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Protective role of STING against gliomagenesis: Rational use of STING agonist in anti-glioma immunotherapy

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Abstract (48 words)

We recently reported that STING contributes to antiglioma immunity by triggering type I IFN induction in glioma microenvironment. Moreover, intratumoral administration of STING agonist improved the efficacy of peptide vaccination in a mouse glioma model, suggesting the rational use of STING agonists in the immunotherapy of brain tumor.
Glioma accounts for approximately 40% of all primary brain tumors and are responsible for approximately 13,000 cancer-related deaths in the US each year, representing a large unmet medical need. We have previously demonstrated the protective role of type I interferon (IFN) signaling against glioma progression using a clinically relevant de novo mouse glioma model, and identified single nucleotide polymorphisms (SNPs) in human IFNA genes associated with the prognosis of glioma patients. However, it remained elusive how type I IFNs were induced in the glioma microenvironment. We have recently demonstrated that type I IFNs are induced in de novo glioma tissues and directly impact on functions of immune cells. Glioma-bearing brain tissues showed higher levels of type I IFNs than non-tumor-bearing brains. Using a type I IFN-reporter mice (tdTomato mice), type I IFN signaling was detected in a variety of glioma-infiltrating immune cell populations. Especially, type I IFN signaling down-regulated Foxp3 and Tgfβ1 expression levels and immuno-suppressive activity in CD4+ T cells, while up-regulated Tbx21 and Ifnγ expression levels and cytotoxic activity in CD8+ T cells, suggesting that type I IFN signaling directly enhances antitumor activity of T cells in the glioma-microenvironment.

We next focused on the signaling mechanism responsible for the type I IFN production in the glioma microenvironment. STING (stimulator of IFN genes) plays a critical role as one of the adaptors for cytosolic DNA sensing thereby triggering type I IFN production. Due to the presence of apoptotic or necrotic cells in the tumor microenvironment, we hypothesized that double strand DNA (dsDNA) such as genomic DNA (gDNA) from the dead cells would induce type I IFN signaling through STING. Using wild type (WT) and STING-deficient (Sting<sup>G<sub>0/G0</sub></sup>) mouse-derived macrophages, we demonstrated in vitro that gDNA up-regulated type I IFN mRNA levels at least partially in a STING-dependent manner, implying that STING mediates type I IFN induction during glioma progression. When we induced de novo gliomas in WT
and Sting\textsuperscript{Gt\textbackslash Gt} mice, glioma tissues of Sting\textsuperscript{Gt\textbackslash Gt} mice showed lower levels of type I IFN mRNA and type I IFN-inducible ISG54 protein compared with those of WT mice. Furthermore, glioma-bearing Sting\textsuperscript{Gt\textbackslash Gt} mice showed shorter survival, associated with increased immuno-suppressor cells, such as CD11b\textsuperscript{+} Gr-1\textsuperscript{+} immature myeloid cells and CD25\textsuperscript{+} Foxp3\textsuperscript{+} CD4\textsuperscript{+} regulatory T cells, and lesser IFN\textsubscript{γ}-producing CD8\textsuperscript{+} T cells in the glioma microenvironment compared with WT mice. These observations suggest that STING is at least partially responsible for spontaneous type I IFN production in glioma and positively affects the activity of immune cells in the glioma microenvironment (Fig. 1).

On the basis of these observations, we attempted to evaluate if administration of STING agonist would enhance the antiglioma immunity. Intratumoral administration of STING ligand, cyclic-di-GMP (c-di-GMP) significantly prolonged survival of glioma-bearing mice, increased Ccl5 and Cxcl10 mRNA levels, and enhanced infiltration of effector cells, such as CD4\textsuperscript{+} T cells and CD8\textsuperscript{+} T cells compared with control treatment in a STING-dependent manner. Also, in the de novo glioma model, c-di-GMP treatment significantly inhibited glioma growth. These suggest that direct intratumoral administration of c-di-GMP enhances antiglioma immunity by enhancing the recruitment of T cells into the brain tumor site. Moreover administration of c-di-GMP significantly enhanced the efficacy of peptide vaccinations targeting a tumor-specific antigen by recruiting peptide-specific CD8\textsuperscript{+} T cells in the tumor site. This strongly supports the development of combination strategy with vaccine and a STING agonist. Although we selected c-di-GMP as a STING ligand in this study due to its commercial availability, there are more agonists for STING such as c-di-AMP, eGMP-AMP (2’3’cGAMP or 3’3’ cGAMP), or 10-carboxymethyl-9-acridanone (CMA)\textsuperscript{4, 5}. Moreover, while activities of bacterium-derived c-di-GMP can be dependent upon single nucleotide polymorphisms (SNPs) in human STING, metazoan-derived 2’3’cGAMP stimulate STING regardless of the SNP status\textsuperscript{6}. These observations warrant inclusion of 2’3’cGAMP in our studies evaluating
STING agonists as adjuvants in cancer immunotherapy\textsuperscript{7}. On the basis of our current study, early-phase clinical studies are warranted to evaluate the safety and efficacy for intratumoral administration of a STING agonist in patients with glioma as well as other tumors.
References (up to 10)


**Figure legend**

**Figure 1.** Protective role of STING against glioma by initiating type I IFN signaling in the glioma microenvironment. CD11b⁺ macrophages produce type I IFNs, in a partially STING-dependent manner, in response to dsDNA. We hypothesize that dsDNA is released from dead cells, such as tumor, stroma and immune cells, in the glioma microenvironment. Type I IFNs induce chemokine production to recruit CD4⁺ T cells and CD8⁺ T cells that contribute to the anti-glioma immune response.
Figure 1

Dying or dead cells

Glioma cells

Immune cells

Stroma cells

CD11b+ macrophages

STING

Type I IFNs

Up-regulated chemokines

Enhanced migration of CD4+ T cells and CD8+ T cells into the glioma microenvironment

Inhibition of tumor growth by CD8+ T cells

Enhanced migration of CD4+ T cells and CD8+ T cells into the glioma microenvironment

DSDNA