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ORIGINAL ARTICLE

# CD8<sup>+</sup> T-cell specificity is compromised at a defined MHCI/CD8 affinity threshold

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The CD8 co-receptor engages peptide-major histocompatibility complex class I (pMHCI) molecules at a largely invariant site distinct from the T-cell receptor (TCR)-binding platform and enhances the sensitivity of antigen-driven activation to promote effective CD8<sup>+</sup> T-cell immunity. A small increase in the strength of the pMHCI/CD8 interaction (~1.5-fold) can disproportionately amplify this effect, boosting antigen sensitivity by up to two orders of magnitude. However, recognition specificity is lost altogether with more substantial increases in pMHCI/CD8 affinity (~10-fold). In this study, we used a panel of MHCI mutants with altered CD8-binding properties to show that TCR-mediated antigen specificity is delimited by a pMHCI/CD8 affinity threshold. Our findings suggest that CD8 can be engineered within certain biophysical parameters to enhance the therapeutic efficacy of adoptive T-cell transfer irrespective of antigen specificity.

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CD8<sup>+</sup> T cells recognize antigens in the form of short peptide fragments bound to major histocompatibility complex class I (MHCI) molecules on the target cell surface.<sup>1</sup> Specific engagement of peptide-MHCI (pMHCI) complexes via the clonotypically expressed  $\alpha\beta$  T-cell receptor (TCR) triggers a range of effector functions that play a critical role in protective immunity against intracellular infections and various malignancies. The ability to identify and eliminate cancerous cells *in vivo* is particularly intriguing<sup>2,3</sup> and promises novel therapies based on the immunobiology of CD8<sup>+</sup> T cells. Indeed, adoptive transfer of *in vitro*-expanded CD8<sup>+</sup> T cells can cause tumour regression in the clinical setting.<sup>4,5</sup> These seminal observations have sparked great interest in the use of cellular therapy to combat cancer.<sup>6,7</sup> However, a number of obstacles preclude the widespread use of this approach. In biological terms, one key limitation relates to the naturally low affinity of self-derived antigen-specific TCRs,<sup>8,9</sup> which constrains the functional properties of tumour-associated antigen-specific CD8<sup>+</sup> T-cell populations. This intrinsic problem stems from the negative selection of high-affinity autoreactive  $\alpha\beta$  TCR clonotypes during thymic education and most likely explains why it has proven difficult to develop cancer vaccines in the absence of a clear oncogenic microbial agent. Although high-affinity TCRs can be engineered to circumvent suboptimal antigen recognition, most notably via phage display technology,<sup>10,11</sup> the requirement to reiterate this process for each pMHCI specificity tailored to individual tumour proteomes is a major barrier to therapeutic applicability.

The surface-expressed CD8 $\alpha\beta$  glycoprotein (CD8 from here on) serves as a co-receptor for MHCI-restricted T cells.<sup>12</sup> CD8 binds to a largely invariant region of MHCI at a site distinct from the TCR-binding platform and acts to enhance T-cell antigen sensitivity by up to six orders of magnitude.<sup>12–14</sup> This effect is mediated via several mechanisms, including: (i) promotion and stabilization of the TCR/pMHCI interaction at the cell surface,<sup>15–18</sup> (ii) recruitment of signalling molecules to the intracellular side of the TCR/CD3 $\zeta$  complex,<sup>19–22</sup> and (iii) localization of TCR/pMHCI complexes within specialized membrane microdomains enriched for early intracellular signal transduction molecules.<sup>23,24</sup> These properties can potentially be harnessed to modulate antigen-specific CD8<sup>+</sup> T-cell immunity. It is notable in this regard that pMHCI/CD8 binding is characterized by very low solution affinities (average  $K_D \sim 145 \mu\text{M}$ ).<sup>25</sup> Moreover, an incremental increase in the strength of this interaction ( $K_D \sim 98 \mu\text{M}$ ) can boost antigen sensitivity by up to 100-fold.<sup>17,26</sup> Such manipulations are globally applicable across TCR specificities due to the non-polymorphic nature of CD8, thereby providing a generic opportunity to enhance CD8<sup>+</sup> T-cell reactivity for therapeutic purposes.<sup>27</sup> However, substantial increases in pMHCI/CD8 affinity can abrogate antigen specificity.<sup>28</sup>

