Abstract

Oncogene activation in tumor cells induces broad and complex cellular changes that contribute significantly to disease initiation and progression. In melanoma, oncogenic BRAFV600E has been shown to drive the transcription of a specific gene signature that can promote multiple mechanisms of immune suppression within the tumor microenvironment. We show here that BRAFV600E also induces rapid internalization of MHC class I (MHC-I) from the melanoma cell surface and its intracellular sequestration within endolysosomal compartments. Importantly, MAPK inhibitor treatment quickly restored MHC-I surface expression in tumor cells, thereby enhancing melanoma antigen-specific T-cell recognition and effector function. MAPK pathway–driven relocalization of HLA-A*0201 required a highly conserved cytoplasmic serine phosphorylation site previously implicated in rapid MHC-I internalization and recycling by activated immune cells. Collectively, these data suggest that oncogenic activation of BRAF allows tumor cells to co-opt an evolutionarily conserved MHC-I trafficking pathway as a strategy to facilitate immune evasion. This link between MAPK pathway activation and the MHC-I cytoplasmic tail has direct implications for immunologic recognition of tumor cells and provides further evidence to support testing therapeutic strategies combining MAPK pathway inhibition with immunotherapies in the clinical setting. Cancer Immunol Res 3(6): 602–9. © 2015 AACR.

Introduction

Two hallmarks of melanoma are the frequent presence of MAPK pathway–activating oncogenic mutations and immune suppression within the tumor microenvironment (TME; ref. 1). Several recent studies support that these two hallmarks are intimately linked, with oncogenic signaling regulating the transcription of multiple genes that can collectively suppress the antitumor immune response. These include upregulating immunomodulatory chemokines and cytokines that promote recruitment and activation of suppressive immune cell subsets into the TME, in addition to downregulating the expression of melanoma differentiation antigens that can be recognized by cytotoxic T lymphocytes (2–8). We show here that oncogenic BRAFV600E mutations, which are the most prevalent (~50%) activating kinase mutations in melanoma, may also promote immune escape by directly modulating the surface expression and intracellular distribution of MHC class I (MHC-I) molecules in tumor cells. BRAFV600E signaling in melanoma cells leads to specific, constitutive internalization of MHC-I from the tumor cell surface and its intracellular sequestration within endocytic compartments. This reduces melanoma-specific CD8⁺ T-cell recognition and function. The effect is reversed by clinically relevant MAPK pathway inhibitors. The BRAFV600E–induced cellular redistribution of MHC-I is rapid and requires a highly conserved serine phosphorylation site within the MHC-I cytoplasmic domain, showing strong similarities to a specialized MHC-I trafficking pathway used by activated immune cells (9–12). These results show that oncogenic BRAFV600E mutations directly reduce CD8⁺ T-cell recognition of melanomas by co-opting a conserved internalization pathway involving the MHC-I cytoplasmic tail.

Materials and Methods

Cell culture and lentiviral transduction

Four human melanoma cell lines were studied; two lines expressed V600E-mutated BRAF (Mel888 and WM793) and two lines expressed wild-type (WT) BRAF (CHL1 and Mewo). All cell lines were obtained from the laboratory of Dr. Michael
Davies, at The University of Texas MD Anderson Cancer Center. All cells were verified by DNA fingerprinting within 6 months of initiating these studies. All cell lines were cultured in RPMI-1640 medium containing 10% FBS (Gibco), 1% penicillin–streptomycin (Cellgrow), and maintained at 37°C in 5% CO2. HLA-A2-negative Mel888 and WM793 parental cells were transduced to express HLA-A*0201 variants using lentiviral gene transfer vectors as previously described (13). The human phosphoglycerate kinase (hPGK) promoter was used to drive the expression of WT HLA-A*0201 or one of three cytoplasmic tail variants: ΔTail, S335A, or Y320A. Transduced cells expressing comparable levels of surface HLA-A*0201 were isolated by cell sorting and used in subsequent studies. MART-1(27–35)—specific tumor-infiltrating lymphocytes (TIL) were maintained in TIL culture media containing RPMI-1640, 10% human serum AB (Gemini), 0.1% 2-mercaptoethanol (Gibco), 1% sodium pyruvate, 1% penicillin–streptomycin, and 3,000 IU/mL of IL2 (Proleukin; Novartis).

