Cell Death and Differentiation (2014) 21, 50–58

www.nature.com/cdd

Contribution of humoral immune responses to the antitumor effects mediated by anthracyclines

D Hannani[1,2,3], C Locher[1,2,3], T Yamazaki[1,2,3], V Colin-Minard[2,4], M Vetizou[1,2,3], L Aymeric[1,2,3], S Viaud[1,2,3], D Sanchez[5], MJ Smyth[6,7], P Bruhns[8,9], G Kroemer[2,10,11,12,13] and L Zitvogel*[,1,2,3,14]

Immunogenic cell death induced by cytotoxic compounds contributes to the success of selected chemotherapies by eliciting a protective anticancer immune response, which is mediated by $CD4^+$ and $CD8^+$ T cells producing interferon-γ. In many instances, cancer progression is associated with high titers of tumor-specific antibodies, which become detectable in the serum, but whose functional relevance is elusive. Here, we explored the role of humoral immune responses in the anticancer efficacy of anthracyclines. Chemotherapy reduced the number of tumor-infiltrating B cells, and failed to promote humoral responses against immunodominant tumor antigens. Although anthracycline-based anticancer chemotherapies failed in T cell-deficient mice, they successfully reduced the growth of cancers developing in mice lacking B lymphocytes (due to the injection of a B-cell-depleting anti-CD20 antibody), immunoglobulins (Igs) or Ig receptors (Fc receptor) due to genetic manipulations. These results suggest that the humoral arm of antitumor immunity is dispensable for the immune-dependent therapeutic effect of anthracyclines against mouse sarcoma. In addition, we show here that the titers of IgA and IgG antibodies directed against an autoantigen appearing at the cell surface of tumor cells post chemotherapy (calreticulin, CRT) did not significantly increase in patients treated with anthracyclines, and that anti-CRT antibodies had no prognostic or predictive significance. Collectively, our data indicate that humoral anticancer immune responses differ from cellular responses in, thus far, that they do not contribute to the success of anthracycline-mediated anticancer therapies in human breast cancers and mouse sarcomas.
Cell Death and Differentiation (2014) **21,** 50–58; doi:10.1038/cdd.2013.60; published online 7 June 2013

Cancer often results from a chronic inflammatory process, in which multiple hematopoietic and/or immune components participate.[1,2] The question arises as to which immune cell subset directly or indirectly promote malignancy, and whether these chronic infiltrates are generic across multiple solid tumor types or instead reflect tissue-selective, or oncogenic pathway-selective, profiles. If the contribution of leukocyte populations to oncogenesis or tumor progression was generic, therapeutics aimed at quelling the protumorigenic activities of such subsets could be proposed. Hence, it is of utmost importance to investigate how the interplay between inflammatory cells is orchestrated and modulated during anticancer therapies.

Dendritic cells (DCs) are bone marrow-derived cells that are present in all tissues,[3] where they scan the environment and take up foreign antigens (including tumor antigens) before migrating to lymphoid organs to trigger adaptive immune responses.[3] Upon recognition of a foreign antigen, T and B lymphocytes undergo clonal expansion and mount antigen-specific 'cognate' responses. Once the adaptive immune response has ensued, the source of danger or damage is eliminated, inflammation declines and tissue homeostasis is restored. In tumors, these well-orchestrated series of events fail to resolve and lead to chronic inflammation. Activated leukocytes (mostly represented by myeloid cells) supply direct and indirect mitogenic growth mediators and proteolytic enzymes that stimulate the expansion and dissemination of both neoplastic and stromal cells.[4] Moreover, the chronic presence of paracrine and juxtacrine mitogenic and tissue-remodeling molecules fuels programs that impair antitumor cytotoxic T lymphocyte (CTL) or NK/NKT cell-mediated killing of 'damaged' (cancer) cells (reviewed in[5]).

In addition to myeloid cells, lymphocytes has an important role in chronic inflammation. B cells display variable pro- and anti-tumor bioactivities deriving from their functional plasticity and phenotypic heterogeneity. As the sole producers of immunoglobulins (Igs), B cells are critical initiators and modulators of humoral immunity, tailoring specific responses

[1]INSERM U1015, Equipe labellisée Ligue contre le Cancer, Villejuif, France; [2]Institut de Cancérologie Gustave Roussy, Villejuif, France; [3]University of Paris Sud XI, Villejuif, France; [4]Department of Pediatric and Adolescent Oncology, Villejuif, France; [5]Department of Immunology, Institute of Microbiology, Academy of Sciences of the Czech Republic, Prague, Czech Republic; [6]Queensland Institute of Medical Research, Herston, 4006, Queensland, Australia; [7]School of Medicine, The University of Queensland, Brisbane, QLD 4072, Queensland, Australia; [8]Institut Pasteur, Département d'Immunologie, Laboratoire Anticorps en Thérapie et Pathologie, Paris, France; [9]INSERM U760, Paris, France; [10]INSERM U848, Villejuif, France; [11]Sorbonne Paris Cité, University of Paris Descartes, Paris, France; [12]Equipe 11 labellisée Ligue contre le Cancer, Centre de recherche des Cordeliers, Paris, France; [13]Pôle de Biologie, Hôpital Européen Georges Pompidou, Paris, France and [14]Center of clinical Investigations in Biotherapies of Cancer (CICBT), Villejuif, France
*Corresponding author: L Zitvogel, Department of Immunology, INSERM U805, Institut de Cancérologie Gustave Roussy, 39, rue Camille Desmoulins, 114 rue Edouard Vaillant, Villejuif Cedex 94805, France. Tel: +33 1 42 11 50 41; Fax: +33 1 42 11 60 94; E-mail: zitvogel@igr.fr
Keywords: antibodies; immunogenic cell death; chemotherapy; humoral immunity; FcγR; cancer
Abbreviations: ADCC, antibody-dependent cell cytotoxicity; CRT, calreticulin; CTL, cytotoxic T lymphocyte; DC, dendritic cell; ER, endoplasmic reticulum; FcR, Fc receptor; HMGB1, high-mobility group Box-1; ICD, immunogenic cell death; Mincle, macrophage-inducible C-type lectin; Myd88, myeloid differentiation primary response gene; SNP, single-nucleotide polymorphism; TLR, Toll-like receptor
Received 23.1.13; revised 24.4.13; accepted 26.4.13; Edited by M Piacentini; published online 07.6.13

to infections. In addition, B lymphocyte-derived paracrine factors are causative and/or potentiating mechanisms of disease, as shown in autoimmunity.[6] Moreover, there is an accumulating evidence that B-cell function is relevant to carcinogenesis. Cancer patients often develop specific antibody responses against tumor antigens,[6] which are mostly correlated with poor survival.[7] Progression of human papillomavirus type 16 E6/E7-driven squamous carcinogenesis in transgenic mice is significantly diminished in the absence of B cells.[8,9] In this preclinical tumor model, promotion of the early steps of carcinogenesis is achieved through deposition of IgG autoantibody in the neoplastic parenchyma and immune complex/FcγR ligation of mast cells and macrophages, eventually fostering proangiogenic and immunosuppressive gene expression programs.[8,9] Similarly, skin chemical carcinogenesis by two-stage application of the DNA damaging agent DMBA and the tumor promoter TPA occurs more rapidly in B-cell-proficient mice than in B-cell-deficient mice.[10] As a possibility, B cells may modulate myeloid cell phenotypes through the secretion of IL-10 and TNFα, thereby accelerating tumor progression. Finally, B-cell-derived lymphotoxin β is responsible for promoting castration resistance in mice with transgene-induced prostate cancer, likely by stimulating IKKα and STAT3 activity in the malignant cells.[11] Whereas these studies revealed the protumorigenic potential for B cells, others reported no specific functional significance for B cells during mammary carcinogenesis.[12]