In this study, we used a panel of MHCI mutants with altered CD8-binding properties to show that the specificity of peptide-dependent TCR recognition is maintained within a defined pMHCI/CD8 affinity window. Collectively, the data provide biophysical

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guidelines for the rational design of high-affinity CD8 molecules to optimize the therapeutic efficacy of adoptive T-cell transfer.

## RESULTS

### Development of a novel MHC I mutant to probe the pMHC/CD8 interaction

The pMHC/CD8 interaction is characterized by very low solution binding affinities and extremely rapid kinetics.<sup>29–31</sup> Although some variation exists between different MHC I molecules due to polymorphisms that affect the CD8 binding site, the average pMHC/CD8 interaction occurs with an equilibrium dissociation constant ( $K_D$ )  $\sim 145 \mu\text{M}$  (range = 100–220  $\mu\text{M}$ ).<sup>25,32</sup> Substantially weaker pMHC/CD8 solution binding affinities have been reported for human leukocyte antigen (HLA) A\*6801, HLA B\*4801 and HLA B\*8101.<sup>22,25</sup> The introduction of a glutamine (Q) to glutamic acid (E) substitution at position 115 of the MHC I  $\alpha 2$  domain increases the pMHC/CD8 interaction by  $\sim 1.5$ -fold ( $K_D \sim 98 \mu\text{M}$ ) without impacting the TCR/pMHC I binding platform.<sup>26</sup> This mutation significantly enhances the sensitivity of pMHC I antigen recognition (up to 100-fold) without compromising TCR-mediated specificity. In contrast, a human to murine MHC I  $\alpha 3$  domain switch increases the pMHC/CD8 interaction by  $\sim 15$ -fold ( $K_D \sim 11 \mu\text{M}$ ) and bypasses the requirement for cognate TCR engagement.<sup>28</sup>

To determine the pMHC/CD8 affinity at which antigen specificity is lost, we introduced an alanine (A) to valine (V) substitution at position 245 of A2/K<sup>b</sup> (a fusion molecule comprising the  $\alpha 1/\alpha 2$

