melanoma and cervical cancer.34

The inhibition of indoleamine 2,3-dioxygenase (IDO) is a pivotal area of research in cancer immunotherapy. IDO is a heme-containing enzyme that catalyzes the oxidative cleavage of 2,3 double bond of indole ring.35 IDO has the ability to inhibit T-cell activation by tryptophan starvation, whereas T-cell survival and proliferation are regulated by O2 free radicals and kynurenine derivatives.36 IDO plays a crucial role in autoimmunity,36,37 infections38 and malignancies.39 Overexpression of IDO has been reported in breast,40-42 thyroid,43 pancreatic,44,45 prostate,46,47 lung,48,49 cervical50 and ovarian51 cancers.

It has been reported that IDO expression can be modulated by CD137/CD137L pathway against Ewing sarcoma cells; IL2 plays a role in IDO expression from tumor cells due to interferon gamma (IFN-γ) production by lymphocytes.32 PI3K→AKT→nuclear factor kappa light chain enhancer of activated B-cell pathway is also involved with IDO expression through CD80/CD86 induction.53

It is known that there is a population of CD4+ T cells able to inhibit responses of cytotoxic T cells to specific antigens, which are referred to as T-regulatory cell (T-reg). The phenotype of this cell population is CD4+CD25+FoxP3.54 T-reg can be induced by immature
dendritic cell (DC) that accumulates at the tumor microenvironment. Ipilimumab, an anti-CTLA-4 antibody, has been approved for advanced melanoma patients.55 Two anti-PD-1 antibodies, pembrolizumab and nivolumab, have also been approved for patients with metastatic lung, breast, bladder and renal cancers. PD-1 is a protein of immunoglobulin superfamily that has a co-inhibition function for antigen presentation. It is expressed on the surface of T-lymphocytes activated, NKT cells, B-lymphocytes, monocytes and DCs.56 The interaction with their ligands PD-PD-L1 or L2 leads to the phosphorylation of PD-1 on tyrosine residues with the intracellular portion of the molecule, with subsequent recruitment of phosphatase SHP-2 and inhibition of signaling triggered by TCR. The increased expression of PD-L1 is common in the context of melanoma and appears to be induced by the neoplastic cells through unknown mechanisms.57

### Table 1 Nanotechnological carrier systems used for cancer treatments

<table>
<thead>
<tr>
<th>Indication</th>
<th>Nanotechnological system</th>
<th>Compounds (agents)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leukemia</td>
<td>Liposome</td>
<td>Topotecan + amlodipine18</td>
<td>Preclinical</td>
</tr>
<tr>
<td></td>
<td>Transferrin-conjugated PEGylated liposome</td>
<td>6-Mercaptopurine + daunorubicin19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Folate-G5 poly-propyleneimine dendrimer with ethylenediamine core</td>
<td>Doxorubicin + verapamil20</td>
<td></td>
</tr>
<tr>
<td>Breast cancer</td>
<td>Liposome</td>
<td>Methotrexate + all-trans-retinoic acid24</td>
<td></td>
</tr>
<tr>
<td>Prostate cancer</td>
<td>HER2 conjugated-GMO-MNPs</td>
<td>Gemcitabine + tamoxifen25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HPMA-Gem-Dox</td>
<td>Ceramide + sorafenib26</td>
<td></td>
</tr>
<tr>
<td>Glioblastoma</td>
<td>Aptamer-G4 PAMAM dendrimer conjugates</td>
<td>Gemcitabine + doxorubicin28</td>
<td></td>
</tr>
<tr>
<td></td>
<td>G5 PAMAM dendrimer</td>
<td>Unmethylated CpG-ONTs + doxorubicin29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RGDK-G3 poly-lysine dendrimer</td>
<td>Anti-sense-miRNA21 + 5-fluorouracil20</td>
<td></td>
</tr>
<tr>
<td>Cervical cancer</td>
<td>Liposome</td>
<td>Doxorubicin + siRNA13</td>
<td></td>
</tr>
<tr>
<td>Lung cancer</td>
<td>Liposome</td>
<td>PD0325901 + siMcl13</td>
<td></td>
</tr>
<tr>
<td>Brain cancer</td>
<td>PEG-liposome</td>
<td>Doxorubicin + msurvivin T34A plasmid13</td>
<td></td>
</tr>
<tr>
<td>Hepatocellular carcinoma</td>
<td>PLGA</td>
<td>Topotecan + vincristine13</td>
<td></td>
</tr>
<tr>
<td>Advanced colorectal cancer</td>
<td>Liposome (CPX-1)</td>
<td>Vincristine + verapamil15</td>
<td>Phase II</td>
</tr>
<tr>
<td></td>
<td>Liposome (CPX-31)</td>
<td>Irinotecan + 5-fluorouridine16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Liposome</td>
<td>Cytarabine + daunorubicin17</td>
<td></td>
</tr>
</tbody>
</table>