The efficacy of anticancer therapies is determined by tumor cell-intrinsic as well as by cell-extrinsic, in part immune factors. Thus, therapeutic settings that induce tumor antigen-specific Th1/Tc1 responses (i.e. immune responses that involve specific T cell subsets producing interferon-γ) are particularly efficient in eliminating residual tumor cells. The way cancer cells die when exposed to selected chemotherapeutics (such as anthracyclines and oxaliplatin) die, ultimately dictates the immunogenicity of cell death. 'Immunogenic cell death'(ICD) can be defined as a process, in which cell death is preceded by a preapoptotic endoplasmic reticulum (ER) stress response and autophagic program, facilitating the recruitment, activation and antigen-presenting function of DCs.[13] Indeed, ICD is accompanied by exposure or secretion of cell death-associated molecular patterns, such as calreticulin (CRT) (for the engulfment of dead bodies by DC), high-mobility group Box-1 (HMGB1) (for the Toll-like receptor 4/myeloid differentiation primary response gene-dependent processing of the phagocytic cargo by DC) and ATP (for DC recruitment and the Nlrp3-dependent IL-1β release culminating in Tc1 polarization).[13] Accordingly, after exposure to neoadjuvant chemotherapy, approximately one-third of stage 2/3 breast cancers appeared highly infiltrated by cytotoxic T cells, with a concomitant reduction of B lymphocytes and Th2 cells.[14] Moreover, the relative proportions of macrophages and CD8$^+$ T cells predict the pathological responses to neoadjuvant anthracycline-based therapy and overall survival in locally advanced breast cancer.[15]

As conventional chemotherapies can elicit tumor-specific T cell immunity, which then contribute to durably and negatively inflecting the tumor growth curve, we addressed the question whether anticancer therapies would also stimulate B cell- or Fc receptor (FcR)-dependent immune responses. Using a variety of complementary experimental settings, we came to the conclusion that humoral immune responses are not specifically induced by chemotherapy, and that they do not significantly contribute to tumor control.

Results

Intratumoral accumulation of antigen-specific T cells but depletion of B cells after chemotherapy. To evaluate the possible anticancer immune responses mediated by B cells, we determined the absolute numbers of CD19$^+$B220$^+$ B lymphocytes in the CD45$^+$ leukocytic fraction from tumors established subcutaneously for 18 days and harvested at day 8 post chemotherapy with anthracyclines, following previously established experimental settings.[16,17] MCA205 OVA, a methylcholanthrene-induced sarcoma cell line genetically modified to express the candidate tumor antigen OVA, was injected under the skin of histocompatible C57Bl/6 mice, and the developing cancers were treated by intratumoral injections of anthracyclines (doxorubicin). CD45.2 OVA (SIINFEKL)-specific H2-K^b-restricted TCR transgenic CD8$^+$ T cells (CTL) that were adoptively transferred into CD45.1 congenic mice on the first day post chemotherapy proliferated and accumulated in tumor beds (Figures 1a and b). This expansion of OVA-specific T cells reflects a general increase in the frequency of Th1 and Tc1 cells post chemotherapy.[16,17] In sharp contrast, doxorubicin depleted intratumoral B cells by more than 70% (Figure 1c). Moreover, a single systemic injection of cyclophosphamide reduced the number of splenic B cells, while it increased the frequency of CTL in the spleen (Supplementary Figures 1A–C). Thus conventional chemotherapeutic regimens that stimulate local or systemic T cell responses, can reduce the number of B cells.

Contribution of cytotoxic T cells but not of B lymphocytes to the therapeutic effect of anthracyclines. To further assess the role of B cells, we compared the antitumor effects of doxorubicin on MCA205 cancers established in C57Bl6 WT *versus* μMT mice, which lack Igs and B lymphocytes.[18] In μMT mice, anthracyclines successfully reduced tumor growth, and this effect was undistinguishable from that observed in the WT control mice (Figure 2a). Next, we took advantage of an anti-CD20 antibody,[19] which was applied at different time points pre/post-tumor inoculation and pre/post doxorubicin (Figure 3a) to deplete CD19$^+$ CD20$^+$ B lymphocytes (Figure 3b, not shown). B-cell depletion did not affect the natural expansion of MCA205 cells (which lack CD20 expression, not shown) *in vivo*, and failed to compromise the efficacy of chemotherapy against this MCA205 sarcomas (Figures 3c–e). In contrast, depletion of CTLs using anti-CD8α antibodies completely abrogated the antitumor effects of anthracyclines (Figures 4a and b), confirming their contribution to the efficacy of chemotherapy.[13]

Hence, genetic deficiency or antibody-induced depletion of B lymphocytes did not interfere with the therapeutic activity of anthracyclines.

No contribution of Igs and Fc receptos to the efficacy of anticancer chemotherapy. To investigate to which extent Igs might modulate the therapeutic efficacy of chemotherapy,

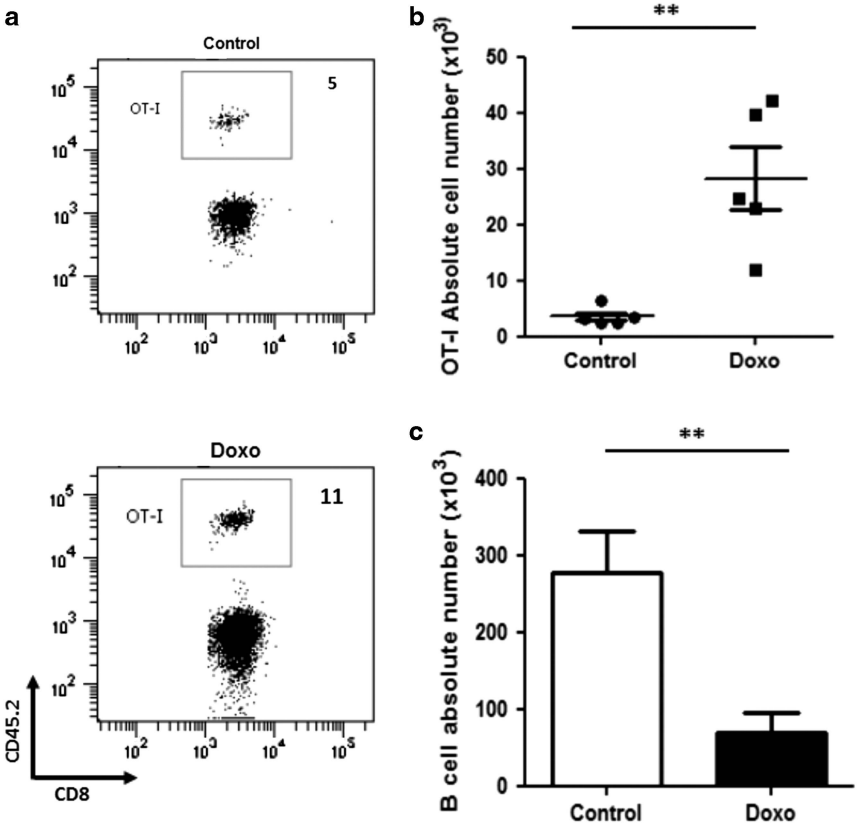

Figure 1 Ag-specific T cells but not B cell accumulation in the tumor bed post chemotherapy. (**a** and **b**) T cell accumulation in tumors post anthracyclines. Day 7 established MCA205 OVA implanted in CD45.1 C57Bl/6 mice were treated with doxorubicin (i.t). One day post chemotherapy, 1×10^6 CD45.2 congenic naive OT-I T cells were injected i.v. and their frequency among CD8/CD45.2 cells (**a**) and absolute number (**b**) were assessed in flow cytometry in TILs. $N = 5$ mice/group. A representative dot plot is shown (**a**) and the data from one representative experiment out of three are depicted (**b**). (**c**) B-cell depletion post doxorubicin. Absolute intratumoral B-cell numbers (defined as $CD19^+$ $B220^+$ live $CD45^+$ cells) were assessed 8 days post chemotherapy in TILs using flow cytometry. $N = 5$ mice/group. A representative graph out of two independent experiments is shown. Student's *t*-test: $^{**}P < 0.01$

