In response to some chemotherapeutic agents such as anthracyclines and oxaliplatin, cancer cells undergo immunogenic apoptosis, meaning that their corpses are engulfed by dendritic cells and that tumor cell antigens are presented to tumor-specific CD8+ T cells, which then control residual tumor cells. One of the peculiarities of immunogenic apoptosis is the early cell surface exposure of calreticulin (CRT), a protein that usually resides in the lumen of the endoplasmic reticulum (ER). When elicited by anthracyclines or oxaliplatin, the CRT exposure pathway is activated by pre-apoptotic ER stress and the phosphorylation of the eukaryotic translation initiation factor eIF2α by the kinase PERK, followed by caspase-8-mediated proteolysis of the ER-sessile protein BAP31, activation of the pro-apoptotic proteins Bax and Bak, anterograde transport of CRT from the ER to the Golgi apparatus and exocytosis of CRT-containing vesicles, finally resulting in CRT translocation onto the plasma membrane surface. Interruption of this complex pathway abolishes CRT exposure, annihilates the immunogenicity of apoptosis, and reduces the immune response elicited by anticancer chemotherapies. We speculate that human cancers that are incapable of activating the CRT exposure pathway are refractory to the immune-mediated component of anticancer therapies.
Subsequent experiments showed that the immunogenicity of apoptosis critically relies on CRT exposure. Thus, the knockdown of CRT abolishes the immunogenicity of cell death in multiple tumor models (13–16), whereas the absorbance of recombinant CRT protein to cells that die of nonimmunogenic cell death restores their immunogenicity (17, 18). In addition, CRT exposure determines the engulfment of dying tumor cells by specific DC subsets (15), in line with previous studies showing that surface CRT can serve as an "eat me" signal (19). Thus, CRT exposure marks a major checkpoint of immunogenic cell death, and the molecular mechanisms that determine the translocation of CRT to the cell surface have been studied in some detail.

The Calreticulin Exposure Pathway

In immunogenic cell death, selective CRT exposure (without exposure of other ER proteins such as calnexin) occurs at a relatively early stage when the cells still have a normal morphology and lack phosphatidylserine exposure (9). This early CRT-exposure contrasts with a later phase of advanced apoptosis (be it immunogenic or nonimmunogenic) when intracellular membranes, mostly from the ER, are recruited to the surface giving rise to a general alteration in the glyocalix as well as to the nonspecific recruitment of ER membrane proteins such as calnexin to the cell surface (20). The CRT exposure that precedes and accompanies immunogenic apoptosis is the result of a complex, stimulus-dependent process, which occurs in several steps (Fig. 1). CRT exposure is potently triggered by pharmacological cell death inducers that provoke the production of reactive oxygen species (ROS) as well as an ER stress response. Quenching of chemotherapy-elicited ROS with antioxidants or, at least in the case of anthracyclines, inhibition of the inducible NO synthase, suffices to abolish CRT exposure (18, 21). However, the addition of ROS or ROS-generating agents alone is not sufficient to induce CRT exposure (18).

One common feature of chemotherapeutic agents that trigger CRT exposure (such as oxaliplatin or the anthracyclines doxorubicine and mitoxantrone) is their capacity to induce an ER stress response (18). This response is accompanied by the activating phosphorylation of the ER stress kinase PERK, as well as by the phosphorylation of the PERK substrate eukaryotic translation initiation factor eIF2α on serine 51. Both the knockout-knockdown of PERK and the replacement of eIF2α by a nonphosphorylatable mutant (S51A) abolish CRT exposure induced by anthracyclines or oxaliplatin. In contrast, the removal of other elements of the ER stress response, ATF6 or IRE1, does not affect CRT exposure (18). Anthracyclines also cause the dissociation of the eIF2α-specific phosphatase PP1 from its obligate cofactor GADD34, implying that PP1 is inhibited (22). Pharmacological agents that directly or indirectly inhibit PP1/GADD34 (such as tautomycin and salubrinal) as well as cell-permeable peptides that competitively dissociate the PP1/GADD34 complex are highly efficient in stimulating CRT exposure even in conditions that do not lead to cell death (9, 22). Altogether these results indicate that the S51 phosphorylation of eIF2α, which is required for other stress responses including translational arrest by ER stress (23), formation of stress granules (24), and autophagy (25), is also critical for CRT exposure. However, ER stress alone is not sufficient to cause pre-apoptotic CRT exposure. Thus, ER stress-inducing agents like tunicamycin or thapsigargin fail to stimulate the translocation of CRT to the cell surface when used alone (9, 26). However, thapsigargin (an inhibitor of the SERCA Ca2+ pump), overexpression of reticulon 1C, as well as targeted expression of the ligand-binding domain of the IP3 receptor, which all reduce the intraluminal ER Ca2+ concentration, improved CRT exposure in neuroblastoma cells that normally failed to expose CRT in response to anthracyclins (26). These results suggest that ER Ca2+ levels contribute to the control of CRT exposure, in line with the direct effects of Ca2+ on the conformation of the CRT protein (27).

