Bortezomib Induces Immunogenic Cell Death in Multiple Myeloma

Laurence Zitvogel1,2,3,4,5,6 and Guido Kroemer1,6,7,8,9,10

Summary: As a general rule, successful antineoplastic treatments induce an antitumor immune response, even if they were initially designed to target cancer cell–autonomous pathways. In this issue of Blood Cancer Discovery, Gulla and colleagues reveal that the proteasome inhibitor bortezomib induces immunogenic stress and death in multiple myeloma cells, thus explaining its therapeutic efficacy.

See related article by Gulla et al. (1).

Until recently, malignant disease has been viewed as a purely cell-autonomous disease mediated by the progressive accumulation of genetic and epigenetic alterations in premalignant and malignant cells that override cell-intrinsic tumor-suppressive mechanisms, including senescence and apoptosis. Nowadays, this view has been challenged, and it has become increasingly clear that malignant disease is also the result of insufficient immunosurveillance, meaning that tumors can only develop after their recognition and after elimination by the immune system has failed. Beyond academic considerations on the etiology of neoplastic disease, this concept has major practical implications. Indeed, the recent approvals of immune-checkpoint blockers (mostly targeting PD-1 and PD-L1) across a wide spectrum of previously intractable malignant diseases illustrates the possibility to transiently reactivate failed immunosurveillance to obtain tangible benefits in a substantial (though admittedly insufficient) fraction of patients with cancer.

The cell-autonomous vision of cancer has profoundly influenced the way in which cancer drugs have been conceived and developed. After the widespread implementation of chemo-therapeutic cytotoxicants that indiscriminately kill proliferating cells of any kind, explaining their major side effects, the idea arose to develop “targeted” or “personalized” anticancer agents as part of a novel “precision medicine.” Thus, drugs should target the oncogene to which a cancer cell is “addicted,” for example, an activating mutation in an oncogenic kinase, thereby acting on malignant but not normal cells. Alternatively, drugs should target “non-oncogene addiction” (NOA), the phenomenon where tumor cells present stress phenotypes that render them vulnerable to specific agents. One such drug that targets NOA is bortezomib, an inhibitor of the 26S proteasome used for the treatment of multiple myeloma (MM). Now, in the current issue of Blood Cancer Discovery, Gulla and colleagues report that bortezomib has the capacity to induce potent anti-cancer immune responses.

Although anticancer drugs, be they nonspecific chemotherapeutics or targeted agents, were supposed to mediate their effects by direct cytostatic or cytotoxic effects on malignant cells, it turned out that their long-term effects in patients relied on the induction of antitumor immune responses. Thus, several major chemotherapeutic agents, including anthracyclines and oxaliplatin, induced “immunogenic cell death” (ICD), meaning that they stress and kill cancer cells in such a way that they become recognizable to the immune system (2). Accordingly, accumulating evidence supports the idea that anticancer immune response elicited by chemotherapy determines patient prognosis (2). Ironically, imatinib, the first drug developed to target an oncogenic tyrosine kinase, BCR–ABL [the ABL kinase constitutively activated by a chromosomal translocation, in Philadelphia chromosome–positive chronic B-cell leukemias (CLL, chronic lymphocytic leukemia)] turned out to owe its long-term success against CLL [and later against gastrointestinal stroma tumors (GIST), which depend on another oncogenic kinase, KIT, also inhibited by imatinib] to immune responses as well (3). In this case, cell-autonomous effects on CLL or GIST cells increase their susceptibility to immune attack by cytotoxic T cells (CTL) and natural killer cells coupled to a reduction of immunosuppressive cell types (such as regulatory T cells and myeloid-derived suppressor cells). Moreover, imatinib inhibits nonmutated tyrosine kinases in immune cells, in particular in dendritic cells (DC), increasing their immunostimulatory action (3). Thus, targeted therapies acting on oncogenic kinases may have immunologic off-target effects that explain their therapeutic success.

Bortezomib has been suspected of having immunostimulatory effects since the discovery that it induces the expression of heat shock protein 90 on MM cells, favoring their recognition by DCs (4). The translocation of intracellular...
proteins to the cell surface is indeed a hallmark of ICD. In particular, the endoplasmic reticulum (ER) chaperone calreticulin (CALR) translocates from the ER lumen to the plasma membrane surface, where it acts as an “eat-me” signal to favor the phagocytosis of dying cells by DCs. CALR exposure has been observed in response to a wide range of ICD-inducing chemotherapeutics (2) and some targeted agents such as crizotinib, a tyrosine kinase inhibitor (5). Gulla and colleagues have now reported that bortezomib induces classic, CALR-dependent ICD while providing molecular and translational insights into the therapeutic relevance of bortezomib-induced ICD (1).