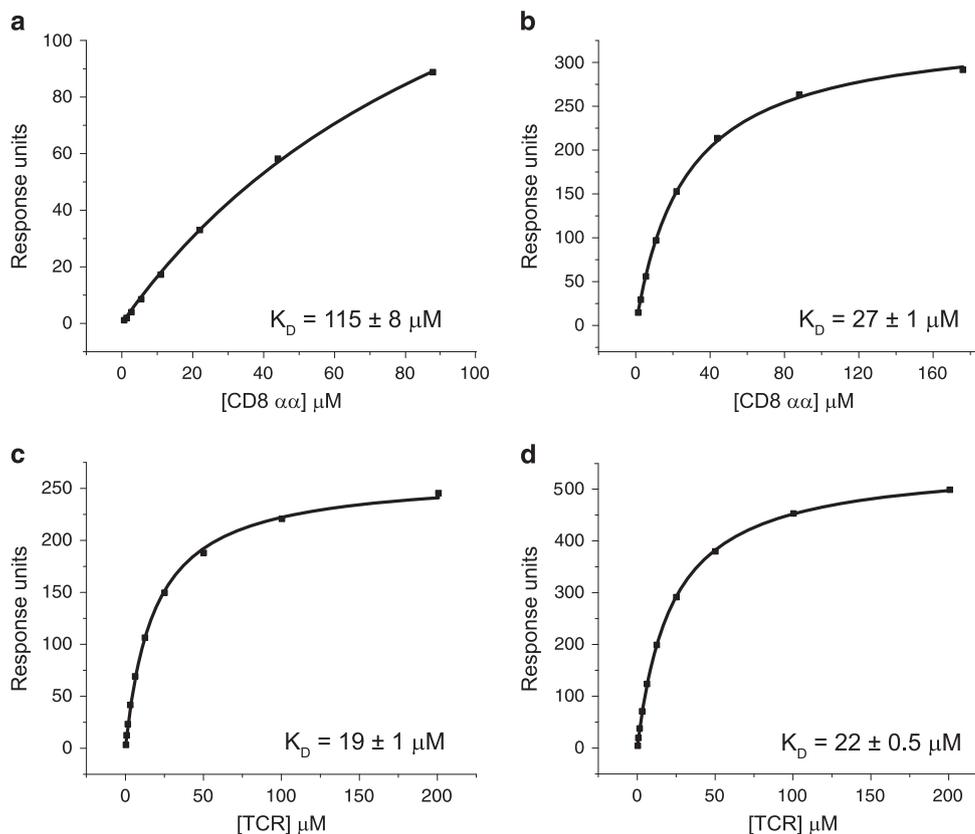
peptide-binding platform of HLA A\*0201 and the  $\alpha 3$  domain of H2-K<sup>b</sup>) to generate the novel MHC I mutant A2/K<sup>b</sup> A245V. Surface plasmon resonance analysis revealed that A2/K<sup>b</sup> A245V binds CD8 with a  $K_D$  of 27  $\mu\text{M}$  (Figures 1a and b), while the TCR/pMHC I interaction remains unchanged (Figures 1c and d). Combined with previously developed mutants, we then had an extended panel for functional analysis that incorporated MHC I molecules spanning a range of CD8 interaction affinities as follows: abrogated (A2 D227K/T228A);<sup>21</sup> weak (A2 A245V);<sup>22</sup> wild type (A2); slightly enhanced (A2 Q115E);<sup>26</sup> enhanced (A2/K<sup>b</sup> A245V); and superenhanced (A2/K<sup>b</sup>).<sup>28</sup> Importantly, none of these mutations affect the integrity of TCR binding to pMHC I (Table 1; Figure 2a).