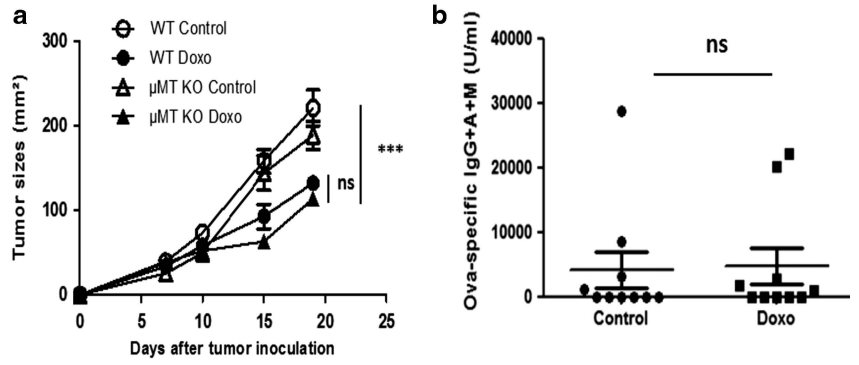

Figure 2 Chemotherapy efficacy is not impaired in $\mu MT^{-/-}$ mice. (**a**) Ig and B-cell depleted mice. Tumor growth curves of MCA205 OVA were monitored in WT or μMT KO mice, treated or not with doxorubicin at day 7 post-tumor inoculation. Tumor growth has been assessed every 4 days using a caliper. $N = 5$ mice/group. The graph is representative of one experiment out of two independent ones. (**b**) Ig levels in serum post anthracyclines. MCA 205 OVA-bearing mice have been treated or not by doxorubicin at day 7 post-tumor inoculation. Three weeks later, sera have been collected and the concentrations of OVA-specific IgG, IgA and IgM have been determined by ELISA. $N = 10$ mice/group. Student's *t*-test: $^{***}P < 0.001$, ns, not significant

we analyzed the titers of Ig directed against the immunodominant tumor antigen OVA in our model system. OVA-specific IgG/M/A antibody titers (monitored at day 15 and 21 post therapy) were not boosted by chemotherapy (not shown and Figure 2b). It is known that leukocyte FcRγ is necessary for squamous carcinogenesis,[8] as well as for short and long-term effects (involving memory T cell responses) in the lymphoma bearing mice treated with antibody-dependent cell cytotoxicity (ADCC)-mediating Ab.[20] Therefore, we assessed the putative contribution of

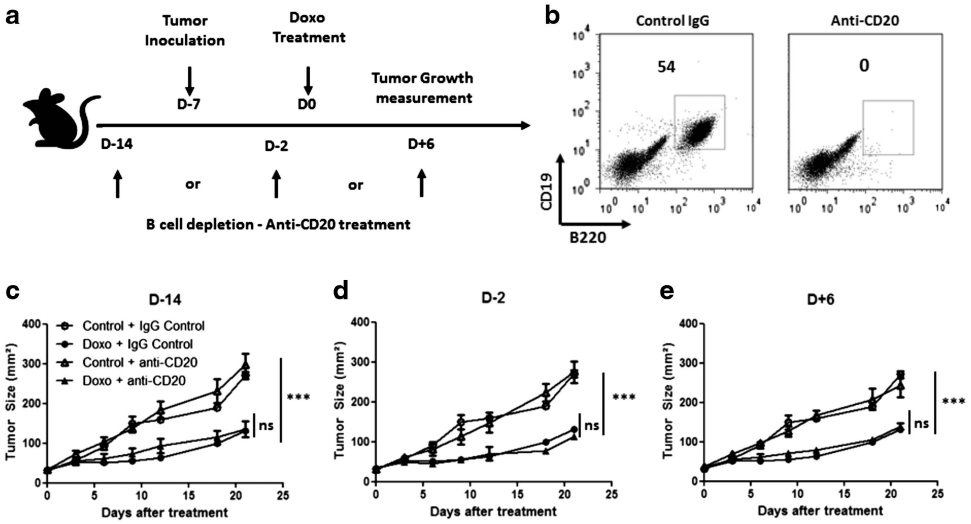

Figure 3 Anti-CD20 Ab-mediated B-cell depletion does not impair chemotherapy efficacy. (**a**) Experimental setting. B cells have been depleted using anti-CD20 antibody either before tumor inoculation (D-14), before chemotherapy (D-2) or 6 days after chemotherapy treatment (D + 6). Mice received doxorubicin (i.t) at day 0, and the tumor growth was monitored every 3–4 days. B-cell depletion was analyzed by flow cytometry in the spleen 1 week after starting anti-CD20 injections. (**b**) Dot plots show the depletion in the 'D-14' group as a representative example. (**c**–**e**) Tumor growth curves of control or doxorubicin-treated MCA205-bearing mice treated with anti-CD20 or IgG control Ab. $N = 5$–7 mice/group. Student's *t*-test or ANOVA: $^{***}P < 0.001$, ns, not significant

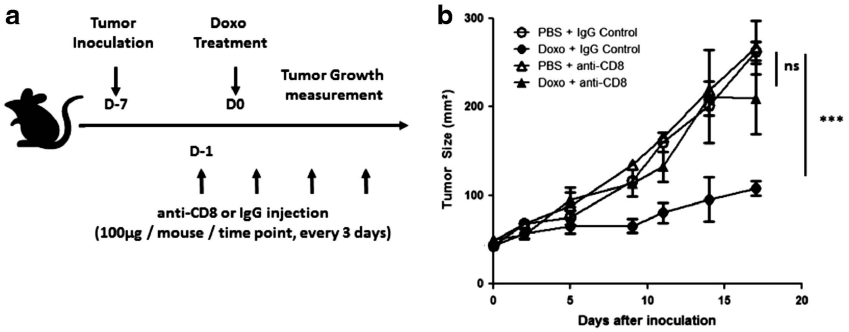

Figure 4 $CD8^+$ T cells are indispensable for chemotherapy efficacy. (**a**) Experimental setting. $CD8^+$ T cells have been depleted from day 1 before chemotherapy throughout the experiment using 100 μg of anti-CD8 antibodies (53.6.72) or rat IgG2a control Ab (2A3) every 3 days. (**b**) Tumor growth curves of control or doxorubicin-treated MCA205-bearing mice treated with anti-CD8 or IgG controls are depicted in a typical experiment out of three. Student's *t*-test: $^{***}P < 0.001$, ns, not significant

FcγR to the efficacy of chemotherapy against MCA205 OVA sarcoma. FcγRs are broadly expressed on immune cells and encompass both activating, for example, FcγRI, III and IV (including the FcRγ subunit), and inhibitory, for example, FcγRIIB and subtype complexes.[21] MCA205 OVA was inoculated into the mice genetically manipulated to lack specific FcRγ subtypes, namely FcγRIII,[22] FcγRI,[23] FcγRIV,[24] as well as into 'FcγRIV only' mice (which lack FcγRI/IIB/III/FcεRI/II genes)[25] or 'FcγRIIB only' mice (which lack the FcγRI/IIIA/IV genes).[26] Thus, anthracyclines similarly reduced tumor growth in these FcRγ-deficient mice (Figures 5a–f), as it did in WT C57Bl6 controls (see above, Figure 2a). Of note, FcRγ does not bind Igs, but is a subunit that mediates signal transduction by other receptors relevant to myeloid cell function, including the macrophage-inducible C-type lectin (Mincle),[27] which has a cardinal role in antimycobacterial responses.[28] In accord with the observation that FcγRIII did not affect anthracycline responses (Figure 5), the efficacy of anthracyclines was not compromised in Mincle knock-out mice either (Supplementary Figure 2).

