The Emerging “Hallmarks” of Metabolic Reprogramming and Immune Evasion: Distinct or Linked?

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Abstract
The role of the immune system in tumor elimination has been shown to be increasingly ambiguous, as many tumors not only escape recognition by the adaptive immune response but sometimes even prime the immune cells to promote tumor growth. This effect is achieved through many mechanisms, which include both direct interference with the cells of the adaptive
immune response and indirect immunosuppression achieved through modification of the tumor microenvironment. We propose that through up-regulation of glycolysis and consequent lowering of pH in the tumor microenvironment, tumors can take advantage of a pH control system, already exploited by specific immune cell subpopulations, to gain control of the immune system and suppress both cytotoxic and antigen-presenting cells. This is accomplished through the direct competition of tumor cells with actively proliferating glycolytic immune cells for glucose, and indirectly through the creation by the tumor of a microenvironment that interferes with maturation and activation of both antigen presenting cells and naïve cytotoxic T cells. Imunosuppressive properties of an acidic microenvironment in the vicinity of the tumor can thus provide additional benefits for up-regulation of glycolysis by tumor cells, suggesting that the two emerging “hallmarks of cancer”, altered glucose metabolism and immune suppression, are in fact fundamentally linked.

Introduction

Tumors have evolved numerous ways to escape recognition by the adaptive immune system. These involve suppressing the adaptive immune response at the level of antigen presentation through promotion of expansion of immunosuppressive myeloid-derived suppressor cells (MDSCs), while preventing their maturation to functional antigen-presenting cells, including dendritic cells (DCs) (1), and by promoting the expansion of tumor-associated macrophages through up-regulated expression of IL-4, IL-10, IL-13 and glucocorticoid hormones (2, 3). Interestingly, low pH has been seen to influence the balance of function among immune subpopulations, including expansion of immunosuppressive MDSCs through stabilization of HIF-1α, as well as direct the priming of naïve T cells towards the tumor-promoting Th2 phenotype and away from the anti-tumor Th1 phenotype by way of denaturation of acid-labile
IFN-γ (4, 5). Here we propose this same ability of low pH to dictate the actions of immune subpopulations may be exploited by tumors to circumvent the anti-tumor immune response, made possible through the up-regulation of glycolysis and avoidance of oxidative phosphorylation by tumor cells. It is noted that such mechanisms may be undermining the efficacy of existing immunotherapies.

**Overview of normal immune response**

As hematopoietic stem cells leave the bone marrow, they differentiate either into lymphoid progenitors that migrate to the thymus, where they further differentiate into T cells, or into myeloid progenitors that differentiate into monocytes and migrate to tissues, where they further differentiate into immature myeloid cells, such as dendritic cells (DCs) and macrophages. Once immature DCs encounter an antigen, they internalize it, display its fragments on the cell surface, and migrate to lymph nodes, where they can activate naïve T cells. DCs mature, i.e., they lose their ability to engulf pathogens and develop an increased ability to communicate with T cells, during migration. Cytotoxic T cells activated by DCs undergo rapid clonal expansion and then migrate throughout the body in search of cells exhibiting the corresponding antigens. T cells perform their cytotoxic function either via secretion of perforin or similar substances that damage the cell membrane and cause the cell to swell and lyse, or through inducing apoptosis, which causes the target cell to shrink and die (6, 7).

Hematopoietic stem cells that do not migrate to thymus but remain to mature in the bone marrow yield antigen-specific precursors of B cells, which then migrate to secondary lymphoid organs, such as lymph nodes and spleen. Upon recognition of antigens by B cell receptors, B lymphocytes become activated and undergo rapid clonal expansion, gaining an augmented ability to recognize foreign antigens (7). While the activity of B lymphocytes is primarily associated
with antigen recognition and presentation, they have also been shown to promote a chronic inflammatory state associated with pre-malignant progression (6).

Myeloid derived suppressor cells (MDSCs) are a heterogeneous population of immunosuppressive cells of myeloid lineage (1), whose concentration has been shown to be increased up to ten-fold in cancer patients (8, 9). As will be seen, MSDCs play an important role in the connection between tumor metabolic reprogramming and immune evasion.