**Table 1** CD8-binding affinity measurements for the MHC I molecules used in this study

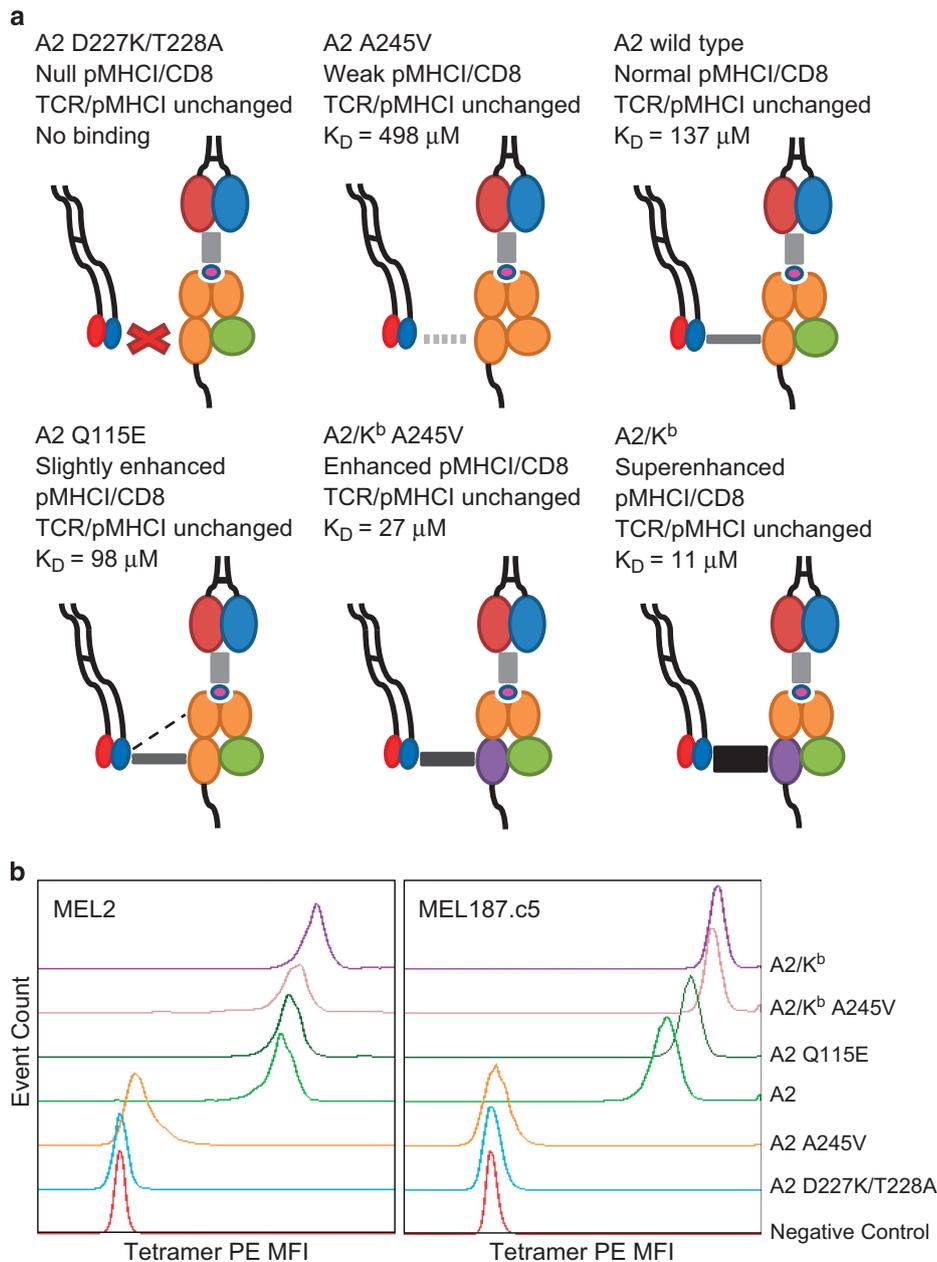
Location of mutation	Description of mutation	pMHC/CD8 $K_D$ ( $\mu\text{M}$ )
MHC I $\alpha 3$ domain	A2 D227K/T228A	> 10 000 (NDB) <sup>a</sup>
MHC I $\alpha 3$ domain	A2 A245V	498 <sup>a</sup>
Wild type	No mutation	137 $\pm$ 9.7 <sup>a</sup>
MHC I $\alpha 2$ domain	A2 Q115E	98 $\pm$ 14.5 <sup>a</sup>
MHC I $\alpha 3$ domain	A2/K <sup>b</sup> A245V	27 $\pm$ 1
MHC I $\alpha 3$ domain	A2/K <sup>b</sup>	11 <sup>a</sup>

Abbreviations: MHC I, major histocompatibility complex class I; NDB, no detectable binding; pMHC I, peptide-MHC I.

<sup>a</sup>Measurements reported previously for MHC I molecules refolded with wild type human  $\beta 2\text{m}$  and the nonamer peptide LLFGYPVYV, an immunodominant epitope derived from the human T-cell lymphotropic virus type 1 Tax protein (residues 11–19).<sup>17</sup>



**Figure 1** A2/K<sup>b</sup> A245V exhibits enhanced affinity for CD8 without impacting the TCR/pMHC I interaction. Biotinylated A2 (a, c) or A2/K<sup>b</sup> A245V (b, d) monomers refolded with wild type  $\beta 2\text{m}$  and the heteroclitic peptide ELAGIGILTV were immobilized on a streptavidin-coated BIAcore chip. Serial dilutions of soluble human CD8 $\alpha\alpha$  (a, b) or MEL5 TCR (c, d) were flowed over the chip to measure equilibrium binding by surface plasmon resonance. Data were analyzed using BIAevaluation 3.1, Microsoft Excel and Origin 6.1.