**Abbreviations:** GMO, glycerol monooleate; HER2, human epidermal growth factor receptor 2; HPMA, N-(2-hydroxypropyl)methacrylamide; miRNA, microRNA; MNPs, magnetic nanoparticles; ONTs, oligonucleotides; PAMAM, polyamidoamine; PEG, polyethylene glycol; PLGA, poly lactic-co-glycolic acid; siRNA, small interfering RNA.

### Table 2 US FDA approved nanomedicines used for cancer treatments

<table>
<thead>
<tr>
<th>Drug</th>
<th>Class</th>
<th>Platform</th>
<th>Drug carried ratio</th>
<th>Diameter (mm)</th>
<th>Dose (mg/m²)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doxorubicin</td>
<td>Liposome</td>
<td>Doxil®</td>
<td>10,000‐15,000</td>
<td>100</td>
<td>25‐80</td>
<td>Gabizon et al14 and Hamilton et al118</td>
</tr>
<tr>
<td>Vincristine</td>
<td>Liposome</td>
<td>Marqibo</td>
<td>–10,000</td>
<td>100</td>
<td>2.0‐2.25</td>
<td>Bedikian et al19 and Silverman and Deitcher146</td>
</tr>
<tr>
<td>Daunorubicin</td>
<td>Liposome</td>
<td>DaunoXome</td>
<td>–10,000</td>
<td>50</td>
<td>10‐190</td>
<td>Gill et al41 and Belliott et al42</td>
</tr>
<tr>
<td>Mertansine</td>
<td>Antibody‐drug conjugates</td>
<td>Trastuzumab emtansine</td>
<td>≤8</td>
<td>–10</td>
<td>10‐160</td>
<td>Lu et al43</td>
</tr>
<tr>
<td>Monomethyl auristan E</td>
<td>Antibody‐drug conjugates</td>
<td>Brentuximab vedotin</td>
<td>≤8</td>
<td>–10</td>
<td>90‐110</td>
<td>Younes et al44 and Bradley et al145</td>
</tr>
<tr>
<td>Paclitaxel</td>
<td>Protein carrier</td>
<td>Abraxane®</td>
<td>&gt;10,000</td>
<td>130</td>
<td>150‐300</td>
<td>Ando et al46</td>
</tr>
</tbody>
</table>

**Abbreviation:** FDA, Food and Drug Administration.

### IDO inhibitors as adjuvant therapy

The mechanism of immune escape developed by a tumor cell may influence the success rate of a specific immuno-therapeutic intervention.56 As IDO plays an important part in the immune escape scenario for a cancer cell,59 thus IDO inhibitors can act as an innovative and promising strategy for cancer therapy.59,60 To obtain better results, adjunct treatment is proposed in which the inhibitors should be administered concomitantly with cytotoxic chemotherapy agents.59,64 Several research groups are working in the search of new and more potent IDO inhibitors whether they are synthetic or endogenous.65 Structural basis of IDO provides different binding sites for substrates and cofactors,66 which allows for the development of competitive and noncompetitive inhibitors,67 leading to an increased number of possible inhibitory molecules to be used for targeted intervention.
A clinical IDO inhibitor should ideally inhibit the local degradation of tryptophan in the tumor microenvironment and significantly in draining lymph nodes where the process of presentation of tumor antigens is most effective. It is most likely that novel potent IDO inhibitors will provide effective treatment when combined with other modalities of cancer therapy.

