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Indoleamine 2,3-dioxygenase: As a potential prognostic marker and immunotherapeutic target for hepatocellular carcinoma

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Abstract

Tumor cells induce an immunosuppressive microenvironment which leads towards tumor immune escape. Understanding the intricacy of immunomodulation by tumor cells is essential for immunotherapy. Indoleamine 2,3-dioxygenase (IDO) is an immunosuppressive enzyme which mediates tumor immune escape in various cancers including hepatocellular carcinoma (HCC). IDO up-regulation in HCC may lead to recruitment of regulatory T-cells into tumor microenvironment and therefore inhibit local immune responses and promote metastasis. HCC associated fibroblasts stimulate natural killer cells dysfunction through prostaglandin E2 and subsequently IDO promotes favorable condition for tumor metastasis. IDO up-regulation induces immunosuppression and may enhance the risk of hepatitis C virus and hepatitis B virus induced HCC. Therefore, IDO inhibitors as adjuvant therapeutic agents may have clinical implications in HCC. This review proposes future prospects of IDO not only as a therapeutic target but also as a prognostic marker for HCC.

Key words: Hepatocellular carcinoma; Hepatitis C virus, Hepatitis B virus; Indoleamine 2,3-dioxygenase

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Core tip: Indoleamine 2,3-dioxygenase (IDO) is an immunosuppressive enzyme which mediates tumor immune escape in hepatocellular carcinoma (HCC). IDO up-regulation in HCC may lead to recruitment of

regulatory T-cells into tumor microenvironment and therefore inhibit local immune responses and promote metastasis. IDO inhibitors as adjuvant therapeutic agents may have clinical implications in HCC.

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INTRODUCTION

Hepatocellular carcinoma (HCC) is one of the top five malignancies and the second leading cause of cancer associated deaths worldwide^[1,2]. The prognosis of HCC is poor, with overall survival rates of 3%-5%^[3]. HCC patients are often diagnosed with advanced disease and therefore, the therapeutic options are limited^[4]. HCC is also characterized as an inflammation associated cancer^[5]. The infection of chronic hepatitis C virus (HCV) and hepatitis B virus (HBV) are well-known etiologic agents of HCC^[6]. The tumor progression has been observed among HCC patients in spite of the presence of tumor specific immune responses^[7], thereby suggesting that HCC adopts tumor immune escape mechanisms. Hence, understanding the HCC-induced immunosuppressive mechanism will be important to potentially design HCC targeted immune based therapies^[7].

HCV INDUCED HCC

HCV is one of the major causes of HCC^[8]. Approximately 700000 people die every year from HCV induced liver diseases^[9]. HCV causes both acute and chronic infections. About 15%-45% of HCV infected individuals spontaneously clear this infection without any treatment. Efficient clearance of acute viral infection is mediated by innate and adaptive immune responses^[10]. The remaining 55%-85% individuals may develop chronic HCV infection leading to liver cirrhosis^[11] and ultimately HCC^[12]. Occult HCV infection is characterized as the presence of HCV-RNA in hepatocytes and absence of HCV in serum according to usual tests^[13]. Occult cases of HCV infection occur as a consequence of infection in particularly non-hepatic immunologically protected sites or due to infection with HCV variant that is exclusively capable of infecting non-hepatic tissues^[14]. Role of occult HCV infection in HCC is still under investigation. The mechanism by which chronic HCV infection progresses and sustains in infected patients is still unclear. Impairment of HCV-specific CD4⁺ and CD8⁺ T-cell responses^[15-21] and abnormal dendritic cells (DCs) function has been observed^[22]. Furthermore, elevated levels of regulatory T (T-reg) cells at the onset

of infection have been noted among patients with chronic HCV infection as compared to those who cleared this infection^[23-26]. Impaired immune responses may contribute to the development of HCV induced HCC.

HBV INDUCED HCC

Similar to HCV, convincing epidemiological data also support the HBV induced HCC^[27]. Approximately 780000 individuals die every year from HBV induced liver diseases^[28]. The integration of HBV DNA and expression of HBV protein may have direct influence on cellular function^[27]. Increased rates of occult HBV infection have also been detected in HCC patients, specifically among HCV carriers^[29,30]. Occult HBV infection may further deteriorate the course of HCV infection^[31-33]. Several studies have shown that CD4⁺ and CD8⁺ T-cell mediated immune responses define the consequence of HBV acute infection. Chronic infection of HBV is associated with late, weak and transient CD4⁺ and CD8⁺ T-cell responses^[34,35]. Among patients with chronic HBV infection increase in the number of T-regs and depletion of effector T-cells may inhibit tumor immune surveillance against HBV induced HCC^[36].

