Psychological Stress Compromises CD8+ T Cell Control of Latent Herpes Simplex Virus Type 1 Infections

Michael L. Freeman, Brian S. Sheridan, Robert H. Bonneau and Robert L. Hendricks

J Immunol 2007; 179:322-328; doi: 10.4049/jimmunol.179.1.322
http://www.jimmunol.org/content/179/1/322

References
This article cites 32 articles, 15 of which you can access for free at:
http://www.jimmunol.org/content/179/1/322.full#ref-list-1

Subscription
Information about subscribing to The Journal of Immunology is online at:
http://jimmunol.org/subscription

Permissions
Submit copyright permission requests at:
http://www.aai.org/About/Publications/JI/copyright.html

Email Alerts
Receive free email-alerts when new articles cite this article. Sign up at:
http://jimmunol.org/alerts
Psychological Stress Compromises CD8\(^{+}\) T Cell Control of Latent Herpes Simplex Virus Type 1 Infections\(^1\)

Michael L. Freeman,*\(^{*,+}\) Brian S. Sheridan,†‡ Robert H. Bonneau,§ and Robert L. Hendricks\(^2+\),$\(|\|$†

Recurrent HSV-1 ocular disease results from reactivation of latent virus in trigeminal ganglia, often following immunosuppression or exposure to a variety of psychological or physical stressors. HSV-specific CD8\(^{+}\) T cells can block HSV-1 reactivation from latency in ex vivo trigeminal ganglia cultures through production of IFN-\(\gamma\). In this study, we establish that either CD8\(^{+}\) T cell depletion or exposure to restraint stress permit HSV-1 to transiently escape from latency in vivo. Restraint stress caused a reduction of TG-resident HSV-specific CD8\(^{+}\) T cells and a functional compromise of those cells that survive. Together, these effects of stress resulted in an approximate 65% reduction of cells capable of producing IFN-\(\gamma\) in response to reactivating virus. Our findings demonstrate persistent in vivo regulation of latent HSV-1 by CD8\(^{+}\) T cells, and strongly support the concept that stress induces HSV-1 reactivation from latency at least in part by compromising CD8\(^{+}\) T cell surveillance of latently infected neurons. *The Journal of Immunology, 2007, 179: 322–328.

H

erpes simplex virus type 1 is a ubiquitous pathogen that infects a majority of people worldwide. Following primary infection, the virus establishes a latent infection in neuronal nuclei housed within sensory ganglia. Most people who harbor latent virus in their sensory neurons do not experience recurrent herpetic disease. However, in some individuals, reactivation of latent virus results in its anterograde transport to the periphery and release of infectious virions at skin or mucosal surfaces. The resulting disease can range in severity from the discomfort and temporary disfigurement of cold sores to potentially blinding corneal lesions. In rare cases, HSV-1 reactivation can result in retrograde transport to the CNS, leading to potentially lethal encephalitis.

The stimuli that induce HSV-1 reactivation from latency in these individuals are poorly defined, but disease recurrence is often associated with exposure to a variety of psychological or physical stressors. These stressors result in the synthesis and release of a wide variety of neuroendocrine-derived peptides and hormones, including products of the sympathetic nervous system and the hypothalamic-pituitary-adrenal axis (reviewed in Refs. 1 and 2). The incidence of HSV-1 reactivation from latency is also increased in persons who are immunologically compromised, suggesting a possible link between the immune system and HSV-1 latency.

A growing body of data is emerging in support of a role for HSV-specific CD8\(^{+}\) T cells in control of HSV-1 latency (3–7). In both mice and humans, CD8\(^{+}\) T cells surround HSV-1-infected neurons within the trigeminal ganglion (TG)\(^3\) and maintain an activation phenotype in the absence of apparent viral reactivation. In C57BL/6 mice, these TG-resident CD8\(^{+}\) T cells are capable of blocking HSV-1 reactivation from latency in ex vivo cultures of latently infected TG in part through the production of the antiviral cytokine IFN-\(\gamma\) (8, 9).