An enormous number of inhibitors have been tested for their pharmacologic activity against IDO (Figure 1). 1-Methyl tryptophan (1-MT) is the most important competitive inhibitor of IDO. Since the discovery of 1-MT in 1991, it has been widely studied because of its favorable pharmacokinetic activity, such as low protein binding, oral availability and low clearance. Currently, 1-MT is regarded as a classical IDO inhibitor in clinical research based on its exponential effectiveness in treating tumors. No case of toxicity has been reported against 1-MT till date except dehydration in a study carried out on mice model where this inhibitor was administered through drinking water. The efficacy of 1-MT is significantly enhanced when given in combination with powerful chemotherapeutic agents, such as paclitaxel, cisplatin, doxorubicin and cyclophosphamide. There are two stereoisomers of 1-MT: the d-isomer and l-isomer. Through in vitro testing by using different cell lines or cell-free assays, it has been revealed that the l-isomer exhibits the highest degree of efficacy against IDO, whereas it does not promote high level of T-cell proliferation in vivo as compared to the d-isomer. Beta-carboline derivatives

**Figure 1** IDO pathway and inhibitors.

**Notes:** Tryptophan catabolism through the kynurenine pathway involves IDO an intracellular rate limiting enzyme and possible natural and synthetic inhibitors of this enzyme acting through various routes. IDO serves as an apoenzyme which is encoded by the *Indo* gene, this gene is upregulated by JAK/STAT signaling pathway induced by IFN-γ, cyclooxygenase-mediating prostaglandin E2, TNF-α and LPS regulated by NF-κB. In contrast, it is downregulated by BIN gene, IL-4, nitric oxide and TGF-β through mRNA degradation pathway. Apart from the natural and synthetic inhibitors certain tryptophan active products, such as tryptamine and DMT, also serve as modulators of this enzyme.

**Abbreviations:** COX-2, cyclooxygenase-2; DMT, N-dimethyltryptamine; IDO, indoleamine 2,3-dioxygenase; IFN-γ, interferon gamma; IL, interleukin; JAK, Janus kinase; LPS, lipopolysaccharides; mRNA, messenger RNA; NAD, aldehyde dehydrogenase; NF-κB, nuclear factor kappa light chain enhancer of activated B cells; PG, prostaglandin; PGE2, prostaglandin E2; STAT, signal transducers and activators of transcription; TGF-β, transforming growth factor β; TNF, tumor necrosis factor; T-reg, T-regulatory cells.

**Natural inhibitors**
- Brassinin
- Anniulin A & B
- Adocioarine A & B
- Eexguain A
- Epigallocatechin gallate
- Trachelogenin
- Curcumin
- Indole-3-carbinol
- Trypanthin
- p-Coumaric acid
- Polyphenols

**Synthetic inhibitors**
- Norharman
- 4-Phenylimidazole
- Ascorbic acid
- Tocopherols
- Tocotrienols
- 2-Mercapto-Benzothiazole
- 2-Mercaptothiophenylthiazole
- Phenylthiazole
- 1-Methyl tryptophan
- Ketoindoles
- Indol-2-yi ethanones
- Aminophenoxazines
- Methyl-thiodytantoin--tryptophan
- Imidodicarbonimidic diamide
- 4-Amino-1,2,5-oxadiazole-3-carboximidamide
comprise the class of noncompetitive inhibitors, which bind to the heme iron different to the active site where the substrate binds. A huge number of beta-carboline inhibitors have been developed, but their development has been restricted by the fact that these inhibitors behave as benzodiazepine ligands. Whether the IDO inhibitors are competitive or noncompetitive in nature; the basic mechanism of inhibition remains independent by the substitution of indole ring. However, now research is being carried out to find the potential inhibitors of IDO that use the mechanism of substitution of the indole ring.

**Natural inhibitors**

Recently, isolation of several natural products has revealed various potent IDO inhibitors. Chen et al investigated the relationship between anti-inflammatory properties of natural products and IDO activity. High concentration of numerous phytochemicals, possessing flavonoid chemical structure, has been reported in various medicinal plants, fruits and vegetables. For instance, curcumin, a natural IDO inhibitor, is an active ingredient of turmeric being used in treating cancer. Physiochemical properties and structures of natural inhibitors are described in Tables 2 and 3 and Figure 2.

**Brassinin**

Brassinin was first identified in the Chinese cabbage. It is a phytoalexin found in the cruciferous vegetables. The inhibition mechanism takes place when methyl dithiocarbamate chain, present in brassinin, substitutes the chain of amino acid in tryptophan. Thus, it presents a great potential to act as an anticancer agent. It is reported to be an active, moderately competitive IDO inhibitor and has shown an inhibitory constant (Ki) value of 97.7 μM.