Gulla and colleagues found that bortezomib induces CALR exposure to the surface of human or mouse MM cells and that CALR is required for the phagocytosis of bortezomib-treated MM cells by monocyte-derived DCs (1). Co-culture of bortezomib-treated human MM cells, DCs, and T lymphocytes led to an increase in the frequency of CD4+bortezomib-treated human MM cells, DCs, and T lymphocytes treated MM cells by monocyte-derived DCs (1). Coculture of exposure to the surface of human or mouse MM cells and bortezomib-induced ICD (1). In particular, the endoplasmic reticulum (ER) chaperone calreticulin (CALR) translocates from the ER lumen to the plasma membrane surface, where it acts as an “eat-me” phenomenon that has previously been linked to ICD and has been dubbed as “viral mimicry” (6). Thus, like other ICD-inducing drugs, bortezomib stresses and kills MM cells in a way that mimics viral infection to the degree that high levels of type-1 interferons are induced.

Gulla and colleagues then characterized the molecular and cellular mechanisms that explain how a 26S proteasome inhibitor can cause several hallmarks of ICD including CALR exposure and a type-1 interferon response (1).

In the context of ICD, CALR exposure is usually preceded by the induction of the integrated stress response, consisting of the phosphorylation of eukaryotic initiation factor 2α (eIF2α) by the ER stress kinase eIF2α kinase-3 (EIF2AK3, best known as PERK; ref. 2). Indeed, this pathway was activated in bortezomib-treated MM cells (1). In response to chemotherapeutic ICD inducers, this phosphorylation event occurs downstream of a general inhibition of DNA-to-RNA transcription (7). High-dose bortezomib reduces global RNA synthesis in osteosarcoma cells (7), suggesting that this might also occur in MM cells (Fig. 1). However, this conjecture remains to be explored.

Bortezomib-induced type-1 interferon responses by an increase in cytosolic DNA in the form of micronuclei, accumulation of the cytosolic DNA sensor cyclic GMP-AMP synthase (cGAS), activation of transmembrane protein 173 (TMEM173, best known as STING), and activating phosphorylation of TANK-binding kinase 1 (TBK1; ref. 1). Knockout of STING abolished this latter event; prevented the induction of IFNA1, IFNB1, and CXCL9 gene transcription by bortezomib; and abolished the capacity of bortezomib-treated human MM cells to stimulate CD4+ and CD8+ EM cells cocultured in immunodeficient mice (Fig. 1). Nonetheless, the STING pathway appeared to be suboptimally activated in response to bortezomib, meaning that a synthetic STING agonist, ADUS-100, could trigger a stronger TBK1 phosphorylation in vitro. When combined with bortezomib, ADUS-100 also improved therapeutic responses in a mouse MM model, as it increased the infiltration of the tumors by T lymphocytes. Such synergistic effects were lost upon knockout of STING in mouse MM cells or in immunodeficient mice (1). Of note, in MM patients, STING mRNA levels positively correlated with the expression of the 57 interferon-stimulated genes found in the ICD cluster, pleading for the clinical relevance of this pathway (1).

In response to cGAS activation, STING is known to translocate to the ER (8), suggesting a possible intersection with the CALR exposure pathway ignited at the ER. However, knockout of STING did not interfere with bortezomib-induced CALR exposure (1). Conversely, knockout of CALR prevented the bortezomib-mediated induction of interferon-stimulated genes in vitro, in the MM mouse model (1), suggesting that CALR is somehow required for the cytosolic DNA-cGAS–STING–TBK1–type-1 interferon pathway to be activated (Fig. 1). However, this conjecture requires further exploration by in vitro experimentation. In particular, the exact level at which CALR deficiency interrupts this pathway remains to be determined. Cancer cells can escape immuno-surveillance by suppressing the CALR exposure pathway at multiple levels (9). Hence, it would not be surprising that MM cells developed such deficiencies as a result of immunoselection, in particular after relapse from bortezomib-based therapeutic regimens.
In summary, the work by Gulla and colleagues reveals that ICD accompanied by CALR exposure and viral mimicry is an important clinical feature of MM treatment by bortezomib (1), echoing recent results on another efficient anti-MM drug, belantamab mafodotin, which also acts as a potent ICD inducer (10). This anti-BCMA antibody conjugated to maleimido-caproyl monomethyl auristatin F was FDA approved in August 2020 for the treatment of relapsed or refractory MM. Logically, clinical studies evaluating the possibility of combining bortezomib or belantamab mafodotin with anti-PD-1 antibodies will be underway soon (ClinicalTrials.gov Identifiers NCT03848845 and NCT04258683). It will be interesting to see whether the combination of ICD inducers with other immunotherapies, including STING agonists, will further improve the clinical management of MM.

Authors’ Disclosures

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