INDOLEAMINE 2,3-DIOXYGENASE

Recently, an intracellular enzyme, indoleamine 2,3-dioxygenase (IDO/IDO-1) has been reported to play a vital role in regulation of liver immunity and inflammation^[37,38]. It is involved in immune homeostasis and immune-related functions in infectious, chronic inflammatory diseases and tumor immune-escaping mechanisms^[39-41]. This enzyme also induces maternal tolerance to fetal allograft^[42]. IDO initiates the first and rate limiting step of tryptophan degradation of the kynurenine pathway^[43]. Deprivation of tryptophan directly affects the cytotoxicity of T cells. In addition, the toxic metabolites produced from tryptophan degradation directly induce T-cell apoptosis *in vitro*^[41]. IDO may inhibit T-cell immunity by inducing differentiation and maturation of T-regs^[44]. IDO overexpression induces immunosuppression and tolerance^[40]. IDO expression and regulation is mediated by numerous immune and inflammatory factors^[45]. IFN- γ is the most potent inducer of IDO^[45].

Among HCC cases, IDO overexpression was associated with poor prognosis^[46]. IDO was expressed in human HCC derived cells following the stimulation of IFN- γ ^[46]. IFN- γ stimulated inflammatory mediators are involved in the progression of carcinogenesis^[47]. IDO expression was found to be elevated during hepatic inflammation^[48,49]. Persistent IDO expression within the liver microenvironment may play a critical role in declining HCV specific T-cell responses^[50]. It is also responsible for immune tolerance against HBV^[51]. The immunosuppressive role of IDO in tumor immunology has recently begun to be elucidated. The molecular