The inhibition of caspases with two broad-spectrum inhibitors, the synthetic peptide Z-VAD-fmk or p35 (a baculovirus-derived protein that can be transfected into mammalian cells), completely abolishes CRT exposure (9) and subverts the immunogenicity of cell death induced by anthracyclines or oxaliplatin (8). Further analyses revealed that caspase-8 is the apical caspase that is activated downstream of ER stress by anthracyclines (18). This result is reminiscent of prior studies showing that caspase-8 can be activated by ER stress and catalyzes the cleavage of Bap31, an ER-sessile protein (28). Selective deletion, depletion, or inhibition of caspase-8 abolished CRT exposure, and similarly, depletion of Bap31 or its replacement by a noncleavable mutant inhibits CRT exposure induced by anthracyclines or oxaliplatin (18). Thus, caspase-8-mediated cleavage of Bap31 is crucial for CRT exposure. Activation of caspase-8 by ligation of death receptors (for instance by addition of TRAIL or an agonistic CD95 antibody) also induces CRT exposure. Antioxidants fail to prevent TRAIL-induced apoptosis, yet they abolish CRT exposure (18), underscoring the contribution of ROS to this process. It is important to note that caspase-8 activation leading to CRT exposure occurs relatively early after addition of anthracyclines, several hours before the apoptosis-associated activation of caspase-3 (18). Bap31 is a Bcl-2 interacting protein, and overexpression of Bcl-2 inhibits CRT exposure. Moreover, the knockout or knockdown of either Bax or Bak prevents CRT translocation, indicating that this process is under the control of the multidomain proteins from the Bcl-2 family (18). Whether this relays to effects of Bcl-2, Bax, and Bak on ER Ca2+ fluxes (29) and/or on the ER stress response (30) has to be clarified in the future.

Once the ER stress response has triggered the "apoptotic module" of the ER exposure pathway (with caspase-8 activation, Bap31 cleavage, and conformational activation of Bax and Bak), CRT is translocated from the ER lumen to the plasma membrane surface. This process involves the actin cytoskeleton-mediated anterograde transport of...
CRT from the ER to the Golgi apparatus, followed by the active exocytosis of CRT-containing vesicles based on the interaction between vesicle-associated SNAREs (such as VAMP1) and plasma membrane-associated SNAREs (such as SNAP23/25; ref. 18). During its voyage from the ER lumen to the cell surface, CRT continues to bind to one of its major interactors, the disulfide isomerase ERp57. This interaction is obligatory for CRT translocation because the deletion and/or depletion of ERp57 abrogates CRT exposure, and vice versa the deletion and/or depletion of CRT precludes ERp57 exposure (17). It has not yet been clarified how endogenous CRT is anchored to the plasma membrane surface. Recombinant CRT protein readily binds to a saturable surface receptor that is present on both healthy and dying tumor cells of any kind and whose molecular identity is elusive. Similarly, the molecular identity of the CRT receptor on DCs is not clearly established. It is still unknown whether the candidate CRT receptors CD91 (19) and scavenger receptor class-A (31) are required for the DC-specific engulfment of CRT-exposing tumor cells.