Overview of glucose metabolism in normal and cancer tissues

All the cells in the human body, whether benign or malignant, depend on metabolizing glucose both for proliferation and physiological maintenance. Once ingested via nutrient transporters, glucose is broken down into pyruvate and 2 molecules of ATP. In the presence of oxygen, pyruvate enters the mitochondrion of the cell, where it is oxidized via the Krebs cycle, yielding up to 30 additional molecules of ATP. Otherwise, pyruvate is converted to lactate by the enzyme lactate dehydrogenase (LDH) and is then released from the cell. With respect to the exploitation by the tumor or immune cells of “glycolysis” or the “glycolytic phenotype”, we will, in deference to literary precedent, be referring henceforth to a process that converts glucose to lactate, rather than pyruvate. This is done with the understanding that normal glycolysis is not a pathway that deviates from oxidative phosphorylation, but links to it when the latter is operative.

While energetically inefficient, glycolysis importantly can provide cells with glycolytic intermediates necessary for biosynthesis of DNA and cell-structural material. This is done via the pentose phosphate pathway and involves generating NADPH, which is then used for fatty acid synthesis, and ribose-5-phosphate, which is used for synthesis of nucleotides (10). That said, a special property of cancer cells is their frequent persistence in using glycolysis even in the areas of ample oxygen supply capable of supporting oxidative phosphorylation, a phenomenon
known as the Warburg effect. As will be discussed, this could confer on cancer cells an ability to synthesize various macromolecules needed to sustain high proliferation rates and otherwise compete with the immune population on its own terms, as actively proliferating cells of the immune system also bypass oxidative phosphorylation during glucose metabolism even in the areas of ample oxygen supply.

Activated immune cells engage in glycolytic metabolism to facilitate expansion

In order to perform their cytotoxic function, activated immune cells need to undergo clonal expansion, a very energy-demanding process (11). To meet this demand, it has been observed that activated T cells can hyper-induce glycolysis quickly, increasing uptake as much as 20-40-fold as cells prepare to divide (12) to reach levels of consumption where an estimated 85% of glucose supply is excreted by T cells as lactate (13). To permit production of the necessary complex macromolecules for proliferation, transition from the resting to the activated state for T cells causes a switch from catabolic to anabolic metabolism. This involves the active suppression of oxidation of amino acids and lipids, diverting them to be used, along with glucose metabolites, as building materials for cell expansion (11). By contrast, failure to increase glucose metabolism during lymphocyte activation prevents cell growth and prevents production of cytokines such as IFN-\(\gamma\), which are required for effector function (14). Notably, activated T cells switch to glycolysis under both hypoxic and normoxic conditions, suggesting that, just as in cancer cells that undergo matching metabolic shifts (15), it is the speed of nutrient uptake and the increased ability for fast proliferation that drive the shift in metabolic strategy for immune cells (11).

Resting T cells, on the contrary, derive most of their ATP from oxidative phosphorylation. Although quiescence is not as energy demanding as proliferation, it is still an actively maintained
state: ATP generated via oxidative phosphorylation is very likely used to actively suppress, by up-regulated protein degradation, the expression of cell-cycle proteins (11). However, without cytokine-dependent signals from their microenvironment, such as IL-2 or IL-7, even resting cells cannot take up nutrients, and thus die by starvation as they internalize Glut1 and other nutrient transporters (14). From an evolutionary point of view, this could arguably be serving as a protective mechanism for the host to ensure that immune cells do not compete for nutrients with somatic cells unless they are performing their function. Notably, cancer cells do not require any additional signals from their microenvironment to enable them to take up nutrients, providing them with a possible additional competitive advantage in the event of low tumor immunogenicity.

Dendritic cells have also been shown to switch to glycolysis in an activated state (16). However, in the tumor microenvironment their activation is often suppressed, yielding an expansion of the population of immature myeloid cells, also known as myeloid derived suppressor cells.