Altogether, humoral immune responses directed against immunodominant tumor antigens as well as FcR are dispensable for the chemotherapeutic activity of anthracyclines.

Humoral immune responses against ICD-related autoantigens in patients. The chaperone CRT is sequestered in the ER in unstressed cells, but relocates to the plasma membrane upon induction of ER stress by anthracyclines[13] or hypericin-based photodynamic therapy.[29] Its immunohistochemical detection in paraffin-embedded primary breast cancer tissues has been correlated with serum levels of anti-CRT antibodies.[30] We analyzed the titers of IgA and IgG antibodies in 75 healthy controls and 63 breast cancer patients (Table 1, Figure 6a) at diagnosis, during and after systemic chemotherapy (Figure 6b). Both anti-CRT IgA and IgG serum levels were slightly higher in

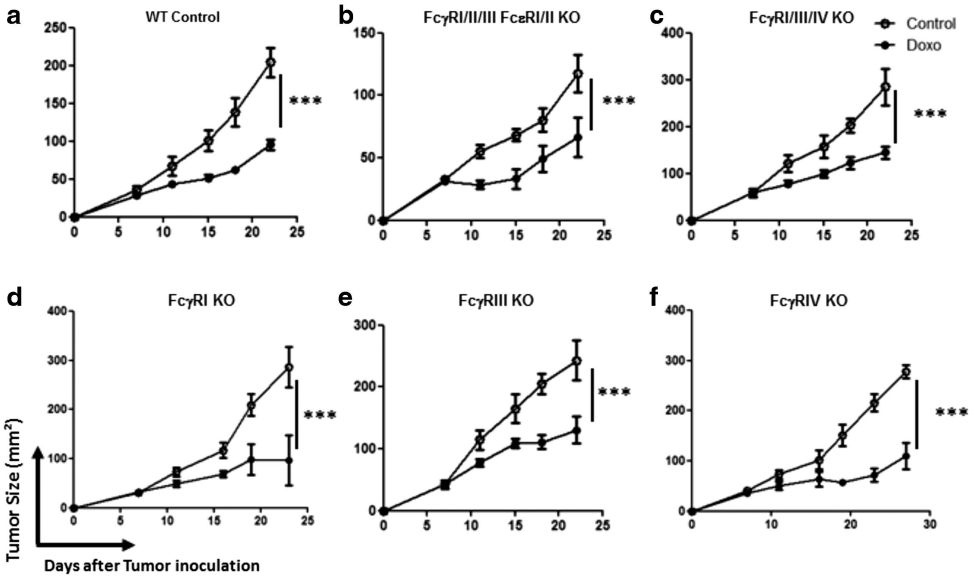

Figure 5 Chemotherapy efficacy does not rely on antibody response. MCA205 OVA was established in various C57BL/6 mouse backgrounds (WT (**a**) or FcR deficient as indicated that is, 'FcγRIV only' (FcγRI/IIB/III FcεRI/II KO) (**b**) FcRγ KO (FcγRI/III/IV KO) (**c**) FcγRI KO (**d**) FcRIII KO (**e**) and FcRIV KO (**f**)) and treated or not with doxorubicin at day 7 post-tumor inoculation. Tumor growth kinetics is indicated in one representative experiment out of two for each group of mice. $N = 5$–7 mice/group. Student's *t*-test: ***$P < 0.001$, ns, not significant

cancer patients than in control individuals (Figure 6a). However, chemotherapy failed to significantly increase the humoral immune response against CRT (Figure 6b). Paired serum specimens were available in four cases, revealing no specific increase post therapy (Supplementary Figure 3). The seroconversion (defined as antibody titers reaching levels above the detection threshold of the ELISA test[30]) of patients either at diagnosis or after neoadjuvant chemotherapy failed to correlate with the pathological complete responses (Figure 6c) or metastases-free survival (Figure 6d). We conclude that in human breast cancer, humoral immune responses directed against CRT lack clinical significance.

Discussion

Our findings strongly suggest that humoral immunity directed against immunodominant tumor antigens or self-epitopes related to ER stress-associated chaperones (CRT) may not contribute to the chemotherapy-mediated control of tumor growth. Using three distinct model systems (B-cell depletion by anti-CD20 antibodies, constitutive Ig deficiency in μMT mice, lack of activatory or inhibitory FcγR resulting from homologous recombination), we demonstrated that B cells or Ig-specific receptors are dispensable for anthracycline-mediated antitumor effects, contrasting with the essential role of T-lymphocyte-mediated immune responses observable in the same settings. Indeed, in these OVA-engineered or wild-type mouse sarcoma models, anthracyclines did not readily mobilize the humoral arm of immunity.

These data do not rule out the possibility that, in other circumstances of dosing or scheduling or other therapeutic regimen, anti-tumor B cell responses could be triggered. Humoral immune responses have been described. Ipilimumab, a fully human mAb directed against cytotoxic

Table 1 Characteristics of breast cancer patients

Patients	N = 63	%
Age at diagnosis		
Mean	48	
Range	10	
Sex		
Female	63	100%
Histology		
Ductal invasive	63	100%
Grade		
1	3	5%
2	23	37%
3	35	56%
ND	2	3%
ER status		
Positive	29	46%
Negative	34	54%
HER2-status		
Positive	4	6%
Negative	59	94%
Chemotherapy		
Neoadjuvant	63	100%
Adjuvant	16	25%
Neoadjuvant therapy		
FEC + TXT	50	79%
TXT + FEC	4	6%
Others (with epirubicine)	9	14%
Adjuvant therapy		
Hormonotherapy	28	44%
RX	41	65%
RX/FUN	12	19%
RX/TXT	4	6%
Others	6	10%

Abbreviations: FEC, 5-fluorouracil/epirubicin/cyclophosphamide; TXT, taxotere; FUN, 5-fluorouracil/navelbine