Clinical-Translational Advances

When CT26 colon cancer cells, B16F1 melanoma cells, or MCA205 fibrosarcoma cells are treated with anthracyclines and then are injected subcutaneously into histocompatible mice, they elicit an antitumor immune response
that precludes the growth of live tumor cells that are inoculated 1 week later into the opposite flank. The immunogenicity of cell death is suppressed when CRT exposure is blocked, for instance by knocking down CRT (13–16) and can be reestablished by absorbing recombinant CRT to the cell surface (9, 10). Similarly, any manipulation that interrupts the CRT exposure pathway abolishes the immunogenicity of anthracycline- and oxaliplatin-induced cell death, although they have no major effect on the lethal effects of the chemotherapeutics on tumor cells in vitro. This anti-immunogenic effect is caused by the knockdown of PERK, caspase-8, Bap31, Bax, Bak, VAMP, SNAP31, or ERp57 and to the use of chemical inhibitors of ROS, caspases, ER-Golgi trafficking, or the actin cytoskeleton (18). Stable knockdown of ERp57 in CT26 tumors had no effect on the sensitivity of the cells to anthracyclines in vitro, as measured by the induction of apoptosis and the loss of clonogenic survival. However, ERp57-deficient tumors failed to respond to anthracycline-based chemotherapy in vivo unless recombinant CRT protein was injected into the tumor bed (17). These results underscore the contribution of immunogenic tumor cell death and the ensuing anticancer immune response to the therapeutic efficacy of chemotherapy.

It is noteworthy that the CRT exposure pathway is phylogenetically conserved—yeast cells translocate CRT toward the cell surface when they are treated with anthracyclines and this pathway involves the yeast orthologs of PERK, Bap31, SNARE, and ERp57—and that multiple viruses including oncoviruses encode proteins that interrupt this pathway. For example, the E5 protein encoded by human papilloma virus (HPV16 and HPV31) binds to Bap31 (34), and the E2 protein encoded by hepatitis C virus (HCV) inhibits PERK and other kinases that can phosphorylate eIF2α (35). HCV also upregulates cellular FLIP (to inhibit caspase-8; ref. 36), and stimulates the generation of CRT fragments that become detectable in the serum of infected patients (37) and that might act as competitive antagonists of CRT receptors on DCs. These findings point to the possibility that viruses might have developed specific strategies to subvert the CRT exposure pathway and hence to avoid the immune recognition of dying virus-infected cells.

On a similar note, it seems plausible that the immune system selects tumor cell variants that lose the ability to expose CRT and then escape from anticancer immune responses, a possibility of “immunoediting” (38) that has not yet been investigated in detail. Profiling of the expression levels (either at the mRNA or protein levels) of these elements of the CRT exposure pathway does not inform on the functional state of this system. For example, the presence of PERK does not show whether it is activated, and the mere expression levels of CRT or ERp57 do not reveal their subcellular localization. In spite of this limitation, some studies show that low protein levels of CRT and ERp57 negatively influence the prognosis of bladder and gastric carcinoma, respectively (39, 40). However, because CRT and ERp57 are also involved in loading antigenic peptides into MHC class I molecules (41), these results are difficult to be interpreted with respect to the CRT exposure pathway. There are multiple studies showing that the loss of caspase-8 expression or altered expression levels in multidomain Bcl-2 family proteins (Bcl-2, Bcl-XL, Mcl-1, Bax, Bak, etc.) have a profound impact on tumor prognosis. Again, the multifunctional nature of these proteins, and notably their role in the regulation of apoptosis and autophagy, makes it difficult to weigh the relative contribution of defective CRT exposure to the observed effects.

As a result, it will be important to precisely determine post-translational modifications in the essential actors of the CRT exposure pathway (such as the phosphorylation of PERK and eIF2α, the proteolytic cleavage of caspase-8 and Bap31, as well as the subcellular redistribution of ERp57 and CRT), as they occur after chemotherapy or radiotherapy in patients, and to study the impact of these modifications on the efficacy of anticancer treatments. We anticipate that exploring such tumor cell-intrinsic parameters that determine the immunogenicity of cell death will yield clinically useful information.

It has already been shown that loss-of-function mutations in two receptors that detect immunogenic cell death signals, namely toll-like receptor 4 (TLR4, which detects HMGB1 released from dying cells) and purinergic receptor P2RX7 (which detects ATP secreted by dying cells), reduce the efficacy of adjuvant chemotherapies with anthracyclines (in breast cancer) and oxaliplatin (in colorectal cancer; refs. 11, 12, 42). These results reinvigorate our quest for the CRT receptor present on dendritic cells and its contribution to the anticancer immune response.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Grant Support

INSERM, Ligue contre la Cancer, Fondation de France, Fondation pour la Recherche Médicale, Institut National du Cancer, Cancéropôle Ile-de-France; AICR, Apoptrain and Fondation Gustave Roussy.

Received 03/08/2010; revised 03/31/2010; accepted 04/06/2010; published OnlineFirst 04/26/2010.

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Clinical Cancer Research

Immunogenic Tumor Cell Death for Optimal Anticancer Therapy: The Calreticulin Exposure Pathway

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