**Annulins and adociaquinones**

Andersen et al demonstrated that a wide range of marine hydroids contain various natural products, which exhibit inhibitory activity (IC50) against IDO. These products act in a noncompetitive manner. Annulins A and B, the pyranonaphthoquinones, are naturally obtained from the extracts of *Garveia annulata*, a marine hydroid. The annulin B has shown a Ki of 0.12 μM and are reported to be more active than 1-MT, whereas Ki value for pyranonaphthoquinones is 0.07 μM. Crude extracts from *Xestospongia* sp. contain adociaquinones A and B, which exhibit activity as IDO inhibitors. Adociaquinone B has shown most potent activity among other compounds with a Ki of 25 nM.

**Exiguamine A**

Another natural product exiguamine A has been revealed to cause the inhibition of IDO activity with a Ki value of 0.04–0.21 μM. However, the cellular mechanisms are still unknown. Nevertheless, this compound might be used further to develop IDO inhibitors synthetically.

**Tryptamine (TRY)**

Although the tryptophan metabolism is mainly degraded through kynurenic pathway, other tryptophan active products include TRY, melatonin, serotonin and N-dimethyltryptamine (DMT). Recently, a study determined IDO inhibitory activities of these compounds. Serotonin and melatonin were not shown to inhibit IDO even at high concentrations, whereas DMT and TRY inhibited IDO activity noncompetitively with Ki values of 506 and 160 μM, respectively.

**Epigallocatechin gallate**

EGCG is a phytochemical and an active component of green tea that exerts chemoprotective role and exhibits anticancer properties.

<table>
<thead>
<tr>
<th>Natural inhibitor</th>
<th>Molecular weight (Da)</th>
<th>Polar surface area (Å²)</th>
<th>Molecular surface area (Å²)</th>
<th>Partition coefficient (log P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brassinin</td>
<td>236.35</td>
<td>27.82</td>
<td>310.98</td>
<td>3.28</td>
</tr>
<tr>
<td>Annulin A</td>
<td>360.35</td>
<td>110.13</td>
<td>501.95</td>
<td>3.20</td>
</tr>
<tr>
<td>Annulin B</td>
<td>386.39</td>
<td>106.97</td>
<td>547.34</td>
<td>4.13</td>
</tr>
<tr>
<td>Adociaquinone A</td>
<td>520.77</td>
<td>110.52</td>
<td>423.43</td>
<td>1.10</td>
</tr>
<tr>
<td>Adociaquinone B</td>
<td>423.43</td>
<td>110.52</td>
<td>520.92</td>
<td>1.10</td>
</tr>
<tr>
<td>Exiguamine A</td>
<td>492.50</td>
<td>146.03</td>
<td>647.56</td>
<td>–1.85</td>
</tr>
<tr>
<td>Tryptamine</td>
<td>160.21</td>
<td>41.81</td>
<td>252.62</td>
<td>1.49</td>
</tr>
<tr>
<td>Curcumin</td>
<td>368.37</td>
<td>93.06</td>
<td>509.73</td>
<td>4.12</td>
</tr>
<tr>
<td>Epigallocatechin gallate</td>
<td>458.37</td>
<td>197.37</td>
<td>556.67</td>
<td>3.08</td>
</tr>
<tr>
<td>Tryptanthrin</td>
<td>248.23</td>
<td>49.74</td>
<td>299.16</td>
<td>2.40</td>
</tr>
<tr>
<td>3,3’-Diindolylmethane</td>
<td>246.30</td>
<td>31.58</td>
<td>352.74</td>
<td>4.26</td>
</tr>
<tr>
<td>p-Coumaric acid</td>
<td>164.15</td>
<td>57.53</td>
<td>216.51</td>
<td>1.83</td>
</tr>
<tr>
<td>Thielavin</td>
<td>580.62</td>
<td>148.82</td>
<td>869.53</td>
<td>9.30</td>
</tr>
</tbody>
</table>

**Table 3 Physicochemical properties of selected natural inhibitors**

*Note: Physicochemical properties of selected natural inhibitors retrieved from Watkins et al.*