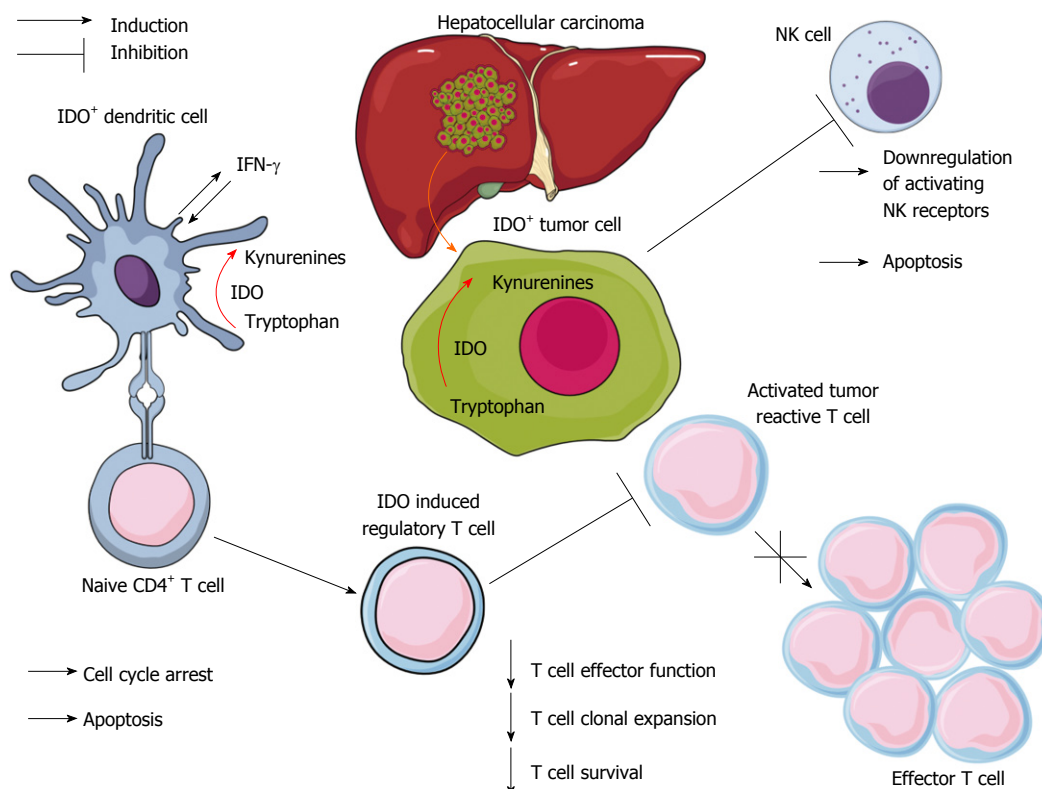


Figure 1 Immunosuppressive role of indoleamine 2,3-dioxygenase in human hepatocellular carcinoma. Indoleamine 2, 3-dioxygenase (IDO) expression is constitutively induced in both IDO⁺ tumor cells and plasmacytoid dendritic cells (DCs) by exposure to IFN-γ. The effector function of the antigen-specific T cells is impaired because of tryptophan degradation via IDO at tumor site, which in turn affects the immune-mediated control of tumor growth. A tolerogenic microenvironment is created by regulatory DCs resulting in the increased number of T-regs and reduced number of antigen-specific T cells leading to cell cycle arrest and apoptosis. IDO⁺ tumor cells lead to down-regulation of activating NK cell receptors.

mechanisms underlying tumor-immune escape are currently the topic of emerging interest. In this review we are addressing the immunomodulatory potential of IDO in HCC.

IDO ROLE IN HCC

It is recognized that IDO emerging from tumor has the capacity to inhibit the antitumor immunity (Figure 1) and promote metastasis^[52,53]. IDO plays a pivotal role in the pathogenesis of HCC (Table 1). Initially, IDO was demonstrated as a necessary enzyme for anticancer immune reactions of tumor infiltrating lymphocytes (TIL). The recurrence-free survival rate of IDO-positive HCC patients was higher than IDO-negative HCC patients^[54]. Further studies were proposed to investigate the difference in recurrence-free survival rate between HCC cases with and without TIL^[54]. IDO overexpression was associated with poor prognosis in HCC patients^[46,55]. IDO expression in HCC cell lines was dependent on IFN-γ. IDO was proposed as a novel favorable prognostic marker and therapeutic target for HCC^[46]. HCC associated fibroblasts stimulate NK cell dysfunction through PGE2 (prostaglandin E2) and IDO, and therefore create favorable condition for tumor metastasis^[56].

Another study added new insight into HCC induced

immunosuppression mechanism which offered a previously unrecognized target for HCC immunotherapy. CD14⁺ CTLA4⁺ DCs suppressed T-cell responses through IDO, which may contribute towards the progression of HCC^[57]. CB1R (cannabinoid receptor 1) system is up-regulated in chemically induced HCC, resulting in the induction of various tumor-promoting genes, including IDO. Peripheral CB1R blockade might play a role in the treatment of HCC^[58].

A comprehensive study explicated the role of hepatic carcinoma associated fibroblasts (CAFs) mediated IDO-producing regulatory DCs. This was the first study to prove that CAFs in HCC recruit DCs and convert them to regulatory DCs through IL-6 mediated STAT3 activation. STAT3 activation in DCs as mediated by CAFs-derived IL-6, is crucial for IDO production. IDO inhibition can reverse the hepatic CAF-DC regulatory function. These findings provide new insights into the mechanism by which CAFs induce tumor immunosuppression and may be targeted by IDO^[59]. IDO-1 expression in tumor cells of HCC showed distinct rather than uniform pattern. IDO-1 expression was induced only in tumor cells when co-cultured with both monocytes and T lymphocytes. This cooperation between T lymphocytes and monocytes played a crucial role in the IDO-1 expression in tumor microenvironment in immunocompromised mice

Table 1 Comprehensive review of indoleamine 2,3-dioxygenase involvement in hepatitis B virus infection, hepatitis C virus infection and hepatocellular carcinoma