MAPK pathway inhibitors and flow-cytometric analyses
The BRAFV600E-specific inhibitor (BRAFi) dabrafenib GSK2118436 and MEK inhibitor (MEKi) trametinib GSK1120212 (Selleckchem) were used in these studies to inhibit MAPK pathway activation. Melanoma cell lines were seeded at 1.0 × 10⁶ cells in a 12-well plate and cultured in the presence of BRAFi (50 nmol/L), MEKi (50 nmol/L), or DMSO (solvent control) for 3 hours with either DMSO, dabrafenib, 50 nmol/L (BRAFi), or trametinib, 50 nmol/L (MEKi), then stained for total HLA-A, B, and C and analyzed by flow cytometry. D, confocal microscopy images of DMSO- or BRAFi-treated Mel888 and CHL1 cells following staining with fluorescently labeled HLA-A, B, and C-specific antibody. E, quantification of confocal imaging, with MHC-I surface expression expressed as mean pixel counts for at least 40 imaged cells within each treatment group. F, time-course experiment showing total MHC-I upregulation in Mel888, WM793, and CHL1 melanoma cells treated with dabrafenib for 30 minutes, 60 minutes, or 3 hours, as measured by flow cytometry. All experiments were performed at least four times with similar results; **, P < 0.01; ns, not statistically significant.
different time points. This concentration was chosen because it effectively blocked the MAPK pathway without inducing rapid cell death or toxicity (Supplementary Figs. S1 and S4). Surface MHC-I expression was quantified by staining cells with anti-human HLA-A, B, C–APC (W6/32) or anti-human HLA-A2–APC (BB7.2; Biolegend) and measuring fluorescence using a FACScanto II flow cytometer (BD Biosciences). Data were further analyzed using FlowJo analysis software (Treestar).

T-cell assays

TILs obtained from a HLA-A*0201–positive melanoma patient TIL infusion product and showing >98% MART-1(27–35) specificity by tetramer staining were used for all CD8+ T-cell assays. Transduced Mel888 cells (which endogenously express MART-1) were cocultured with MART-specific TILs at a 1:1 effector-to-target ratio (10,000 cells each) at 37°C for 4 hours, following a 3-hour preincubation with BRAFi (50 nmol/L) or DMSO. Transduced WM793 cells (which do not express MART-1) were pulsed with titrated concentrations of MART-1(27–35) peptide and washed before coculture. TILs were incubated with melanoma cell lines for 4 hours in the presence of GolgiStop (BD Biosciences), washed, fixed, permeabilized, and stained with anti-human IFNγ conjugated to APC (BD Biosciences). Intracellular IFNγ production by CD8+ T cells was then determined by flow-cytometric analysis. Mel888 cells were also coincubated with TILs for 8 hours, after which time supernatant was collected and analyzed by ELISA to measure IFNγ concentration (eBiosciences). Plates were read using SpectraMax M5/M5e Multimode Plate Reader and analysis program.

Statistical analysis

Graph Pad Prism 6 was used for graphing data and statistical analysis. A Student t test was used to analyze the statistical significance of all flow-cytometry data. A one-way ANOVA test was used to analyze confocal microscopy quantification data. A P value less than or equal to 0.05 was the threshold used to determine statistical significance.

Confocal microscopy

Because of space restrictions, confocal microscopy methods are included in Supplementary Data.
Results

MAPK pathway inhibition induces rapid upregulation of MHC class I surface expression in BRAF-mutant melanoma cell lines

To assess the impact of BRAFV600E mutation on the expression of immunomodulatory genes in melanoma, primary human melanocytes were lentivirally transduced to express GFP alone, or BRAFV600E plus GFP concurrently (4). Flow-cytometric analysis of multiple transduced melanocyte lines revealed that ectopic overexpression of BRAFV600E consistently induced substantial reductions (3- to 10-fold) in surface expression of HLA-A, B, and C (Fig. 1A and B).