Based on these observations, we hypothesized that the link between exposure to stress and HSV-1 reactivation from latency in sensory neurons might lie in a stress-induced transient compromise of CD8\(^{+}\) T cell protection within the latently infected TG. This hypothesis is supported by a significant body of data that demonstrates the ability of stress and stress-associated hormones to compromise CD8\(^{+}\) T cell function (1, 2, 10–12). Psychological stress has been shown to induce HSV-1 reactivation from latency in mice (13) and to significantly compromise the CD8\(^{+}\) T cell response to HSV-1 in lymphoid organs (14–16). However, no link has yet been established among psychological stress, CD8\(^{+}\) T cell function, and HSV-1 reactivation at the level of latently infected neurons.

This study provides direct evidence that CD8\(^{+}\) T cells monitor and regulate the activity of latent HSV-1. We also demonstrate that exposure to psychological stress significantly compromises the capacity of TG-resident HSV-specific CD8\(^{+}\) T cells to respond to reactivating virus in vitro, and results in HSV-1 reactivation from latency with an associated dramatic increase in viral genome copy number within latently infected TG.

Materials and Methods

Mice and virus infection

Six- to 8-wk-old male C57BL/6J (B6; H-2K\(^b\), CD45.2) or B6.SJL-Ptpcr\(^{+/+}\)/BoyJ (B6.SJL; H-2K\(^b\), CD45.1) mice (The Jackson Laboratory) were anesthetized by i.p. injection of 66.7 mg/kg ketamine hydrochloride and 1.33 mg/kg xylazine (Phoenix Scientific) in 0.2 ml of HBSS (BioWhittaker). Purified wild-type RE strain HSV-1 (10\(^5\) PFU) was applied to the scarified corneas of anesthetized mice as previously described (7). All animal

\(^{1}\) This work was supported by National Institutes of Health Grants 5T32 AI049820 (to M.L.F.), T32 AI060525 (to B.S.S.), AI49719 (to R.H.B.), EY05945, P30 EY08098 (to R.L.H.), an unrestricted grant from Research to Prevent Blindness (New York, NY), and the Eye and Ear Foundation of Pittsburgh.

\(^{2}\) Address correspondence and reprint requests to Dr. Robert L. Hendricks, Eye and Ear Institute, Room 922, 203 Lothrop Street, Pittsburgh, PA 15213. E-mail address: hendricksr@upmc.edu

\(^{3}\) Abbreviations used in this paper: TG, trigeminal ganglia; gB, glycoprotein B; MFI, mean fluorescence intensity.

Copyright © 2007 by The American Association of Immunologists, Inc. 0022-1767/07/$2.00
experiments were conducted according to the guidelines of the Institutional Animal Care and Use Committee of the University of Pittsburgh.

### In vivo CD8 depletion

Latently infected mice received a single i.p. injection of 0.5 mg of anti-CD8 mAb (clone 2.43, rat IgG2b) 3 days before TG excision.

### Restraint stress

On 4 consecutive nights beginning 30 days after infection, mice were physically restrained in a 50-ml conical tube containing approximately one hundred 0.4-cm diameter holes. The 12-h restraint sessions in their home cages were begun 2 h into the dark cycle. Each restraint session was followed by a 12-h period without restraint. Because the stressed mice lacked access to food and water during the restraint sessions, nonstressed control mice were similarly food and water deprived, but not restrained.

### Serum corticosterone assay

Serum corticosterone levels were assayed using a standard radioimmunoassay (MP Biomedicals) according to the manufacturer’s protocol. Levels were determined using a standard curve and expressed in nanograms per milliliter.

### Single-cell suspensions of TG

At various times after infection, mice were euthanized by exsanguination. TG were excised, pooled, digested with 100 l of DMEM (BioWhittaker) containing 10% FCS (HyClone) and 400 U/ml collagenase type I (Sigma-Aldrich) per TG for 1 h at 37°C, and dissociated into a single-cell suspension by trituration. Proliferation was assayed by labeling TG suspensions with 2.5 M CFSE (Molecular Probes) and incubating for 72 h with or without HSV-1 glycoprotein B (gB)498–505 peptide (Invitrogen Life Technologies).