Tumor-immune interaction is modulated by microenvironmental acidification due to glycolysis dependence

Lowered pH due to glycolysis dependence can prevent HIF-1α denaturation under normoxia

A possible link between immune modulation and glycolysis dependence of the tumor-immune system lies in the body’s response to hypoxia, which is often observed in tumor microenvironments as a result of up-regulated cell growth and insufficient vascularization. Exposure to hypoxic conditions causes the cells to up-regulate production of hypoxia-inducible factor 1 (HIF-1), which is a heterodimer that consists of the oxygen sensitive HIF-1α and a constitutively expressed HIF-1β subunit (17, 18). In the absence of oxygen, HIF-1α binds to hypoxia-response elements (HRE), activating the expression of numerous hypoxia-response
genes, including vascular endothelial growth factor (VEGF) (19) and other angiogenesis-promoting factors that stimulate blood flow and bring oxygen to the hypoxic areas. In the presence of oxygen, HIF-1α normally binds to the tumor suppressor von Hippel-Lindau (VHL) protein, which causes the ubiquitylation and subsequent degradation of HIF-1α by proteasomes (18).

The environmental effect of glycolysis dependence may work predominantly through lowered pH. Mekhail et al. (20) have shown that both hypoxia and normoxic acidosis can neutralize the function of VHL protein, which suggests that an acidic microenvironment, such as can be observed in many tumors that up-regulate glycolysis and increase their production of lactic acid, can “simulate” the effects of hypoxia even in the presence of an adequate oxygen supply. This effect has been observed in the 5.8-6.6 pH range, while many hypoxic tumors have pH ranges from 6.4 to 7.0 (21). Consequently, in low pH, created as a by-product of up-regulated glycolysis, HIF-1α may not be degraded even in the presence of an adequate oxygen supply, resulting in increased production of VEGF and increased angiogenesis. This, in turn, could stimulate expansion of myeloid derived suppressor cells (MDSCs) (1). Expansion of the MDSC population both within tumor microenvironment and at its periphery results in up-regulated expression of immunosuppressive factors such as arginase (arg1), as well as in an increased production of nitric oxide and reactive oxygen species (ROS). Increased activity of arg1 in MDSCs leads to enhanced L-arginine catabolism; consequent shortage of L-arginine can inhibit CD8+T cell function (22). Nitric oxide can suppress T cell function through inhibition of MHC-II expression and T cell proliferation, and apoptosis (23, 24). Tumor-derived factors, such as TGF-β, induce production of ROS by MDSCs; inhibition of ROS production has been shown to nullify the suppressive effect of these cells (25). Interestingly, peripheral MDSCs migrating to
the tumor site may themselves differentiate into tumor-associated macrophages (TAMs), which produce cytokines that can further suppress T cell responses in a non-specific manner (1). MDSCs can also suppress cytotoxic lymphocytes both by not differentiating into functional dendritic cells and thus not fulfilling their antigen-presenting function. Moreover, Corzo et al. (26) showed that in the tumor microenvironment, up-regulation of HIF-1α can also promote MDSC differentiation towards tumor-associated macrophages, which in turn suppress both specific and non-specific T cell functions. Doedens et al. (27) further showed that loss of HIF-1α in myeloid cells directly counters hypoxia-induced suppression of T cell activation and leads to slowed tumor progression. Interestingly, permanent dysfunction of VHL protein, which results from loss-of-function mutations, can cause von Hippel-Lindau disease, characterized by sporadic hemangioblastomas found in kidney, cerebellum, retina and spinal cord, and renal clear-cell carcinomas (28).

In summary, the acidic microenvironment created in tumor vicinity by glycolytic activity can cause up-regulation of the expression of HIF-1α and VEGF, both of which can contribute not only to increased angiogenesis but also to decreased antigen presentation and the expansion of the population of immunosuppressive MDSCs.

Lowered pH due to glycolytic activity can promote tumor growth through inhibition of IFN-γ and TNF

Another way by which tumors can suppress immune function is through interfering with maturation of regulatory T cells. One possible mechanism can be traced to interferon γ (IFN-γ), which is a cytokine produced by natural killer (NK) cells of the innate immune system, and by cytotoxic lymphocytes (CTLs) (29). It is one of the primary mediators of both innate and adaptive immunity, playing a key role in macrophage activation, promoting adhesion and
binding required for leukocyte progression, and modulating the differentiation both of helper (Th) and regulatory (Treg) T cells (29, 30).