**Figure 2** Increasing the strength of the pMHC/CD8 interaction enhances pMHC binding at the cell surface. **(a)** Schematic representation of the six different MHC mutants spanning a range of pMHC/CD8 interaction affinities. None of the introduced mutations affect TCR/pMHC binding. **(b)**  $5 \times 10^4$  clonal MEL2 or MEL187.c5 CD8<sup>+</sup> T cells were stained with ViViD and the indicated ELAGIGILTV tetramer (A2 D227K/T228A, A2 A245V, A2, A2 Q115E, A2/K<sup>b</sup> A245V or A2/K<sup>b</sup>) at  $25 \mu\text{g ml}^{-1}$ . Viable events are shown in concatenated histogram plots. Data were acquired using a FACSCantoII flow cytometer and analyzed with FlowJo software version 10.6.

### Increasing the strength of the pMHC/CD8 interaction enhances pMHC engagement at the cell surface

To investigate the relationship between pMHC/CD8 affinity and pMHC engagement at the cell surface, we generated fluorescent tetrameric complexes of A2 D227K/T228A, A2 A245V, A2, A2 Q115E, A2/K<sup>b</sup> A245V and A2/K<sup>b</sup> refolded with wild type  $\beta_2$  microglobulin ( $\beta_2\text{m}$ ) and the decamer peptide ELAGIGILTV, which is a heteroclitic variant of the Melan-A<sub>26-35</sub> epitope EAAGIGILTV. These pMHC tetramers were used at standardized concentrations to stain two different ELAGIGILTV-specific CD8<sup>+</sup> T-cell clones (MEL2 and MEL187.c5). Tetramer staining of MEL2 and MEL187.c5 was very

poor in the absence of an interaction with CD8 (A2 D227K/T228A) (Figure 2b). As the strength of the pMHC/CD8 interaction increased, however, progressive increments in pMHC tetramer staining were observed for both CD8<sup>+</sup> T-cell clones. Thus, pMHC engagement at the cell surface is enhanced in the presence of stronger pMHC/CD8 interactions.