### Flow cytometry

TG cell suspensions were passed through a 40-μm filter-cap tube to remove debris. Ab surface staining was performed as described previously (7), with minor modifications. Fluorochrome-conjugated Abs against CD8 (53-6.7), CD8.2 (53-5.8), CD45 (30-F11), and CD45.1 (A20) were purchased from BD Pharmingen. Proper isotype control Abs were used. PE-conjugated H-2Kb/gB498–505(SSIEFARL) tetramers (National Institute of Allergy and Infectious Diseases Tetramer Core Facility) were used to identify the H-2Kb-restricted HSV-1 gB498–505-specific CD8 T cell population. Intracellular IFN-γ (XMG1.2; BD Pharmedics) assays were performed using the Cytofix/Cytoperm kit with GolgiPlug (BD Pharmingen) according to the manufacturer’s instructions. Preliminary studies established that TG-resident gB498–505-CD8 T cells were optimally stimulated for IFN-γ production by adding 10⁻¹² M gB498–505 peptide-pulsed B6WT3 cells (17).

### Quantitative real-time PCR

Total DNA was isolated from single-cell TG suspensions using DNeasy columns (Qiagen), diluted to 1 ng/μl in nuclease-free dH₂O, and 25 ng of DNA or water control was mixed in duplicate with 25 μl of TaqMan

---

**FIGURE 1.** CD8 T cells are required to prevent viral DNA synthesis. Thirty days after HSV-1 corneal infection, mice harboring latent virus in their TG received a single i.p. injection of anti-CD8α mAb. Three days after treatment, TG were excised from CD8-depleted and nondepleted mice, and dispersed cells were analyzed by flow cytometry for their expression of CD8α and CD8β. A, Dot plots demonstrate a lack of CD8⁺ T cells in TG of anti-CD8α mAb-treated mice gated on CD45⁺ cells. B, DNA from ganglia of CD8-depleted mice (n = 5) contained a significantly (p < 0.009, Student’s t test) higher viral genome copy number than that from nondepleted mice (n = 20) when analyzed by quantitative real-time PCR for the HSV-1 glycoprotein H gene.

**FIGURE 2.** Restraint stress during latency increases HSV-1 genome copy number in the TG. A, Model of restraint stress protocol. B, Sera of nontreated mice or mice that were food and water deprived (FWD) but not stressed (nonstressed) contained significantly (p < 0.0001, one-way ANOVA and Tukey’s post test) less corticosterone (CORT) than sera from stressed mice when analyzed by a standard radioimmunoassay. C, TG were excised from stressed and nonstressed mice at the indicated time after infection and the HSV-1 genome copy number was determined by real-time PCR. ***, p = 0.0039, Student’s t test. D, Frozen sections of TG obtained from stressed and nonstressed mice at 34 days after infection and stained for HSV-1 Ags. Arrows, Regions of positive staining for HSV-1 Ags.
Universal PCR Master Mix (Roche) and a HSV-1 glycoprotein H-specific primer-probe set, custom-designed and synthesized by Applied Biosystems Assays-by-Design Service. Samples (50 µl/well) were assayed in 96-well plates with an Applied Biosystems Prism 7700 sequence detector. Applied Biosystems Primer Express version 1.5a software default settings were used for instrument control and data analysis. The glycoprotein H sequences were: forward primer (5’-CGACCACCAGAAAACCCTCTTT-3’), reverse primer (5’-ACGCTCTCTAGATCAAAGC-3’), and probe (5’-(FAM)TCCGGACCATTTTC(NFQ)-3’).

**Results**

**CD8\(^+\) T cells are required in vivo to prevent viral DNA synthesis**

Although HSV-specific CD8\(^+\) T cells block HSV-1 reactivation from latency in ex vivo TG cultures (4, 7), a similar protective function has not been established in vivo. In this study, we show that within 3 days of a single injection of anti-CD8\(\alpha\) mAb, CD8\(^+\) T cells were effectively depleted from mouse TG that harbored latent HSV-1 (Fig. 1A), and the HSV-1 genome copy number in the TG was significantly increased (Fig. 1B). Thus, CD8\(^+\) T cells actively monitor latent HSV-1 in sensory neurons and inhibit replication of the viral genome.