T helper cells consist of CD8+ cytotoxic cells and CD4+ helper cells (Th), the latter of which are further subdivided into Th1 cells that primarily express IFN-γ and tumor necrosis factor (TNF-α), and Th2 cells expressing IL-4, 5 and 13 (5). Th1 cells maximize the killing efficiency of macrophages and proliferation of CD8+ T cells, and inhibit production of IL-4. Th2 cells can stimulate B cells, which have been associated with tumor-promoting inflammatory responses (6), although Th2 cell differentiation itself is inhibited by IFN-γ (30). Indeed, mice with inhibited IFN-γ signaling display increased Th2 polarization and are consequently more susceptible to tumor development (31). In vitro, IL-4 expression increases expression by TAMs of epidermal growth factor (EGF), which improves entry of cancer cells into the circulation (5). IFN-γ promotes activation of M1, or ‘classically activated’ macrophages, which are involved in combating acute-phase parasitic infections (2-4, 32) and anti-tumor immunity (4). Meanwhile, M2, or ‘alternatively activated’ macrophages, are stimulated by IL-4, IL-13 and IL-10 (3, 4, 31), are associated with tissue repair (2) and encourage tumor progression (4).

As it so happens, IFN-γ is acid-labile and can be denatured in low pH (33), which will likely cause T cell maturation to be diverted away from the anti-tumor Th1 phenotype towards the pro-tumor Th2 phenotype, as well as prevent the activation of tumoricidal M1 macrophages. Further support for a link between immune competency and expression of IFN-g and TNF-a may be drawn from a study by Barth et al. (34), who showed using mice irradiated to abolish cytotoxic lymphocytes, that the adoptive transfer of noneytolytic CD8+ tumor infiltrating lymphocyte (TIL) cultures into these hosts can bring about regressions of established tumors. Interestingly, they found 1) that the effectiveness of the cultures related more to their production of IFN-γ and
TNF-α than to their direct cytotoxicities; and 2) that antibodies to IFN-γ and TNF-α inhibited their anti-tumor potencies independently of their cytotoxicities. Suggested was a novel delayed-type hypersensitivity (DTH) reaction mechanism for IFN-γ- and TNF-α-dependent CD8+ anti-tumor action, involving stimulated resident macrophages as the final effectors of the DTH. In a second study coupling acidity with macrophage action (35), it was found that TNF-α secretion by activated alveolar macrophages was reduced for lower pH values. Taken together, these findings may be suggesting that sufficient acidification of tumor microenvironment, with accompanying inactivation of IFN-γ and/or suppression of TNF, may encourage tumor progression by limiting the maturation and function of Th1 lymphocytes and M1 macrophages, while encouraging the expansion of tumor-promoting Th2 lymphocytes.

**Humoral and non-adaptive immune effects**

Beyond the generally immunosuppressive action usually attributed to low pH, evidence suggests it may also be a differential regulator of immune function, promoting certain humoral and cellular immune activities as well (36). Indeed, Lopez et al. (37) demonstrated that acidic pH increases the activity of human immunoglobulin G (IgG) binding to human neutrophils, monocytes and NK cells. Further, as demonstrated by a number of studies (38-43), increased activity of complement system is also observed at lower pH. Trevani et al. (44) showed delayed apoptosis of neutrophils in low pH, as well as increased binding of neutrophils to endothelial cells during inflammation via up-regulated expression of surface molecules, such as CD18. Some years later, Tong et al. (45) demonstrated that exposure of cells to pH 6.5 can in fact promote maturation of dendritic cells through significant up-regulation of expression of CD11c, MHC class II, as well as co-stimulatory molecules CD86 and CD80; an effect that is not observed at pH 7.3. Other groups (46, 47) have also reported increased activation and improved
efficacy of DCs cultured in acidic conditions, accompanied by increased production of Th1-associated cytokines, such as IL-12, as well as MHC-class I molecules. One may conclude the role of extracellular acidosis is not clearly immunosuppressive, as is commonly believed, but that acidosis can have both promoting and suppressive effects on different classes of immune cells.