**OncoTargets and Therapy** 2017:10
Figure 2 Natural inhibitors with structures.

Notes: (A) Brassinin, (B) annulin A, (C) annulin B, (D) adociaquinone A, (E) adociaquinone B, (F) exiguamine A, (G) tryptamine, (H) curcumin, (I) epigallocatechin gallate, (J) tryptanthrin, (K) 3,3′-dindolylmethane, (L) p-coumaric acid, and (M) thielenalin.
effects in several organs. Recent studies revealed that the treatment of EGCG inhibits IDO enzyme activity in CRC cells through the inhibition of STAT1 activation.\(^8\)

**Crinum latifolium leaf extract**

Genus *Crinum* (Amaryllidaceae) consists of plants comprising \(~130\) species, widely present and frequently used in traditional medicine worldwide. A strong suppressive action of leaf extract of *C. latifolium* activity of IDO in prostate tumor cells has been demonstrated. This inhibitory action is specifically attributed to alkaloids present in *C. latifolium*.\(^8\)

**Carthamus tinctorius**

*C. tinctorius*, the herbaceous plant also known as safflower, belongs to the family Asteraceae and traditionally used in Chinese medicine. In Mediterranean area, its role has been recently demonstrated as anticancer, antihelminthic and diuretic. Three lignans (a group of chemical compounds found in plants), namely trachelogenin, matairesinol and arctigenin, were isolated and investigated for their inhibitory capability for IDO. Subsequent experiments showed that trachelogenin and arctigenin prevent the mitogen-induced breakdown of tryptophan in a dose-dependent manner, and no negative influence of these compounds recorded on the viability of cells.\(^8\)

**Curcumin**

Curcumin, a phenolic natural and active compound, obtained from *Curcuma longa* (turmeric) possesses anti-inflammatory, anticancer and antioxidant properties.\(^8\) Recently, it was revealed that curcumin-inhibited IFN-\(\gamma\)-induced IDO activity both at protein and messenger RNA (mRNA) level through Janus kinase (JAK)1/2 and protein kinase C delta (PKC\(\delta\)) signaling pathways. Thus, this immunomodulatory effect of curcumin might be exploited therapeutically to treat and control various types of cancers.\(^7\)

**3,3'-Diindolylmethane (DIM)**

The nutritional supplement, indole-3-carbinol and its metabolites, DIM contain indole ring and are structurally similar to tryptophan. It has been reported that DIM competitively inhibit tryptophan degradation. It has a moderate activity which is an IDO-specific inhibitor.\(^7\)

**Tryptanthrin**

A natural product tryptanthrin is found in *Polygonum tinctorium* and *Isatis tinctoria*. These two plants are frequently used in Chinese medicine. Tryptanthrin has revealed immunomodulatory\(^7\) and various inhibitory activities against microbes and parasites.\(^4\) Tryptanthrin has been identified as a potent novel IDO inhibitor, which has an IC\(\text{50}\) of 7.15 \(\mu\)M\(^8\) and reported to have Ki value of 4.8 \(\mu\)M.\(^7\)

**Neem (Azadirachta indica) leaf glycoprotein (NLGP)**

Various immunotherapeutic strategies are used to treat cancer by downregulating IDO activity, possibly by using IDO inhibitors, and thus reducing T-regs. NLGP, the naturally occurring immune system modulator, has revealed various unique activities. Most significant of which are to inhibit T-regs and mature DCs. As IDO is induced by T-regs and their hyperactivity is the hallmark of cancer, thus it has been proposed that NLGP may inhibit IDO induction in DCs by suppressing T-regs.\(^9\)

**p-Coumaric acid**

*p-Coumaric acid* exists abundantly in various plant products, fruits and vegetables, for example, potatoes, tea and beans, and has been anticipated to exhibit antioxidant activity.\(^8\) Numerous antioxidants are suggested to suppress IDO activity through posttranscriptional and translational regulations. In addition, it has been demonstrated to inhibit prolactin secretion. Lymphoid organs and pituitary gland also secrete prolactin. Based on the fact that prolactin increases IDO secretion. Lymphoid organs and pituitary gland also secrete prolactin. Based on the fact that prolactin increases IDO activity induced by IFN-\(\gamma\), researchers have proposed that *p*-coumaric acid and various other antioxidants suppress IDO activity in macrophages.\(^8\)