| Year | Investigator | Description |
|------|---|---|
| 2004 | Ishio <i>et al</i> ^[54] | IDO is an essential enzyme for anticancer immune reactions of tumor-infiltrating cells. Authors also proposed to clarify the phenotype of IDO-producing cells in PBMC or tumor-infiltrating cells. |
| 2007 | Larrea <i>et al</i> ^[49] | Both human and chimpanzees express hepatic IDO that is directly correlated with CTLA-4. IDO induction may suppress the T-cell reactivity to viral antigens in chronic HCV infection. Hepatic IDO expression declined in animals who recovered from HCV infection. |
| 2008 | Pan <i>et al</i> ^[46] | IDO overexpression is significantly linked with metastasis. IDO may be a novel promising prognostic marker and candidate adjuvant therapeutic target for HCC. |
| 2008 | Iwamoto <i>et al</i> ^[67] | HBV infection helps the IDO induction in response to proinflammatory cytokines, specifically IFN- γ . |
| 2009 | Chen <i>et al</i> ^[51] | IDO associates with viral load and is accountable for immune tolerance against HBV. IDO inhibition can be a novel approach to break tolerance in chronic HBV infection. |
| 2012 | Li <i>et al</i> ^[56] | HCC associated fibroblasts stimulate NK cell dysfunction through PGE2 and IDO and therefore create favorable condition for tumor metastasis. |
| 2013 | Higashitani <i>et al</i> ^[48] | Elevated IDO activity is linked with liver inflammation and fibrosis in chronic HCV patients. In response to the inflammatory stimuli, DCs from patients tend to induce T-regs through IDO dependent mechanism. |
| 2013 | Lin <i>et al</i> ^[55] | IDO overexpression may be associated with poor prognosis in HCC patients. |
| 2014 | Han <i>et al</i> ^[57] | CD14 ⁺ CTLA4 ⁺ DCs suppressed T-cell response through IDO and IL-10. CD14 ⁺ DCs expansion induce systemic immunosuppression in HCC. |
| 2014 | Ohtaki <i>et al</i> ^[68] | IDO inhibition through 1-MT may facilitate in treatment of patients with fulminant hepatitis caused by HBV infection. |
| 2015 | Mukhopadhyay <i>et al</i> ^[58] | High IDO activity and consequent induction of immunosuppressive T-regs promote immune tolerance in tumor tissue. CB1R system is up-regulated in chemically induced HCC, resulting in the induction of various tumor-promoting genes, including, IDO. |
| 2015 | Lepiller <i>et al</i> ^[63] | Hepatic IDO performs a dual role during HCV infection by decelerating viral replication and regulating host immune responses. |
| 2015 | Barathan <i>et al</i> ^[64] | IDO is involved in the onset of immune exhaustion that eventually leads to HCC. |
| 2015 | Asghar <i>et al</i> ^[65] | IDO overexpression in the cirrhotic livers of HCV-infected patients may contribute to the development of HCC. IDO may also serve as therapeutic target against HCV. |
| 2016 | Shibata <i>et al</i> ^[62] | Elevation of L-kynurenine may play a critical role in both the early and late phases of liver carcinogenesis. IDO inhibition may act as an emerging approach for the prevention of liver cancer. |
| 2016 | Cheng <i>et al</i> ^[59] | IDO inhibitors can reverse hepatic CAF-DC regulatory function. IDO may be used as novel immunotherapeutic target for tumor immune escape. |
| 2016 | Salem <i>et al</i> ^[66] | IDO is overexpressed in IFN- α non-responder patient as compared with responder or healthy control. IDO induced immunosuppression may play role in non-responsiveness of chronic HCV patients to IFN- α based therapy. |
| 2016 | Zhao <i>et al</i> ^[60] | IDO is up-regulated in the hepatoma cells and serves as a counter regulatory mechanism stimulated by inflammatory response. IDO may be targeted as immunotherapeutic agent. |
| 2016 | Yoshio <i>et al</i> ^[69] | IDO activation in the early phase followed by a successive increase of chemokines and cytokines is involved in successful HBV clearance in patients with acute hepatitis. IDO possibly acts as a noncytopathic anti-HBV effector. |
| 2016 | Ye <i>et al</i> ^[61] | HIF-1 α /CCL20/IDO axis in HCC is crucial for promoting tumor metastasis through both the induction of epithelial-to-mesenchymal transition and the establishment of an immunosuppressive tumor microenvironment. |

HCC: Hepatocellular carcinoma; IDO: Indoleamine 2,3-dioxygenase; PBMC: Peripheral blood mononuclear cells; CTLA-4: Cytotoxic T-lymphocyte associated protein-4; DCs: Dendritic cells; NK: Natural killer cells; HCV: Hepatitis C virus; HBV: Hepatitis B virus; PGE2: Prostaglandin E2; T-reg: Regulatory T-cells; HIF-1 α : Hypoxia-inducible factor-1 α ; 1-MT: 1-Methyl tryptophan; CB1R: Cannabinoid receptor 1; CAF: Carcinoma-associated fibroblasts.

as well. IDO up-regulation in hepatoma cells might serve as a counter regulatory mechanism. Further investigations are warranted to understand the clinical benefit of cancer immunotherapy targeting IDO-1 in HCC patients^[60]. Recently, the role of IDO in metastasis of HCC has been investigated. Hypoxia inducible factor-1 α (HIF-1 α)/CCL20/IDO axis plays a key role in tumor metastasis by promoting epithelial to mesenchymal transition as well as inducing an immunosuppressive microenvironment^[61]. IDO up-regulation may facilitate the progression of liver carcinogenesis. IDO overexpression might be responsible for creating inflammatory and immunosuppressive tumor microenvironment. Hence, IDO inhibition might lead to the development of novel therapy for HCC^[62].