**Restraint stress during latency increases viral DNA copy number and protein expression**

Because stress inhibits CD8\(^+\) T cell function and induces HSV-1 reactivation, we hypothesized that reactivation results at least in part from a stress-induced transient compromise in the immunosurveillance capability of CD8\(^+\) T cells within latently infected TG. To test this hypothesis, latently infected mice were subjected...
FIGURE 5. CD8⁺ T cells in TG of stressed mice exhibit an intrinsic compromise of IFN-γ production. A, The preparation of mixed TG cultures from stressed (CD45.1) and nonstressed (CD45.2) latently infected congenic mice. Congenic mice were infected with HSV-1 and 30 days later were stressed or not, TG were obtained and dispersed into single-cell suspensions, and mixed cultures of TG from stressed and nonstressed mice were prepared as depicted. After 90 h, GolgiPlug was added to cultures without (B) or with (C) HSV-1 gB498–505 peptide for the last 6 h of incubation. Cells were recovered from cultures and surface stained with anti-CD8α and anti-CD45.1 mAb followed by intracellular stain for IFN-γ. Representative dot plots show recovery of CD8⁺ T cells that originated from stressed (CD45.1) and nonstressed (CD45.2) TG from the mixed cultures and IFN-γ expression in each population. Percentages in lower right corner indicate the percentage of CD8⁺ T cells in the gated population. The graph shows the mean (±SEM) percentage of CD8⁺ T cells from stressed and nonstressed TG that expressed IFN-γ in the mixed TG cultures (n = 18). Data were analyzed with a Student’s paired t test.

Stress to four 12-h restraint sessions as illustrated in Fig. 2A. The effectiveness of the stress protocol was established by uniformly elevated serum levels of the hypothalamic-pituitary-adrenal-derived effector molecule corticosterone following treatment (Fig. 2B). That this stress protocol influenced the state of viral latency was established by an ~2-fold increase in the viral genome copy number in DNA from TG of stressed relative to nonstressed mice (Fig. 2C), similar to the increased copy number observed following CD8⁺ T cell depletion (Fig. 1B).

Stress-induced reactivation was further established by direct ex vivo detection of infectious HSV-1 in one of eight stressed TG and detection of HSV-1 proteins in serial sections of one of four stressed TG (Fig. 2D and data not shown). The inconsistent detection of replicating virus in the presence of uniformly elevated viral genome copy number probably reflects the enhanced sensitivity of viral DNA detection by real-time PCR relative to detection of infectious virions on monolayers of susceptible cells (18).

Stress reduces CD8⁺ T cells in latently infected TG

The increased viral copy number was associated with a 30% reduction in the number of CD8⁺ T cells within the TG of stressed mice (Fig. 3A). This reduction was transient and by 2 days after stress cessation CD8⁺ T cell numbers returned to nonstressed levels (data not shown). A similar reduction was observed in the spleen (data not shown), indicating that the effects of stress were systemic and not limited to the TG. Most, if not all, HSV-specific CD8⁺ T cells in latently infected TG of C57BL/6 mice are specific for the gB498–505 epitope and can be quantified by staining dispersed TG-derived immune cells with tetramers containing this epitope (gB498–505/H-2Kb) followed by flow cytometric analysis (7). Tetramer staining of CD8⁺ T cells from stressed and nonstressed TG revealed a similar frequency of gB498–505-specific CD8⁺ T cells demonstrating that stress did not selectively deplete HSV-specific CD8⁺ T cells (Fig. 3B). Nonetheless, the absolute number of TG-resident HSV-specific CD8⁺ T cells was reduced by 30% following stress.

HSV-specific CD8⁺ T cells that are retained in the TG following stress are functionally compromised

In our model, HSV-1 begins to reactivate from latency in ex vivo TG cultures within the first 72 h of incubation, and reactivation can be inhibited by gB498–505-specific CD8⁺ T cells (7). Therefore, we tested the effects of in vivo stress on the functional capabilities of TG-resident CD8⁺ T cells during a 72-h incubation of latently infected TG alone (latently infected neurons are the only source of viral Ags) or when an optimal stimulatory dose of gB498–505 peptide was added to the TG cultures. Latently infected TG obtained from stressed and nonstressed mice were dispersed into single-cell suspensions, stained with CFSE, and cultured for 72 h with or without gB498–505 peptide. The cells were then removed from culture, stained with anti-CD8α mAb, and CD8⁺ T cells were analyzed by flow cytometry for proliferation as assessed by CFSE dilution.