**Polyphenols**

Numerous flavonoids have been reported to exhibit anti-inflammatory and antioxidant activities.\(^9\) However, the chemical structure is the main determinant of their potency. Wogonin, baicalein, apigenin and chrysin have shown similar basic flavonoid chemical structure. Despite possessing OH group in their structures, all these compounds inhibit the IDO-1 protein in a similar way.\(^9\)

**Benzomalvin**

Jang et al isolated benzomalvin, a new benzodiazepine from the extracts of fungus during their search for IDO inhibitors. During the screening process, one of the culture broths from soil fungus showed activity and was later identified as *Penicillium* sp. on the basis of having sequence homology with two species of *Penicillium* sp. The IC\(\text{50}\) values for benzomalvin were found to be 21.4\(\pm\)1.2 \(\mu\)M.\(^7,9\)
Thielavin

Jang et al have identified several IDO inhibitors from the microbial source, especially soil fungi during the past few years. Thielavin-Q a new benzoate trimer is one of the compounds identified by them, recently, from the broth of Coniochaeta sp. during the fermentation process. Thielavin-Q has shown an IC$_{50}$ value for IDO of 15 μM.\(^{59}\)

β-Lapachone

β-Lapachone occurs naturally and is derived from 1,2-naphthoquinone. It is already well-known that it possesses anticancer properties and based on that it has been advanced into the clinical trials. Recently, Flick et al discovered that β-lapachone also possesses nanomolar IDO inhibitory enzymatic activity and shows K$_i$ value of 0.10–0.45 μM.\(^{78,93}\)

Naphthoquinones

After elucidating the crystal structure of IDO in 2006,\(^{35}\) it practically became possible to predict which other nuclei could become potential inhibitors. Simultaneously, other compounds such as the naphthoquinone were identified, which were extracted from marine invertebrates.\(^{94}\) These compounds presented K$_i$ values in nanomoles; however, they were shown to be inactive in cellular assays, which suggested that they faced difficulties in crossing the cell membrane.\(^{95}\)

Synthetic inhibitors

Physiochemical properties and structures of synthetic inhibitors are described in Table 4 and Figure 3.

Norharman (9H-pyrido [3,4-b]indole)

Norharman, also termed as β-carboline is a non-competitive inhibitor of IDO. Norharman (K$_i$ of 176 μM) competes with molecular oxygen (O$_2$), necessary for the activity of dioxygenase.\(^{96}\)

4-Phenylimidazole (PIM)

PIM is another noncompetitive inhibitor discovered in 1989 and has a different mechanism of action to that of Norharman. PIM (K$_i$ of 8 μM) binds to the enzyme at the inactive ferric (Fe$^{3+}$) form and prevents its reduction to the catalytically active ferrous form.\(^{97}\)

Salicylates and glucocorticoids

A study involving prostaglandins revealed that enzymes phospholipase A2 and cyclooxygenase-2 (COX-2), which are essential for its synthesis, play a significant role in IDO induction through IFN-γ pathway.\(^{98}\) It was also assessed that these inhibitors are able to block this induction.\(^{99}\)

Antioxidants

Antioxidants, such as ascorbic acid, tocopherols and tocotrienols, that inhibit reactive oxygen species also perform an important role in the IDO inhibition-mediated activity by IFN-γ in macrophages-derived monocytes.\(^{100}\)

5-Bromo-brassinin

Another natural compound called brassinin was identified\(^{72,101}\) from Chinese cabbage and broccoli with a K$_i$ of 27.9 μM. Beside its synthetic derivative, 5-bromo-brassinin with a K$_i$ of 24.5 μM presented chemoprotective activity in mammary cancer and melanomas in animal models.\(^{102,103}\)

Nitric oxide

Nitric oxide (NO) negatively modulates the expression of IDO activity.\(^{104}\) The same happens with the production of