To determine whether this modulation of MHC-I surface expression was physiologically relevant for melanoma, we initiated a series of MAPK pathway inhibitor studies in melanoma cell lines harboring either V600E-mutated or WT BRAF. Following MAPK pathway inhibition (Supplementary Fig. S1), CHL1 melanoma cells bearing WT BRAF showed no detectable alterations in MHC-I expression with either the BRAFV600E-specific inhibitor dabrafenib (BRAFi) or the MEK inhibitor trametinib (MEKi; Fig. 1C). By contrast, BRAFi or MEKi treatment of two V600E-positive melanoma cell lines (Mel888 and WM793) significantly increased total cell surface MHC-I (Fig. 1C). This upregulation was specific for MHC-I, as expression of other melanoma cell surface molecules HLA-DR, PD-L1, and MSCP was unaffected by drug treatment (Supplementary Fig. S2). Confocal microscopy analysis of inhibitor-treated cells confirmed these findings (Fig. 1D and E).

The extent of MHC-I upregulation observed varied depending on the experiment, cell line, and dose of inhibitor used, but
Modulation of MHC-I expression by the MAPK pathway is mediated by MHC-I cytoplasmic tail Serine-335

The ~35-amino acid cytoplasmic domain of MHC-I contains two conserved phosphorylation sites, Tyrosine-320 and Serine-335, which have both been previously linked to MHC-I trafficking in immune cells (10, 12, 17–20). To explore whether MAPK pathway activation modulates MHC-I melanoma cell surface expression through a cytoplasmic tail-dependent mechanism, we generated lentiviral constructs designed to express tail variants of HLA-A’0201 (A2; ref. 13). Mel888 and WM793 melanoma cells were then transduced to express either WT or one of three cytoplasmic tail mutants of HLA-A2: ΔTail, containing a deletion of the entire cytoplasmic domain; Y320A or S335A, containing alanine point substitutions to either the tyrosine or serine phosphorylation sites, respectively (Fig. 2A).

As expected, WT A2 surface expression rapidly increased in both transduced cell lines following MAPK pathway inhibition with either BRAFi or MEKi (Fig. 2B and C and Supplementary Figs. S3 and S4). By contrast, cytoplasmic tail-deleted A2 showed no change in surface expression following treatment with either inhibitor. Interestingly, point mutations to the cytoplasmic tyrosine or serine phosphorylation sites of HLA-A2 showed distinct consequences: Although cell surface levels of the Y320A mutant increased in response to MAPK pathway inhibition (similar to WT A2), expression of the S335A mutant did not change. Surface expression of WT HLA-A’0101, endogenously expressed by all melanoma cell lines, was monitored as a positive control for MHC-I expression (Fig. 2E and Supplementary Figs. S6 and S7). In addition, because WM793 cells do not naturally express MART-1, we also measured TIL reactivity in response to A2-transduced WM793 cells pulsed with MART-1 peptide following DMSO or BRAFi treatment (Fig. 2F and Supplementary Fig. S6). These data were consistent with those from earlier experiments and demonstrated that MHC-I upregulation resulting from MAPK pathway inhibition led to significantly increased melanoma-specific CD8+ T-cell recognition and function.

BRAFV600E promotes rapid MHC-I internalization and intracellular sequestration that is reversible with MAPK pathway inhibition

We performed confocal microscopy studies to further characterize the regulation of MHC-I trafficking and intracellular localization by the MAPK pathway in melanoma cells. Melanoma cells harboring WT or V600E-mutated BRAF were surface stained with a fluorescently labeled, HLA-A, B, and C–specific mAb. At different time points after being returned to tissue culture, cells were stained with a secondary antibody conjugated to a different fluorophore (red). This protocol allowed us to readily visualize and distinguish MHC-I molecules internalized over the course of time in culture (green) from MHC-I remaining at the cell surface (yellow in merged image). BRAFV600E-expressing WM793 cells accumulated a significantly higher level of internalized MHC-I over 30 and 60 minutes compared with that accumulated by WT BRAF-expressing CHL1 cells (Fig. 3A). Similar differences in MHC-I internalization were observed between Mel888 (BRAFV600E) and MeWo (BRAF WT) melanoma cell lines (data not shown).