Fig. 4A shows a representative dot plot in which cells that underwent one or more rounds of proliferation are gated and the mean fluorescence intensity (MFI) of proliferated cells is indicated for a rough comparison of the number of rounds of proliferation
these cells underwent in the various groups. In cultures of non-
stressed TG, ~50% of CD8⁺ T cells proliferated during the 72-h
incubation in the presence or absence of gB498–505 peptide. In
contrast, significantly fewer CD8⁺ T cells in stressed TG pro-
gressed in response to reactivating virus (Fig. 4B). The addition of
the gB498–505 peptide to stressed TG cultures increased CD8⁺ T
cell proliferation slightly (29% no peptide, 41% with peptide), but even
in the presence of added peptide fewer CD8⁺ T cells in stressed
TG proliferated when compared with similarly stimulated CD8⁺ T
cells in nonstressed TG (Fig. 4C). Moreover, those CD8⁺ T cells
in stressed TG that did proliferate in response to peptide underwent
fewer rounds of proliferation than their counterparts in nonstressed
TG as indicated by higher MFI (Fig. 4C).

A very low frequency (<2%) of TG-resident CD8⁺ T cells ex-
pressed detectable intracellular IFN-γ when tested directly ex vivo.
However, when dispersed cells from latently infected TG were
incubated for 72 h, IFN-γ production was induced in ~10% of
CD8⁺ T cells in nonstressed TG. In contrast, IFN-γ production by
CD8⁺ T cells in stressed TG was not significantly increased during
the 72-h incubation and was significantly lower than that of their
counterparts in nonstressed TG (Fig. 4D). The addition of gB498–505
peptide to cultures greatly augmented IFN-γ production such
that 40% of CD8⁺ T cells in both stressed and nonstressed TG
were IFN-γ positive (Fig. 4E). These findings are consistent with
the tetramer staining results showing a similar frequency of
HSV-1 gB498–505-specific CD8⁺ T cells in the TG of stressed
and nonstressed mice, but demonstrate that CD8⁺ T cells in
stressed TG are compromised in their ability to produce IFN-γ
in response to viral reactivation in neurons.

CD8⁺ T cells in TG of stressed mice exhibit an intrinsic
compromise of IFN-γ production

The reduced IFN-γ production in response to latently infected neu-
rons alone could reflect either an intrinsic compromise in the func-
tion of the CD8⁺ T cells in stressed TG or an extrinsic effect such
as less Ag production and presentation by neurons in stressed TG.
To eliminate possible extrinsic effects, mixed cultures of latently
infected TG from stressed (CD45.1) and nonstressed (CD45.2)
congenic mice were used (illustrated in Fig. 5A). In these mixed
TG cultures, CD8⁺ T cells from stressed and nonstressed mice
experienced identical antigenic exposure and could be identified
based on expression of different CD45 allelic. As illustrated in Fig.
5B, 40% fewer CD8⁺ T cells from stressed than nonstressed TG
produced IFN-γ in response to identical exposure to reactivating
virus. However, when an optimal stimulatory dose of the gB498–505
peptide was added to the mixed cultures, the percentage of IFN-γ-
producing CD8⁺ T cells was increased and the effect of stress on
IFN-γ production was lost (Fig. 5C). Thus, the reduced response of
CD8⁺ T cells from stressed mice does not reflect a reduced frequency
of HSV-specific CD8⁺ T cells or altered antigenic expression by
stressed neurons, but rather appears to result from a stress-induced
functional compromise that can be overcome by addition of gB498–505
peptide to cultures.

Discussion

The association of stress and HSV-1 reactivation from latency is
well established in mice, but a specific mechanism by which stress
facilitates HSV-1 reactivation has not been elucidated. The poten-
tial involvement of CD8⁺ T cells in maintaining HSV-1 in a latent
state has only recently been appreciated (3, 5–8). CD8⁺ T cells
surround HSV-1-infected neurons in latently infected TG of both
mice and humans (4, 7), maintain an activation phenotype (7),
form an apparent immunological synapse with neurons (7), and
can block HSV-1 reactivation from latency in ex vivo cultures of
latently infected TG (7, 8). These findings are consistent with a
dynamic form of latency in which HSV-specific CD8⁺ T cells
constantly monitor and repress viral reactivation in at least a por-
tion of latently infected neurons. This study provides the first direct
evidence that constant monitoring by CD8⁺ T cells is required to
uniformly maintain HSV-1 latency. The rapid rise in HSV-1 ge-
nome copy number following CD8⁺ T cell depletion (>2-fold
increase in genome copy number within 3 days) demonstrates that
some latently infected neurons are reactivation competent at any
given time, and prevented from progressing to full reactivation
with virion formation only through the constant vigilance of CD8⁺
T cells.