IDO up-regulation has been reported in human and chimpanzee livers with chronic HCV infection. HCV infection was observed to promote IDO induction in response to the pro-inflammatory cytokines and activated T-cells. IDO was considered as a therapeutic target for HCV infection^[49]. IDO activity was elevated in chronic HCV infected patients. Furthermore IDO-DCs from patients induced more T-regs *in vitro* as compared to healthy controls. T-regs induced by IDO-DCs were decreased with IDO specific inhibitor 1-methyl tryptophan (1-MT). 1-MT could serve as possible approach to improve the immune responses in HCV infection^[48].

IDO plays a dichotomous role in HCV infection. Hepatic IDO might be beneficial in acute infection and damaging in chronic infection. HCV infection stimulates

the IDO expression. IDO induction during HCV infection down-regulated the viral replication but with the course of disease it had significant inhibitory effect on CD4⁺ T cell proliferation. IDO induction in acute and chronic HCV infection may provide an insight into novel therapeutic intervention^[63]. IDO is one of the factors that are involved in the onset of immune exhaustion during chronic HCV infection, ultimately leading to HCC^[64]. Our group has already established that IDO overexpression in the cirrhotic livers of HCV-infected patients might contribute to the development of HCC^[65]. IDO may also serve as a novel therapeutic target against HCV^[65]. Another study added that IDO expression was higher in IFN- α non-responder patients as compared to responders or healthy controls. These findings opened a new avenue for targeting IDO in HCV therapy^[66].

IDO expression and its activity was significantly higher in the chronic HBV infected patients than healthy controls^[51]. IDO was responsible for immune tolerance against HBV. IDO has a potential to be used as therapeutic target in chronic HBV infection^[51]. Mice model study showed that HBV infection facilitated the induction of IDO particularly through IFN- γ in hepatocytes. IDO elevation was responsible for the transduction of cytotoxic T lymphocytes which ultimately inhibit the T-cells responses^[67]. Another study reported that IDO in murine fulminant hepatitis model is induced by HBV-specific T lymphocytes. IDO inhibition can reduce liver injury^[68]. IDO has an antiviral activity in early phase of HBV infection which is supported by various immune mediators. IDO activity is boosted by NK cells and plasmacytoid DCs through IFN- α and IFN- γ dependent mechanisms^[69]. These findings demonstrated the promising role of IDO in HBV therapy.

THERAPEUTIC CHALLENGES AND FUTURE DIRECTION

Although several reviews have been published that explain the immunomodulatory role of IDO in chronic infection and neoplasia^[70,71], the aim of the present paper is to summarize the recent data about IDO expression in HCV and HBV induced HCC and its role as a potential therapeutic target in HCC. IDO overexpression was associated with poor prognosis in HCC patients^[46,55-62]. However a study by Ishio *et al.*^[54] also reported that recurrence-free survival rate of IDO-positive HCC patients was higher than that of IDO-negative HCC patients^[54]. Serum tryptophan concentration was also lower in patients with chronic HCV and HBV infection than healthy controls^[72]. Moreover an antiviral activity of IDO has been reported in early phase of HBV infection supported by various immune mediators^[69]. Hepatic IDO might be beneficial in acute infection and damaging in chronic infection^[63]. IDO overexpression in HCV and HBV infection is associated with impairment of immune response

and diseases progression^[48,49,51,63-68]. In view of the contradictory findings, further studies are warranted to understand the precise role of IDO in HCV and HBV induced HCC.

Recently, IDO inhibitors have been found as adjuvant therapeutic agents with clinical implications in HCC^[62]. Investigating an efficient and less toxic IDO inhibitor is emergent. Targeted hepatic IDO inhibition using nanoparticles may provide a better outcome. Tryptophan-2,3-dioxygenase (TDO) has a biochemical activity similar to that of IDO^[73,74]. IDO-2 is also a recently discovered isoform of IDO^[75,76]. Both IDO-2 and TDO are involved in the degradation of tryptophan^[77]. Future studies should explore the role of IDO as well as IDO-2 and TDO in HCC. Therapeutics of IDO are unquestionable but its potential as prognostic biomarker may also have significant outcomes.

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