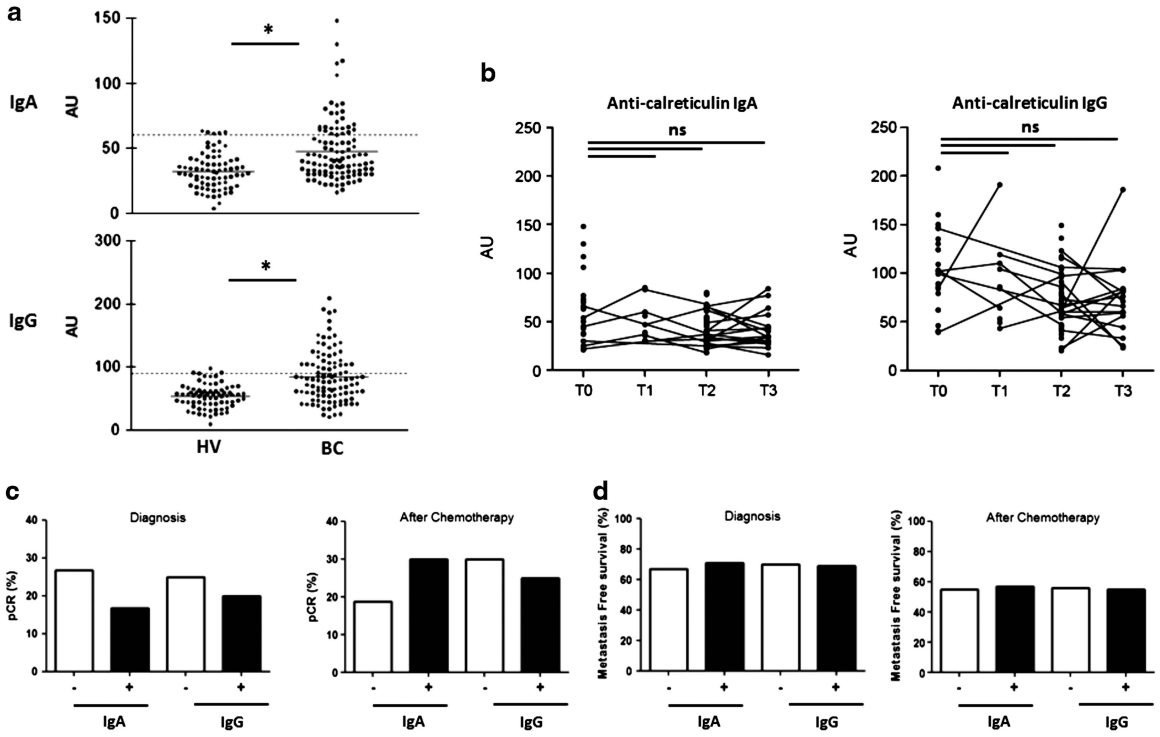

Figure 6 No clinical significance of anti-CRT antibodies in neoadjuvant chemotherapy-treated advanced breast cancers. (**a**) Comparisons of anti-CRT IgA and IgG serum levels in sex and age matched-75 healthy volunteers and 63 advanced BC patients. (**b**) Kinetics of anti-CRT IgA and IgG serum levels in advanced BC patients defined in Table 1. T0: diagnosis, T1: under chemotherapy, T2: follow up 1 and T3: follow up 2. (**c** and **d**) Frequency of pathological complete responses (pCR (**c**)) and metastasis free survival (**d**) in patients bearing advanced BC treated with neoadjuvant anthracycline-based chemotherapy. Probability to develop a pCR or to remain free of metastases at 3 years and 6 months of follow up are represented according to patients' seropositivity for anti-CRT IgA or IgG (threshold of 60 and 90 arbitrary units, respectively). Diagnosis $n=26$; after chemotherapy $n=36$. Student's *t*-test: $^*P<0.05$, ns, not significant

T-lymphocyte antigen-4 that improves overall survival in metastatic melanoma patients, slightly increased antibody levels against tumor antigens (NY-ESO-1, MART-1, SSX2, p53 and MAGE-A4) and boosted humoral immune responses against tetanus, pneumococcal and influenza vaccines.[31,32] However, NY-ESO-1 seropositivity was only predictive of clinical benefit in cases of the concomitant elicitation of NY-ESO1-specific $CD8^+$ T cell responses.[32] Repeated vaccination with NY-ESO-1 protein in the adjuvants (Montanide plus CpG ODN) induced an integrated Th1 $CD4^+$ T cell and antibody response against NY-ESO-1 that was eventually completed by $CD8^+$ T cell immunity. Vaccine-induced antibodies facilitated cross-presentation of NY-ESO-1 epitopes by DCs to $CD8^+$ T cells.[33] Similarly, therapy-induced antibodies directed against anti-MHC class I-like chain-related protein A molecules (MICA) enhanced cross-presentation to T cells and immune-mediated antitumor effects.[34] Antibody responses developed towards neovessels following immunization were instrumental to create ischemic tumor necrosis.[35] Hence, GM-CSF-engineered tumor vaccines combined with anti-CTLA4 engendered a co-ordinated cellular and humoral immunity associated with clinically significant tumor regressions in advanced solid cancers.[36] In such regressing tumor burdens, T cell infiltrates were juxtaposed to antibody-producing B cells in long-term responders. Humoral reactivity was reported against proangiogenic cytokines such as angiopoietin-1 and -2 blocking the endothelial cell tube formation and/or macrophage inhibitory factor attenuating macrophage Tie-2 and MMP9 expression.[35] Likewise, antibodies against protein disulfide isomerases (PDI, ERp5,[37]) or an accessory unit of the vacuolar H^+-ATPase complex[38] appeared of clinical significance. These data are in line with other observations, stating that the presence of tertiary lymphoid organogenesis (TLO), high endothelial venules (HEV) or germinal centers (GC) residing around the tumor nests are associated with good prognosis in breast carcinoma, non-small cell lung cancer and melanoma.[39–42] Although some particular chemotherapy regimens elicit a therapy-relevant T cell immunity, they fail to ignite protective B-cell responses, at least in mouse sarcomas and human breast cancers, which however, have been investigated at a relatively early time points. Further in-depth investigation should address antitumor serum reactivities in clinical cases, where TLO or HEV or GC are observed post chemotherapy.

We found that anti-CD20 antibodies did not affect the efficacy of anthracyclines. As a caveat, it should be noted that a subset of regulatory $CD5^+$ $CD1d^{high}$ IL-10 producing B cells (B1 cells) fails to be depleted by anti-CD20 antibodies.[43] Interestingly, the secretion of autoantibodies is a function exclusive to the B1 subset, and the majority of human cancer patients mount specific autoantibody responses against their tumors.[44] Moreover, the population of CD20-resistant B cells has been reported to enhance A20 lymphoma growth in an IL-10-dependent manner.[19] Future studies must evaluate, in which particular settings B1 cells may modulate the growth of human tumors.

FcγR (CD64 and CD16) have been shown to have a positive role in the treatment of mouse melanomas with specific antibodies.[45] These preclinical findings are in accordance with human data showing that single-nucleotide polymorphisms (SNP) affecting the protein structure of FcγRIIIA/CD16A determine the *in vivo* efficacy of monoclonal ADCC-mediating antibodies (such as rituximab, trastuzumab and erbitux).[46] To our knowledge, the clinical significance of such SNPs has not been reported for anthracyclines or oxaliplatin, supporting the findings reported in this paper.

Antibodies against CRT, a Ca^{+}-binding ER residing chaperone, represent a diagnostic tool for various infectious, autoimmune and cancer-associated disorders.[47–50] Interestingly, anti-CRT IgA titers are more useful than anti-CRT IgG levels for detecting mammary, colorectal, hepatocellular and pancreatic carcinomas, alcoholic hepatitis, refractory celiac disease or primary biliary cirrhosis.[30,51–53] High concentrations of anti-CRT IgA antibodies were more frequently detected in lymph node-positive breast cancers than IgG antibodies, but failed to correlate with CRT membrane expression.[30] The biological significance of anti-CRT antibodies is unclear. However, experimental immunization against CRT could induce liver focal necrosis and hepatitis.[54] Trypanosoma cruzi CRT is highly immunogenic and exhibits cross-reactivity with isogenic cardiomyocytes, thus causing a local autoimmune reaction relevant to Chagas disease.[55]

The observation that anti-CRT IgA or IgG serum levels did not significantly increase after anthracycline-based chemotherapy of breast cancer patients may reflect the inability of many tumors to translocate CRT to the cell surface,[56,57] defects in other hallmarks of ICD such as absent expression of HMGB1 (Yamazaki T *et al*., In Press), or deficient autophagy,[58] or the general irrelevance of humoral responses to clinical outcome. Future studies must correlate the therapy-induced raise in anti-CRT IgA antibodies or other immunological alterations, including changing frequencies in tumor antigen-specific T lymphocytes, with tumor cell-intrinsic, ICD-relevant parameters.