A similar increase in viral DNA was observed in mice that were
subjected to restraint stress. The increase in viral DNA was ap-
parent by the end of the 4-day stress protocol and reached statis-
tical significance by 4 days after stress cessation. Although all
stressed TG showed elevated viral DNA, the degree of increase
varied substantially in individual stressed TG. Only one of eight
test TG exhibited replicating HSV-1 directly ex vivo (data not
shown). The detection of replicating virus in even one stressed TG
is highly significant as we and others have uniformly failed to
detected infectious virions in any latently infected nonstressed TG
(19, 20). A recent study showed only 30% of samples containing
1 × 10⁵ genome copies were culture positive (18). Thus, it is likely
that only those stressed TG with the greatest increase in viral DNA
achieved a necessary threshold for detection in culture.

The similar rise in viral genome copy number following CD8⁺
T cell depletion and exposure to restraint stress is consistent with
the possibility that stress-induced HSV-1 reactivation results from
a transient compromise in CD8⁺ T cell surveillance. In support
of this concept is the observed 30% reduction of CD8⁺ T cells in
stressed TG. The reduced numbers of CD8⁺ T cells might reflect
in part the impaired proliferative capacity of CD8⁺ T cells in
stressed TG when responding to reactivating virus. The latter
finding is in agreement with the previous observation that restraint
stress can impair mitogen-stimulated T cell proliferation (21). We
demonstrated that the basal rate of proliferation of HSV-specific
memory CD8⁺ T cells in latently infected TG is regulated at least
in part by Ag stimulation, whereas their counterparts in nonin-
fected tissue are maintained by homeostatic proliferation in re-
sponse to cytokines including IL-15 (17). Thus, a reduced capacity
to proliferate in response to reactivating virus would likely result
in a gradual reduction in the TG-resident CD8⁺ T cell pool. How-
ever, it is unlikely that impaired proliferation alone would account
for the 30% reduction in CD8⁺ T cell numbers in stressed TG
because the rate of turnover of these cells is quite low, ~20% of
CD8⁺ T cells incorporate BrdU during a 1-wk treatment period
(17). Moreover, we demonstrated a higher rate of apoptosis in
CD8⁺ T cells in stressed as compared with those in nonstressed
TG (data not shown). Thus, proliferative impairment and elevated
apoptosis likely contribute to the reduced CD8⁺ T cell pool in
stressed TG.

In addition to the reduced numbers of HSV-specific CD8⁺ T
cells in stressed TG is the observed functional impairment of the
surviving cells. When tested directly ex vivo, ~2% of CD8⁺
T cells in stressed or nonstressed TG exhibited detectable IFN-γ pro-
duction. However, when nonstressed TG were incubated for 72 h,
~10% of the endogenous CD8⁺ T cells were stimulated to pro-
duce IFN-γ. Our studies have established that TG-resident CD8⁺
T cells in part through IFN-γ production prevent HSV-1 reactiva-
tion from latency that is first apparent by 72 h of culture. Because
only neurons harbor latent virus in latently infected ganglia (8,
22–24), and CD8⁺ T cells prevent full HSV-1 reactivation with
virion formation in TG cultures (7, 8), we conclude that TG-resident HSV-specific CD8+ T cells produce IFN-γ in ex vivo TG cultures in response to reactivating HSV-1 in sensory neurons. Therefore, it is important to note that TG-resident CD8+ T cells in nonstressed TG did not significantly increase IFN-γ production during a 72-h ex vivo TG culture. The stressed TG contained a similar frequency of HSV-specific CD8+ T cells, and the addition of an optimal stimulatory dose of gB498–505 peptide induced a similar frequency of IFN-γ-producing CD8+ T cells in stressed and nonstressed TG cultures. Together these findings suggest that the stress-induced functional impairment of CD8+ T cells is not absolute, but rather appears to specifically inhibit the capacity of HSV-specific CD8+ T cells to respond to reactivating HSV-1 in sensory neurons.