**Aerobic glycolysis by tumor cells can promote immune evasion**

A preponderance of evidence therefore suggests that tumor development in the immune context can be modulated by environmental acidification, made possible by tumor adoption of the same glycolytic dependency as seen in the immune system. In turn, as the immune system can both be promoted and suppressed by the microenvironmental consequences of glycolysis, tumor cooption of these same responses through adoption of a glycolytic program provides the makings of an elaborate competitive dynamic. All of these considerations are summarized in Figure 1. Interestingly, the observed abilities of cancer cells to evade the immune system and reprogram their energy metabolism have recently been identified as distinct “emerging hallmarks of cancer” (48). Given the shared strategic dependence of both cancer and immune systems on glycolysis, however, the two hallmarks would appear fundamentally linked. Both immune and cancer cells can hyper-induce glycolysis for glucose metabolism when they switch to a highly proliferative state, satisfying a need shared by both systems for large amounts of readily available energy and building materials (10). However, while unactivated immune cells are largely dependent on oxidative phosphorylation (11) and may completely shut down glucose transporters (14), activated T cells often continue being glycolytically-dependent even in well-oxygenated areas. A similar phenomenon occurs in cancers and is known as the Warburg effect (49-51). In this case, since both cancer and immune cells are heavily dependent on the glycolytic pathway for active proliferation, the competition may well become limiting for immune response in the tumor.
microenvironment, should cancer cells be more efficient at exploiting the glycolytic state. Also, while activated T cells cannot survive without adequate glucose supply and require both large amounts of glucose and receptor co-stimulation in order to be able to successfully take up the nutrients (11), tumor cells can enter quiescence for an extended period of time, or even become “dormant” (52, 53) until conditions improve. Moreover, since tumor cells can primarily accommodate self-perpetuation, while immune cells must carry out functions beyond their own survival, the shortfall may further disadvantage the ability of T cells to expand in the hostile environment (54).

These events in combination could allow cancer cells to effectively escape elimination by the adaptive immune response. Indeed, up-regulation of glycolysis has been hypothesized to give a number of other selective advantages to cancer cells, including increased proliferative capacity that results from utilization of intermediate products of glycolysis for biosynthesis of nucleic acids (10) and increased invasiveness that results from pH-induced damage to somatic cells in the vicinity of the tumor (21, 55). It is possible that tumors that maintain a tight control over pH in their vicinity, and successfully compete with immune cells for necessary nutrients, are those that are able to circumvent the anti-tumor immune response and progress to full malignancy. One could speculate that the established ability of low pH to selectively promote certain humoral and cellular immune activities is something that the tumor, through its own evolving bias to glycolytic acidosis, could exploit to promote the tumor population itself. In this way, low pH could, in the net, favor the tumor population in the tumor-immune competition and improve the likelihood of tumor escape.

These considerations may provide an explanation for the limited success of immunotherapy (56). Whether immunotherapy is targeted towards increasing the activity of antigen presenting
cells, such as DCs (57), or towards directly promoting the activity of cytotoxic T cells via adoptive transfer therapies (58), the conditions in the tumor microenvironment can be such that even the most potent immune cells will not accomplish their cytotoxic function. If, for instance, resources in the tumor microenvironment are limited due to up-regulation of glycolysis by tumor cells, then activated cytotoxic T cells will not be able to undergo clonal expansion due to nutrient deprivation. Supporting evidence for this hypothesis comes from observations of an apparent synergistic effect when chemotherapy is administered concurrently with immunotherapy (59), possibly in part due to decreased competition for resources that follows from extensive mortality of cancer cells. Finding ways to manipulate the tumor microenvironment may thus be an important therapeutic step towards improvement of immune response, whether induced naturally or augmented through immunotherapy. More broadly, our increasing knowledge of the influences of altered glucose metabolism and increased immune invasion on tumor growth is revealing that two “hallmarks” of cancer thought to be distinct are in fact fundamentally linked, carrying vital implications for both biological understanding and clinical approach.

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References


Figure Caption.

Figure 1. The cascade of effects resulting from up-regulated glycolysis and consequent lowering of pH in the tumor microenvironment on the cells of the adaptive immune system.
Figure 1
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