Materials and Methods

Mouse strains. All the mice were bred and maintained according to both the FELASA and the Animal Experimental Ethics Committee Guidelines (Val de Marne, France). WT SPF C57Bl/6J mice were obtained from Harlan. OT-1 C57Bl/6J mice and Ly5.1 congenic mice were obtained from Jackson Lab, (Bar Harbor, ME, USA). C57Bl/6J $Fc\gamma RI^{-/-}$ mice,[23] FcγRI/IIIA/IV ('FcγRIIB-only'),[26] $Fc\gamma RIII^{-/-}$ mice,[22] $Fc\gamma RIV^{-/-}$ mice,[24] and FcγRI/IIB/III FcεRI/II (5KO, also known as 'FcγRIV-only') mice[25] have been reported previously and bred at the Institut Pasteur animal facility. C57Bl/6J μM KO mice were obtained from Centre d'Elevage d'Orléans (Dr Ryffel) and bred at the Institut Gustave Roussy animal facility.

Reagents and antibodies. Doxorubicin was purchased from Sigma-Aldrich (St Louis, MO, USA). Anti-mouse antibodies for CD3ε (145-2C11), CD4 (GK1.5), CD8α (53-6.7), CD16/32 (2.4G2), CD19 (1D3), CD45.2 (104), were obtained from Biolegend (Ozyme, St Quentin, France) or eBioscience (Paris, France). LIVE/DEAD fixable yellow stain fluorescence for viability staining was purchased from Invitrogen/Molecular Probes (Life technologies, St Aubin, France). Flow cytometry analyses have been performed on a Cyan (Beckman Colter, Marseille, France) flow cytometer with FloJo (Tree Star, Ashland, OR, USA) software or on a FACSCanto II and Diva software (BD Bioscience, Le Pont de Claix, France).

Transplantable tumor cell lines. MCA205 OVA fibrosarcoma cells (syngenic from C57Bl/6 mice) were cultured at 37 °C under 5% CO_2 in RPMI 1640 containing 10% FCS, 2 mM L-glutamine, 100 IU/ml penicillin/streptomycin, 1 mM sodium pyruvate and MEM nonessential amino acids (Invitrogen). OVA expressing tumor cells have been selected by antibiotic selection (Hygromycin (50 μg/ml, Invitrogen))

Chemotherapy treatment of established tumors in mice. Tumors were subcutaneously inoculated in the right flank by injecting 1×10^6 of MCA205 OVA cells. When the tumor size reached 30–45 mm^2, the mice were treated with 2 μM doxorubicin, injected intratumorally in 50 μl of PBS, or PBS alone as control. Tumor growths were monitored every 3–4 days using a caliper. In some experiments, MCA205 OVA tumor cell line has been subcutaneously inoculated to CD45.1 C57Bl/6 mice. Seven days later, the mice have been treated or not by doxorubicin (i.t). One day post chemotherapy, 1×10^6 CD45.2 congenic naive OT-I T cells have been injected i.v. day 8 post chemotherapy. After mouse sacrifice, tumor harvesting and enzymatic dissociation (see below), the amounts of tumor-infiltrating OT-I or B cells have been assessed by flow cytometry.

Tumor-infiltrating lymphocytes analyses. At indicated time points, tumors were harvested, cut into small pieces and digested in Liberase TM 25 μg/ml (Roche, Boulogne Billancourt, France) and DNase I 150 U/ml (Calbiochem, Millipore, Molsheim, France) for 30 min at 37 °C. Single-cell suspension was obtained by crushing the digested tissue with a syringe plunger and filtering through a 100-μm cell strainer. After washing, cells have been used for subsequent immunostaining.

***In vivo* cell depletion.** At indicated time point, MCA 205 OVA tumor-bearing mice received a single 250 μg of anti-CD20 (MB20-11)or IgG2a control i.v, as previously described.[59] B-cell depletion was checked in the spleen and tumors from the antibody administrated mice. CD8 + T cells have been depleted by using anti-CD8α Ab (53-6.72, Bioxcell, West Lebanon, NH, USA) or Rat IgG2a control (2A3, Bioxcell). The depletions have been started 1 day prior chemotherapy treatment and maintained during the whole experiment. Mice received 100 μg of Ab in 100 μl of PBS, i.p, every 3 days. T cell depletion was checked in the spleen and tumor from the antibody administrated mice.

Mouse anti-OVA Ig dosing. MCA 205 OVA-bearing mice have been treated or not with doxorubicin at day 7 post-tumor inoculation. Two to three weeks later, sera were collected and the presence of OVA-specific IgG, IgA and IgM was determined by using mouse anti-ovalbumin Igs (total G + A + M) ELISA kit (alpha diagnostic, Interchim, Montlucon, France), according to manufacturer's instructions.

Patients' cohort. Breast cancer patients who has signed an informed consent for investigations of research purposes were selected from a database of 591 patients who received preoperative anthracyclines-based chemotherapy regimen (plus or minus taxanes and herceptin for HER2 BC) at the Institut Gustave Roussy between 1987 and 2003 (Table 1). Pathologic complete response (pCR) was defined as the absence of any invasive cancer or isolated tumor cells only in the breast and lymph nodes after completion of chemotherapy. Serum was drawn for CA15.3 dosages and the remaining material kept frozen for parallel investigations, including anti-CRT IgG/A concentration assessments. Therefore, serum withdrawn at diagnosis before chemotherapy, during the 8 cycles of therapy and/or after completion of neoadjuvant treatment at follow up consultations was kept at − 20 °C until ELISA was performed.

Human Anti-CRT IgG dosing. Human anti-CRT IgG and IgA sera concentrations have been evaluated as previously described.[60] Antibody response against CRT has been assessed in a cohort of 63 breast cancer patients and 75 healthy volunteers. The cut-off values for Ig were as follows: detection threshold of 30 UI/ml for IgA and 100 for IgG.

Statistical analyses. Results are expressed as mean ± S.E.M. All experiments were repeated at least twice, yielding similar results. Normal distributions were compared by unpaired, two-tailed Student's *t*-tests. Statistical analyses were performed by means of the software Prism 5 (GraphPad, San Diego, CA, USA) and *P*-values < 0.05 were considered as statistically significant.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgements. We thank TF Tedder (Duke University) for anti-CD20 mAb and useful discussions. DH is supported by l'Association pour la Recherche sur le Cancer (ARC). NP is supported by la Ligue contre le cancer. DS is supported by Czech Science Foundation (grant number 13-14608S). LZ is supported by Institut National du Cancer (INCa), la Ligue contre le cancer (équipe labellisée), Fondation pour la Recherche Médicale (FRM) and Fondation de France. GK is supported by the European Commission (ArtForce); Agence National de la Recherche (ANR); Ligue contre le Cancer (Equipe labellisée); Fondation pour la Recherche Médicale (FRM); SIRIC SOCRATES, Institut National du Cancer (INCa); LabEx Immuno-Oncologie; Fondation de France; Fondation Bettencourt-Schueller; AXA Chair for Longevity Research; Cancéropôle Ile-de-France and Paris Alliance of Cancer Research Institutes (PACRI) and European Research Council (ERC).