Several factors point to a low epitope density as a likely explanation for the selective inability to respond to latently infected neurons. First, HSV-1 gB is a yl gene that is expressed at low levels before the initiation of viral DNA synthesis. Therefore, gB gene expression would be very low during the early stages of HSV-1 reactivation from latency in neurons. Moreover, neurons typically express very low levels of MHC class I, but appear to up-regulate expression during the HSV-1 lytic cycle (25, 26). Thus, it is likely that neurons express a low density of the gB498–505 epitope early in the reactivation process.

It appears that the impaired response of CD8+ T cells to reactivating virus primarily reflects an intrinsic effect of stress on the functional program of the CD8+ T cells. Mixed cultures of stressed and nonstressed TG in which the origin of the CD8+ T cells could be determined by expression of different CD45 alleles showed less IFN-γ production by CD8+ T cells from stressed TG, even when exposed to an identical stimulatory environment. These studies ruled out the possibility that stress-induced differences in Ag presentation or cytokine milieu accounted for the reduced IFN-γ production by CD8+ T cells in stressed TG. Moreover, the frequency of IFN-γ+ CD8+ T cells in nonstressed TG was similar when nonstressed TG were incubated alone or combined with stressed TG, suggesting that the function of CD8+ T cells in nonstressed TG is not influenced by exposure to cells from stressed TG.

Our studies demonstrate that the function of resident CD8+ T cells is very significantly compromised when mice are exposed to restraint stress. The combination of a 30% reduction in the number of HSV-specific CD8+ T cells and a 40% reduction in the frequency of CD8+ T cells capable of producing IFN-γ in response to reactivating neurons would translate into a 65% reduction in the capacity of CD8+ T cells to react to a reactivation event. This might represent an underestimation of the actual CD8+ T cell functional impairment because the IFN-γ response was measured after the CD8+ T cells were removed from the inhibitory microenvironment within the stressed animal. In addition to direct effects on the T cells, there may also be stress-induced effects on the ability of target cells to respond to cytokines. The synthetic glucocorticoid dexamethasone has been demonstrated to inhibit IL-2, IL-4, IL-7, IL-15, and IFN-γ signaling in part by disrupting expression of Jak-STAT pathway components (27, 28). Glucocorticoids have also been shown to repress activation of the transcription factor NF-κB (29, 30), as well as impair transcriptional activation by AP-1 (31). Whether signaling by these and other cytokines are disrupted in the latently infected TG and, in particular, within latently infected neurons, is the subject of current ongoing research in our laboratory.

Viewed in the context of these findings, the “spontaneous” HSV-1 reactivation observed in humans but not in mice might reflect periodic exposure of humans to a more stressful environ-ment. Moreover, human neurons might express a lower density of HSV-1 epitopes than mouse neurons during HSV-1 reactivation from latency due to the selective capacity of the HSV-1 immediate-early protein ICP47 to block human TAP transport of viral peptides for loading on MHC class I for presentation to CD8+ T cells (32). In conjunction with a stress-induced elevation in the threshold of epitope density required to activate CD8+ T cells, this would render humans more susceptible to HSV-1 reactivation than mice.

Our findings provide a broader conceptual framework in which to consider HSV-1 latency and reactivation. The fact that latency appears to be uniquely established in neurons underscores the importance of the neuronal microenvironment in the establishment and maintenance of the latent state. However, a growing body of data including this report supports the notion that maintenance of latency in some latently infected neurons requires ancillary support from contiguous CD8+ T cells. Moreover, our findings provide a link between stress, a known inducer of HSV-1 reactivation, and transient functional compromise of TG-resident CD8+ T cells. We propose that the incidence of recurrent herpetic disease might be reduced by strategies that augment the numbers or function of HSV-specific CD8+ T cells within the latently infected sensory ganglia, or by reducing the effects of stress on the function of these cells.

Acknowledgments
We thank Dawn McKissic for excellent technical assistance and the National Institute of Allergy and Infectious Diseases Tetramer Core Facility (Emory Vaccine Center, Atlanta, GA) for tetramers.

Disclosures
The authors have no financial conflict of interest.

References