We repeated the experiment after pretreating the WM793 cells for 2 hours with either DMSO or BRAFi. BRAFi treatment dramatically reduced the amount of internalized MHC-I, while maintaining a relatively high level of cell surface expression (Fig. 3B). Conversely, the removal of BRAFi from the cell media resulted in a rapid and progressive disappearance of cell surface MHC-I in V600E-expressing Mel888 cells, but not in WT BRAF-expressing MeWo cells (Fig. 3C). The BRAFi-induced shift toward a higher level of internalized MHC-I over 30 and 60 minutes was confirmed by permeabilizing WM793 cells before staining to visualize the steady-state distribution of total cellular MHC-I (Fig. 3D).

To better understand the fate of internalized MHC-I molecules, we obtained permeabilized melanoma cells for total HLA-ABC along with the endolysosomal marker LAMP-1. Although control WM793 cells showed a clear colocalization of MHC-I molecules within LAMP-1–positive endocytic compartments, BRAFi-treated cells showed approximately 3- to 4-fold less colocalization of the two markers (Fig. 3E and F). To determine whether this increased endolysosomal trafficking induced by MAPK pathway activation might be associated with an increased rate of MHC-I degradation, we performed an 35S-methionine pulse-chase experiment designed to assess the molecular half-life of MHC-I molecules. Neither BRAFi nor MEKi treatment of melanoma cells had any measurable effect on MHC-I half-life (Supplementary Fig. S8). Taken together, the results support that BRAFV600E and MAPK pathway activation do not directly promote MHC-I degradation, but instead regulate the trafficking and cellular localization of MHC-I in
Figure 3. **BRAFV600E** induces intracellular sequestration of MHC-I

**A** WM793 (V600E) and CHL1 (WT BRAF) melanoma cells were surface-labeled with Alexa488-conjugated HLA-A, B, and C-specific mAb (green, 1st label) and then cultured at 37°C for 2 hours before HLA-A, B, and C surface labeling, and then cultured at 37°C for 90 minutes with continued exposure to DMSO or BRAFi. **B** Time course of MHC-I surface expression in Mel888 (BRAFV600E) or MeWo (BRAF WT) melanoma cells following removal of dabrafenib from cell culture medium, as measured by flow cytometry. **C** Confocal images showing cellular distribution of total HLA-A, B, and C in permeabilized WM793 cells following a 2-hour treatment with DMSO or dabrafenib. White arrows indicate increased cell surface localization following BRAFi treatment. **D** Double staining of total MHC-I (green) and the endolysosomal marker LAMP-1 (red), with white color indicating overlap of the two markers. **E** The percentage of colocalized pixels was calculated from at least 40 imaged cells within each treatment group. **F** The percentage of colocalized pixels was calculated from at least 40 imaged cells within each treatment group.

**Discussion**

MHC-I–mediated antigen presentation by cancer cells constitutes a central focus of antitumor CD8+ T-cell responses. Herein, we report a novel mechanism of oncogene-induced immunomodulation in which oncogenic BRAFV600E–mutant proteins promote cellular redistribution of MHC-I molecules in melanoma cells. Our data support a model in which the BRAFV600E mutation drives rapid and constitutive internalization of MHC-I from the cell surface and subsequent sequestration within endocytic compartments, as depicted in Fig. 4. Inhibition of BRAFV600E or MEK in human melanoma cells with a BRAFV600E mutation decreases MHC-I internalization, resulting in less endolysosomal sequestration and increased surface expression, which in turn augments CD8+ T-cell recognition of tumor cells.