1. Fridman WH, Galon J, Pages F, Tartour E, Sautes-Fridman C, Kroemer G. Prognostic and predictive impact of intra- and peritumoral immune infiltrates. *Cancer Res* 2011; **71**: 5601–5605.
2. Hanahan D, Weinberg RA. Hallmarks of cancer: the next generation. *Cell* 2011; **144**: 646–674.
3. Steinman RM, Banchereau J. Taking dendritic cells into medicine. *Nature* 2007; **449**: 419–426.
4. Balkwill F, Charles KA, Mantovani A. Smoldering and polarized inflammation in the initiation and promotion of malignant disease. *Cancer Cell* 2005; **7**: 211–217.
5. Hanahan D, Coussens LM. Accessories to the crime: functions of cells recruited to the tumor microenvironment. *Cancer Cell* 2012; **21**: 309–322.
6. Pillai S, Mattoo H, Cariappa A. B cells and autoimmunity. *Curr Opin Immunol* 2011; **23**: 721–731.
7. Tanchot C, Terme M, Pere H, Tran T, Benhamouda N, Strioga M *et al.* Tumor-infiltrating regulatory T cells: phenotype, role, mechanism of expansion in situ and clinical significance. *Cancer Microenviron* 2013; **6**: 147–157.
8. Andreu P, Johansson M, Affara NI, Pucci F, Tan T, Junankar S *et al.* FcRgamma activation regulates inflammation-associated squamous carcinogenesis. *Cancer Cell* 2010; **17**: 121–134.
9. de Visser KE, Korets LV, Coussens LM. *De novo* carcinogenesis promoted by chronic inflammation is B lymphocyte dependent. *Cancer Cell* 2005; **7**: 411–423.
10. Schioppa T, Moore R, Thompson RG, Rosser EC, Kulbe H, Nedospasov S *et al.* B regulatory cells and the tumor-promoting actions of TNF-alpha during squamous carcinogenesis. *Proc Natl Acad Sci USA* 2011; **108**: 10662–10667.
11. Ammirante M, Luo JL, Grivennikov S, Nedospasov S, Karin M. B-cell-derived lymphotoxin promotes castration-resistant prostate cancer. *Nature* 2010; **464**: 302–305.
12. DeNardo DG, Barreto JB, Andreu P, Vasquez L, Tawfik D, Kolhatkar N *et al.* CD4(+) T cells regulate pulmonary metastasis of mammary carcinomas by enhancing protumor properties of macrophages. *Cancer Cell* 2009; **16**: 91–102.
13. Kroemer G, Galluzzi L, Kepp O, Zitvogel L. Immunogenic cell death in cancer therapy. *Annu Rev Immunol* 2013; **31**: 51–72.
14. Ruffell B, Au A, Rugo HS, Esserman LJ, Hwang ES, Coussens LM. Leukocyte composition of human breast cancer. *Proc Natl Acad Sci USA* 2012; **109**: 2796–2801.
15. DeNardo DG, Brennan DJ, Rexhepaj E, Ruffell B, Shiao SL, Madden SF *et al.* Leukocyte complexity predicts breast cancer survival and functionally regulates response to chemotherapy. *Cancer Discov* 2011; **1**: 54–67.
16. Ma Y, Aymeric L, Locher C, Mattarollo SR, Delahaye NF, Pereira P *et al.* Contribution of IL-17-producing gamma delta T cells to the efficacy of anticancer chemotherapy. *J Exp Med* 2011; **208**: 491–503.
17. Ma Y, Adjemian S, Mattarollo SR, Yamazaki T, Aymeric L, Yang H *et al.* Anticancer chemotherapy-induced intratumoral recruitment and differentiation of antigen-presenting cells. *Immunity* 2013; **38**: 729–741.
18. Angeli V, Ginhoux F, Llodra J, Quemeneur L, Frenette PS, Skobe M *et al.* B cell-driven lymphangiogenesis in inflamed lymph nodes enhances dendritic cell mobilization. *Immunity* 2006; **24**: 203–215.
19. Horikawa M, Minard-Colin V, Matsushita T, Tedder TF. Regulatory B cell production of IL-10 inhibits lymphoma depletion during CD20 immunotherapy in mice. *J Clin Invest* 2011; **121**: 4268–4280.
20. Minard-Colin V, Xiu Y, Poe JC, Horikawa M, Magro CM, Hamaguchi Y *et al.* Lymphoma depletion during CD20 immunotherapy in mice is mediated by macrophage FcgammaRI, FcgammaRIII, and FcgammaRIV. *Blood* 2008; **112**: 1205–1213.
21. Bruhns P. Properties of mouse and human IgG receptors and their contribution to disease models. *Blood* 2012; **119**: 5640–5649.
22. Hazenbos WL, Gessner JE, Hofhuis FM, Kuipers H, Meyer D, Heijnen IA *et al.* Impaired IgG-dependent anaphylaxis and Arthus reaction in Fc gamma RIII (CD16) deficient mice. *Immunity* 1996; **5**: 181–188.
23. Ioan-Facsinay A, de Kimpe SJ, Hellwig SM, van Lent PL, Hofhuis FM, van Ojik HH *et al.* FcgammaRI (CD64) contributes substantially to severity of arthritis, hypersensitivity responses, and protection from bacterial infection. *Immunity* 2002; **16**: 391–402.
24. Nimmerjahn F, Lux A, Albert H, Woigk M, Lehmann C, Dudziak D *et al.* FcgammaRIV deletion reveals its central role for IgG2a and IgG2b activity *in vivo*. *Proc Natl Acad Sci USA* 2010; **107**: 19396–19401.
25. Mancardi DA, Iannascoli B, Hoos S, England P, Daeron M, Bruhns P. FcgammaRIV is a mouse IgE receptor that resembles macrophage FcepsilonRI in humans and promotes IgE-induced lung inflammation. *J Clin Invest* 2008; **118**: 3738–3750.
26. Takai T, Li M, Sylvestre D, Clynes R, Ravetch JV. FcR gamma chain deletion results in pleiotrophic effector cell defects. *Cell* 1994; **76**: 519–529.
27. Yamasaki S, Ishikawa E, Sakuma M, Hara H, Ogata K, Saito T. Mincle is an ITAM-coupled activating receptor that senses damaged cells. *Nat Immunol* 2008; **9**: 1179–1188.
28. Behler F, Steinwede K, Balboa L, Ueberberg B, Maus R, Kirchhof G *et al.* Role of Mincle in alveolar macrophage-dependent innate immunity against mycobacterial infections in mice. *J Immunol* 2012; **189**: 3121–3129.
29. Galluzzi L, Kepp O, Kroemer G. Enlightening the impact of immunogenic cell death in photodynamic cancer therapy. *EMBO J* 2012; **31**: 1055–1057.
30. Eric-Nikolic A, Milovanovic Z, Sanchez D, Pekarikova A, Dzodic R, Matic IZ *et al.* Overexpression of calreticulin in malignant and benign breast tumors: relationship with humoral immunity. *Oncology* 2012; **82**: 48–55.
31. Weber JS, Hamid O, Chasalow SD, Wu DY, Parker SM, Galbraith S *et al.* Ipilimumab increases activated T cells and enhances humoral immunity in patients with advanced melanoma. *J Immunother* 2012; **35**: 89–97.
32. Yuan J, Adamow M, Ginsberg BA, Rasalan TS, Ritter E, Gallardo HF *et al.* Integrated NY-ESO-1 antibody and CD8 + T cell responses correlate with clinical benefit in advanced melanoma patients treated with ipilimumab. *Proc Natl Acad Sci USA* 2011; **108**: 16723–16728.
33. Valmori D, Souleimanian NE, Tosello V, Bhardwaj N, Adams S, O'Neill D *et al.* Vaccination with NY-ESO-1 protein and CpG in Montanide induces integrated antibody/Th1 responses and CD8 T cells through cross-priming. *Proc Natl Acad Sci USA* 2007; **104**: 8947–8952.
34. Jinushi M, Hodi FS, Dranoff G. Therapy-induced antibodies to MHC class I chain-related protein A antagonize immune suppression and stimulate antitumor cytotoxicity. *Proc Natl Acad Sci USA* 2006; **103**: 9190–9195.
35. Schoenfeld J, Jinushi M, Nakazaki Y, Wiener D, Park J, Soiffer R *et al.* Active immunotherapy induces antibody responses that target tumor angiogenesis. *Cancer Res* 2010; **70**: 10150–10160.
36. Hodi FS, Butler M, Oble DA, Seiden MV, Haluska FG, Kruse A *et al.* Immunologic and clinical effects of antibody blockade of cytotoxic T lymphocyte-associated antigen 4 in previously vaccinated cancer patients. *Proc Natl Acad Sci USA* 2008; **105**: 3005–3010.
37. Fonseca C, Soiffer R, Ho V, Vanneman M, Jinushi M, Ritz J *et al.* Protein disulfide isomerases are antibody targets during immune-mediated tumor destruction. *Blood* 2009; **113**: 1681–1688.
38. Hodi FS, Schmollinger JC, Soiffer RJ, Salgia R, Lynch T, Ritz J *et al.* ATP6S1 elicits potent humoral responses associated with immune-mediated tumor destruction. *Proc Natl Acad Sci USA* 2002; **99**: 6919–6924.
39. Erdag G, Schaefer JT, Smolkin ME, Deacon DH, Shea SM, Dengel LT *et al.* Immunotype and immunohistologic characteristics of tumor-infiltrating immune cells are associated with clinical outcome in metastatic melanoma. *Cancer Res* 2012; **72**: 1070–1080.
40. Martinet L, Garrido I, Girard JP. Tumor high endothelial venules (HEVs) predict lymphocyte infiltration and favorable prognosis in breast cancer. *Oncoimmunology* 2012; **1**: 789–790.
41. Martinet L, Le Guellec S, Filleron T, Lamant L, Meyer N, Rochaix P *et al.* High endothelial venules (HEVs) in human melanoma lesions: major gateways for tumor-infiltrating lymphocytes. *Oncoimmunology*, 2012; 1: 829–839.
42. Dieu-Nosjean MC, Antoine M, Danel C, Heudes D, Wislez M, Poulot V *et al.* Long-term survival for patients with non-small-cell lung cancer with intratumoral lymphoid structures. *J Clin Oncol* 2008; **26**: 4410–4417.
43. Haas KM, Poe JC, Steeber DA, Tedder TF. B-1a and B-1b cells exhibit distinct developmental requirements and have unique functional roles in innate and adaptive immunity to *S. pneumoniae*. *Immunity* 2005; **23**: 7–18.
44. Reuschenbach M, von Knebel Doeberitz M, Wentzensen N. A systematic review of humoral immune responses against tumor antigens. *Cancer Immunol Immunother* 2009; **58**: 1535–1544.
45. Albanesi M, Mancardi DA, Macdonald LE, Iannascoli B, Zitvogel L, Murphy AJ *et al.* Cutting edge: FcgammaRIII (CD16) and FcgammaRI (CD64) are responsible for anti-glycoprotein 75 monoclonal antibody TA99 therapy for experimental metastatic B16 melanoma. *J Immunol* 2012; **189**: 5513–5517.
46. Lejeune J, Thibault G, Ternant D, Cartron G, Watier H, Ohresser M. Evidence for linkage disequilibrium between Fcgamma RIIIa-V158F and Fcgamma RIIa-H131R polymorphisms in white patients, and for an Fcgamma RIIIa-restricted influence on the response to therapeutic antibodies. *J Clin Oncol* 2008; **26**: 5489–5491; author reply 91-2.
47. Boehm J, Orth T, Van Nguyen P, Soling HD. Systemic lupus erythematosus is associated with increased auto-antibody titers against calreticulin and grp94, but calreticulin is not the Ro/SS-A antigen. *Eur J Clin Invest* 1994; **24**: 248–257.
48. El Aswad Bel D, Doenhoff MJ, El Hadidi AS, Schwaeble WJ, Lynch NJ. Use of recombinant calreticulin and cercarial transformation fluid (CTF) in the serodiagnosis of Schistosoma mansoni. *Immunobiology* 2011; **216**: 379–385.
49. Watanabe K, Ohira H, Orikasa H, Saito K, Kanno K, Shioya Y *et al.* Anti-calreticulin antibodies in patients with inflammatory bowel disease. *Fukushima J Med Sci* 2006; **52**: 1–11.
50. Winter JA, Davies OR, Brown AP, Garnett MC, Stolnik S, Pritchard DI. The assessment of hookworm calreticulin as a potential vaccine for necatoriasis. *Parasite Immunol* 2005; **27**: 139–146.