Table 4 Physicochemical properties of selected synthetic inhibitors

<table>
<thead>
<tr>
<th>Synthetic inhibitors</th>
<th>Molecular weight (Da)</th>
<th>Polar surface area (Å$^2$)</th>
<th>Molecular surface area (Å$^2$)</th>
<th>Partition coefficient (log P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norharman (9H-pyrido [3,4-b]indole)</td>
<td>168.19</td>
<td>28.68</td>
<td>230.63</td>
<td>1.87</td>
</tr>
<tr>
<td>4-Phenylimidazole</td>
<td>144.17</td>
<td>28.68</td>
<td>211.56</td>
<td>1.89</td>
</tr>
<tr>
<td>Saliicylic acid</td>
<td>138.12</td>
<td>57.53</td>
<td>183.54</td>
<td>1.98</td>
</tr>
<tr>
<td>Ascorbic acid</td>
<td>176.12</td>
<td>107.22</td>
<td>208.27</td>
<td>–1.91</td>
</tr>
<tr>
<td>Nitric oxide</td>
<td>30.00</td>
<td>34.14</td>
<td>48.22</td>
<td>–0.35</td>
</tr>
<tr>
<td>1-Methyl tryptophan</td>
<td>218.25</td>
<td>68.11</td>
<td>322.23</td>
<td>1.32</td>
</tr>
<tr>
<td>2-Mercapto-benzothiazole</td>
<td>167.25</td>
<td>12.89</td>
<td>191.43</td>
<td>2.89</td>
</tr>
<tr>
<td>2-Mercapto-4-phenylthiazole</td>
<td>193.28</td>
<td>12.89</td>
<td>236.29</td>
<td>3.44</td>
</tr>
<tr>
<td>Phenylthiazole</td>
<td>161.22</td>
<td>12.89</td>
<td>215.12</td>
<td>2.66</td>
</tr>
<tr>
<td>Imidodicarbonimidic diamide</td>
<td>101.11</td>
<td>111.77</td>
<td>130.40</td>
<td>–1.46</td>
</tr>
<tr>
<td>4-Amino-1,2,5-oxadiazole-3-carboximidamide</td>
<td>127.10</td>
<td>114.81</td>
<td>147.82</td>
<td>–1.37</td>
</tr>
<tr>
<td>Phenformin</td>
<td>205.25</td>
<td>102.78</td>
<td>302.68</td>
<td>0.34</td>
</tr>
<tr>
<td>Cinnabarinic acid</td>
<td>300.22</td>
<td>139.28</td>
<td>311.10</td>
<td>0.44</td>
</tr>
</tbody>
</table>
The catalytic activity of the enzyme was affected by replacing the nitrogen in the ring with an oxygen or sulfur, resulting in enhanced affinity to inhibit the enzyme in nanomolar quantities. So far 1-MT is the only compound that has been allowed to be passed into clinical trials based on its potency, efficacy and safety profile.

**I-MT**

For a long time, the best anti-IDO compound was derived from changes in the molecule tryptophan, including inserting a methyl group in the nitrogen present in the indole ring, resulting in a synthetically active 1-MT with \( K_i \) of 34 \( \mu M \). The catalytic activity of the enzyme was affected by replacing inducible NO synthase, which directly interferes with IDO activity and eventually promotes degradation through proteolytic cleavage. This led to the belief that certain agonists exhibit the potential to reverse the state of immunosuppression caused by IDO in cases of cancer, thus contributing to anticancer therapy.

**2-Mercapto-benzothiazole, 2-mercapto-4-phenylthiazole and phenylthiazole**

In 2010, a study was conducted based on the structure–activity relationship between IDO and 55 possible synthetic inhibitors, which were analyzed by docking. It was assessed that 2-mercaptobenzothiazole, 2-mercapto-4-phenylthiazole and phenylthiazole were characterized as the
most efficient. These compounds presented Ki of 7.4 and 8.9 μM, respectively, and exhibited safety and efficacy both in the cellular and cell-free systems. In this study, Röhrig et al demonstrated that for an efficient inhibitory action, IDO inhibitors should contain: 1) a bicyclic fragment to fill the aromatic binding site, 2) an atom with pairs of free electrons that can coordinate with the iron present on the heme molecule (such as sulfur, oxygen or nitrogen), 3) a group able to establish van der Walls connections and 4) a group able to establish hydrogen bonds with fragments of specific amino acid structures on IDO.

**Ketoindoles**

Recently, noncompetitive inhibitors of IDO have been discovered with a micromolar range of inhibitory potency. A screening strategy was used to discover these compounds based on virtual tools, such as filters for exhibiting high throughput docking profiles. Calorimetric inhibition of in vitro assays revealed IC₅₀ of 13 μM with a Ki of 190 μM.