MAPK pathway inhibition has previously been reported to drive increased expression of MHC-I, in addition to that of melanoma differentiation antigens such as MART-1 and gp100 (3, 13–15). However, these changes were shown to take place over days of inhibitor treatment and relied largely on transcriptional upregulation. By contrast, the changes in MHC-I expression we observed occurred within 1 to 2 hours of drug treatment, preceding a transcriptional explanation. This short time of onset for the effects is more suggestive of a posttranslational mechanism (22), and our data support that phosphorylation of Serine-335, but not Tyrosine-320, on the MHC-I cytoplasmic domain was required for this MAPK pathway inhibition has previously been reported to abrogate the rapid internalization and recycling of MHC-I that occurs in lymphocytes upon activation (9, 10). This region has also been shown to control the rate of surface MHC-I internalization in dendritic cells (DC), in which recycling of MHC-I is known to play a critical role in antigen cross-presentation (12, 19, 20, 23). Moreover, the MHC-I cytoplasmic tail has
been shown to mediate surface clustering of MHC-I, which can significantly affect CD8+ T-cell recognition (24). Interestingly, although Tyrosine-320 was required for transit of MHC-I into LAMP-1–positive endocytic compartments of DCs (12, 19), these studies suggest that Serine-335 may play a more dominant role in controlling endocytic trafficking in melanoma cells. Although MHC-I phosphorylation has been associated with intracellular trafficking of MHC-I in lymphoblastoid cell lines (25), it remains to be determined whether the same mechanism plays a role in tumor cells and which kinases and/or phosphatases might mediate this process. Studies are currently ongoing to address this question, in addition to examining whether MAPK pathway inhibition can induce qualitative shifts in the global immunopeptidome, which could have critical consequences for antitumor T-cell responses.

Although many questions remain, the results presented here are in accordance with and add to a number of recent studies demonstrating that the oncogenic BRAFV600E mutation, which is a frequent event in melanoma and also detected in several other cancer types, promotes immune suppression in cancer through multiple mechanisms (2–7, 26). Intracellular sequestration or degradation of MHC-I through targeting the cytoplasmic tail is a common immune-evasion strategy used by viruses (27–29); therefore, it is perhaps not surprising that some tumors have evolved similar mechanisms to avoid T-cell recognition (30). These findings have potentially important clinical implications for cancer patients and support the emerging notion that oncogene-targeted agents will show therapeutic synergy when used in combination with immune-based therapies.

Disclosure of Potential Conflicts of Interest
C. Bernatchez is a consultant/advisory board member for Lion Biotechnologies. L.G. Radvanyi is chief scientific officer at Lion Biotechnologies. M.A. Davies reports receiving commercial research support from AstraZeneca, Genentech/Roche, GlaxoSmithKline, Merck, Myriad, Oncothyreon, and Sanoﬁ Aventis, and is a consultant/advisory board member for GlaxoSmithKline, Genentech/Roche, Novartis, and Sanoﬁ Aventis. No potential conflicts of interest were disclosed by the other authors.

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Acknowledgments
The authors thank Drs. Willem Overwijk and Lisa Boulanger for critical reading of the article.

Grant Support
This work was funded by the National Institute of Allergic and Infectious Diseases (NIADC, (15R01AI085371)), the Cancer Prevention and Research Institute of Texas (CPRIT; RP110248), and a Melanoma SPORE grant (CA093459).

February 15, 2014; revised March 16, 2015; accepted March 17, 2015.

Figure 4.
The proposed model of melanoma cell MHC class I trafficking in the context of MAPK pathway activation or inhibition. Oncogenic activating BRAF mutations (e.g., V600E) in melanoma cells drive the rapid and constitutive internalization of MHC-I molecules from the cell surface and their subsequent sequestration within LAMP1-positive endolysosomal compartments (left). This redistribution process requires the conserved Serine-335 phosphorylation site (S) found within the cytoplasmic tail of MHC-I. Pharmaceutical inhibition of MAPK signaling can inhibit MHC-I internalization, thus altering the equilibrium and resulting in reduced endolysosomal sequestration and enhanced MHC-I surface expression within hours (right). This augmented MHC-I surface expression in turn leads to increased tumor cell recognition and function of melanoma antigen-specific CD8+ T cells.
BRAFV600E Induces Intracellular Sequestration of MHC-I

References

BRAF\textsuperscript{V600E} Co-opts a Conserved MHC Class I Internalization Pathway to Diminish Antigen Presentation and CD8 + T-cell Recognition of Melanoma


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