51. Kreisel W, Siegel A, Bahler A, Spamer C, Schiltz E, Kist M *et al.* High prevalence of antibodies to calreticulin of the IgA class in primary biliary cirrhosis: a possible role of gut-derived bacterial antigens in its aetiology? *Scand J Gastroenterol* 1999; **34**: 623–628.
52. Pekarikova A, Sanchez D, Palova-Jelinkova L, Simsova M, Benes Z, Hoffmanova I *et al.* Calreticulin is a B cell molecular target in some gastrointestinal malignancies. *Clin Exp Immunol* 2010; **160**: 215–222.
53. Sanchez D, Palova-Jelinkova L, Felsberg J, Simsova M, Pekarikova A, Pecharova B *et al.* Anti-calreticulin immunoglobulin A (IgA) antibodies in refractory coeliac disease. *Clin Exp Immunol* 2008; **153**: 351–359.
54. Abe K, Ohira H, Kobayashi H, Saito H, Takahashi A, Rai T *et al.* Breakthrough of immune self-tolerance to calreticulin induced by CpG-oligodeoxynucleotides as adjuvant. *Fukushima J Med Sci* 2007; **53**: 95–108.
55. Ribeiro CH, Lopez NC, Ramirez GA, Valck CE, Molina MC, Aguilar L *et al.* Trypanosoma cruzi calreticulin: a possible role in Chagas' disease autoimmunity. *Mol Immunol* 2009; **46**: 1092–1099.
56. Panaretakis T, Kepp O, Brockmeier U, Tesniere A, Bjorklund AC, Chapman DC *et al.* Mechanisms of pre-apoptotic calreticulin exposure in immunogenic cell death. *EMBO J* 2009; **28**: 578–590.
57. Tufi R, Panaretakis T, Bianchi K, Criollo A, Fazi B, Di Sano F *et al.* Reduction of endoplasmic reticulum Ca2+ levels favors plasma membrane surface exposure of calreticulin. *Cell Death Differ* 2008; **15**: 274–282.
58. Ladoire S, Chaba K, Martins I, Sukkurwala AQ, Adjemian S, Michaud M *et al.* Immunohistochemical detection of cytoplasmic LC3 puncta in human cancer specimens. *Autophagy* 2012; **8**: 1175–1184.
59. Hamaguchi Y, Xiu Y, Komura K, Nimmerjahn F, Tedder TF. Antibody isotype-specific engagement of Fcgamma receptors regulates B lymphocyte depletion during CD20 immunotherapy. *J Exp Med* 2006; **203**: 743–753.
60. Sanchez D, Tuckova L, Mothes T, Kreisel W, Benes Z, Tlaskalova-Hogenova H. Epitopes of calreticulin recognised by IgA autoantibodies from patients with hepatic and coeliac disease. *J Autoimmun* 2003; **21**: 383–392.

Supplementary Information accompanies this paper on Cell Death and Differentiation website (http://www.nature.com/cdd)