**Indol-2-yl ethanones**

In an effort to investigate novel compounds for IDO inhibition, indol-2-yl ethanones were identified and in vivo and in vitro tests were conducted to access the inhibitory concentrations. Results revealed that variations in inhibitory concentrations were obtained by altering the substituent at positions 5 and 6 of the indole ring, leading to IC₅₀ of 24–153 μM.

**Aminophenoazinones**

Oxidative cyclo-oxidation of 2-aminophenols led to the formation of a range of 2-aminophenoxazin-3-one compounds. Naturally, this reaction is catalyzed by a copper-containing oxidase enzyme referred as phenoxazinone synthase. A series of results were obtained after certain experiments to evaluate the concentrations required to inhibit IDO. It was reported that cinnabarinic acid was the most potent inhibitor out of the series of compounds with the IC₅₀ of 0.46 μM with a Ki at 326 nM.

**Methyl-thiohydantoin-L-tryptophan (MTH-Trp)**

To find a structurally distinct inhibitor for IDO, several commercially available compounds with indolamine, as the key component, were identified and tested. After biochemical analysis, the results indicated that MTH-Trp acts as a competitive inhibitor of IDO with Ki of 12 μM. Interestingly, in a cell-based assay, MTH-Trp shows ~20-fold more potency than 1-MT.

**Imidodicarbonimidic diamide**

A non-indolic IDO inhibitor was identified with an excellent potency against IDO. This compound which is classified as NSC 401366 has not been reported to have any other biological targets except its activity against IDO. On the basis of the experimental data, it was assessed that it demonstrated a Ki of 1.5±2 μM.

**4-Amino-1,2,5-oxadiazole-3-carboximidamide**

During the high throughput screening of a collection (Incyte’s corporate) of compounds, a potent inhibitor of IDO was identified. This compound serves as a competitive inhibitor with a Ki of 1.5 and an IC₅₀ of 1 μM when tested in HeLa cells. It has been confirmed by absorption spectroscopy that this compound binds to the active site of heme in the ferrous form of IDO.

**Conclusion**

Targeted drug delivery to cancer cells has been achieved by nanomedicine. Nanotechnology is used to design specific drug delivery platforms that have the ability to carry anticancerous compounds to the target cells ensuring safety and efficacy of the treatment.

Nanomedicine has taken a giant step into cancer therapeutics, but researchers still face a number of challenges in this field. Most of the nanomedicines have been in the preclinical phase in the drug discovery pipeline and it will take years in order to lead them with confidence from laboratory to the bedside. Undoubtedly, nanomedicine has shown foreseeable progress in the last decade and is a leading determinant for personalized and targeted cancer treatment.

A nanotechnology-based device has been tested, which can detect the association of protein that interacts with thioredoxin and functions to distinguish between the prostate cancer associated stroma from that of benign prostatic hyperplasia.

In a preclinical study, oral presentation of a nanoparticle-encapsulated active ingredient of green tea showed greater therapeutic benefits to combat xenografts of prostate cancer in mice presentation unencapsulated control.

Encapsulation of lutelina, a compound naturally found in the green vegetables in a water-soluble polymer to form nanoparticles, improved the ability of the compound to inhibit the growth of human cells of lung cancer and head and neck in crops cellular and mice, suggesting that the administration of nanoparticles similar to natural nutritional supplements could be applied in chemoprevention.
A multifunctional nanomedicine platform created from a single polymer can increase the sensitivity of the images, convert efficiently light into heat within tumors (photothermal therapy) and effectively deliver drugs in tumors, demonstrating the wide range of relevant clinical uses.\textsuperscript{115}

IDO inhibition is a pivotal area of research in cancer immunotherapy. A constitutive IDO expression in most human tumors is demonstrated in 2003.\textsuperscript{116,117} Commercial scale production of IDO inhibitors in conjunction with nanomedicine is, therefore, an important area of immunotherapy that should develop fairly soon. In conclusion, naturally occurring or synthetic IDO inhibitors have been shown to contain an antiproliferative function for cancer cells. These inhibitors are bound to find their way into the pharmaceutical industry to play a critical role in cancer immunotherapy,\textsuperscript{118–120} organ transplantation and treatment of infectious and autoimmune diseases.

Acknowledgment

We acknowledge the contributions of all researchers whose work could not be cited in this review because of space limitations.

Author contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure

The authors report no conflicts of interest in this work.

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