### pMHC binding specificity is compromised at a defined pMHC/CD8 affinity threshold

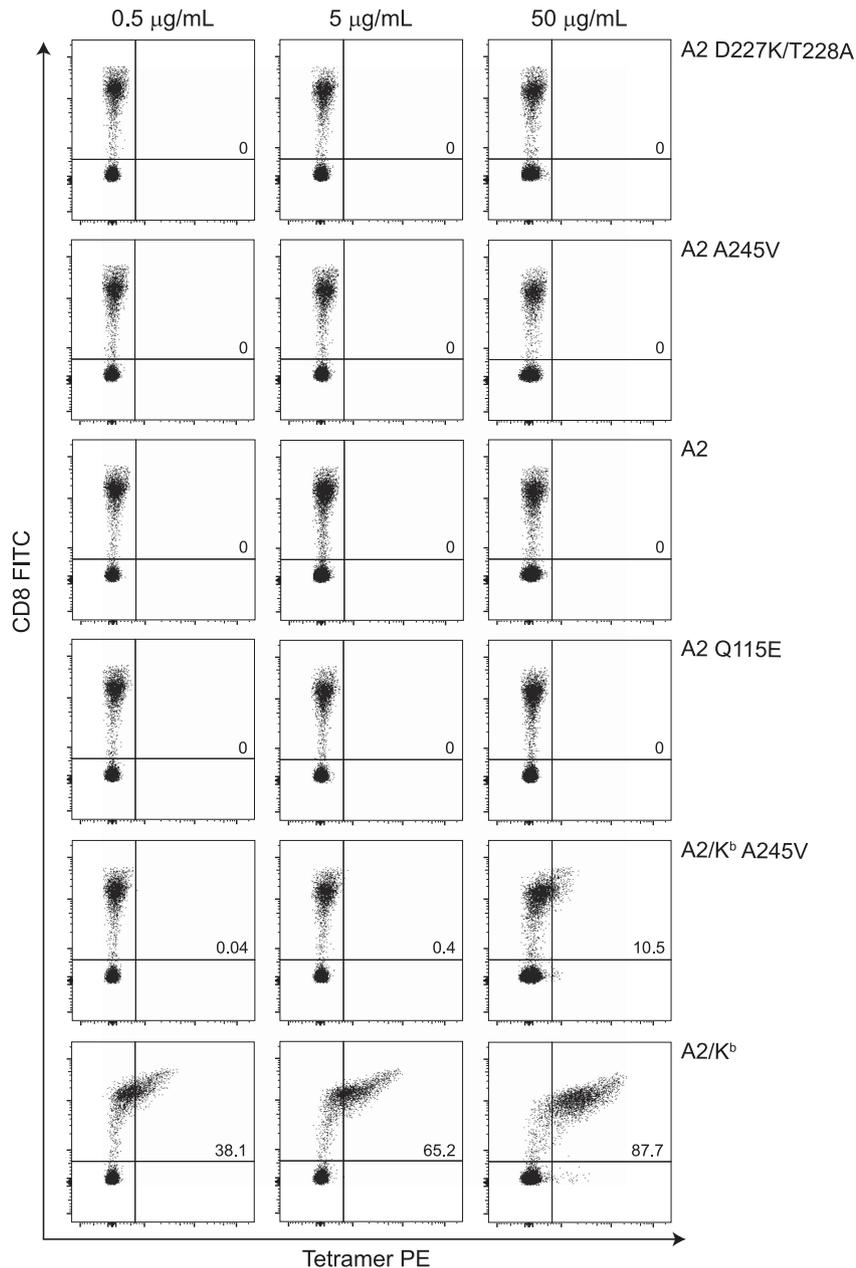
Standard wild type pMHC tetramers bind cell surface TCRs with exquisite specificity.<sup>33,34</sup> In contrast, nonspecific binding occurs in the

presence of a superenhanced pMHC/CD8 interaction ( $K_D \sim 11 \mu\text{M}$ ).<sup>28</sup> To define the pMHC/CD8 affinity threshold at which pMHC binding specificity is compromised, we stained healthy donor peripheral blood mononuclear cells (PBMCs) with fluorescent tetrameric complexes of A2 D227K/T228A, A2 A245V, A2, A2 Q115E, A2/K<sup>b</sup> A245V and A2/K<sup>b</sup> refolded with wild type  $\beta_2\text{m}$  and ELAGIGILTV.

First, we stained A2<sup>-</sup> PBMCs. In the absence of alloreactivity, we would not expect these samples to harbour TCRs that recognize peptides in the context of A2. Any observable tetramer staining under these circumstances can therefore be attributed to peptide-independent recognition of pMHC. No background staining was

detected when A2<sup>-</sup> PBMCs were stained with the A2 D227K/T228A, A2 A245V, A2 or A2 Q115E tetramers up to a concentration of  $50 \mu\text{g ml}^{-1}$  (Figure 3). A similar pattern was observed with the A2/K<sup>b</sup> A245V tetramer at 0.5 and  $5 \mu\text{g ml}^{-1}$ . In line with a concentration-dependent effect, however, the same reagent displayed moderate background staining at  $50 \mu\text{g ml}^{-1}$ . The A2/K<sup>b</sup> tetramer was almost entirely nonspecific, as described in a previous report.<sup>28</sup>

Next, we repeated this analysis using A2<sup>+</sup> PBMCs, which frequently harbour TCRs specific for ELAGIGILTV. The clonotypic repertoire in these samples is also shaped by positive selection to ensure an intrinsic level of reactivity with A2. Staining specificity was maintained with the

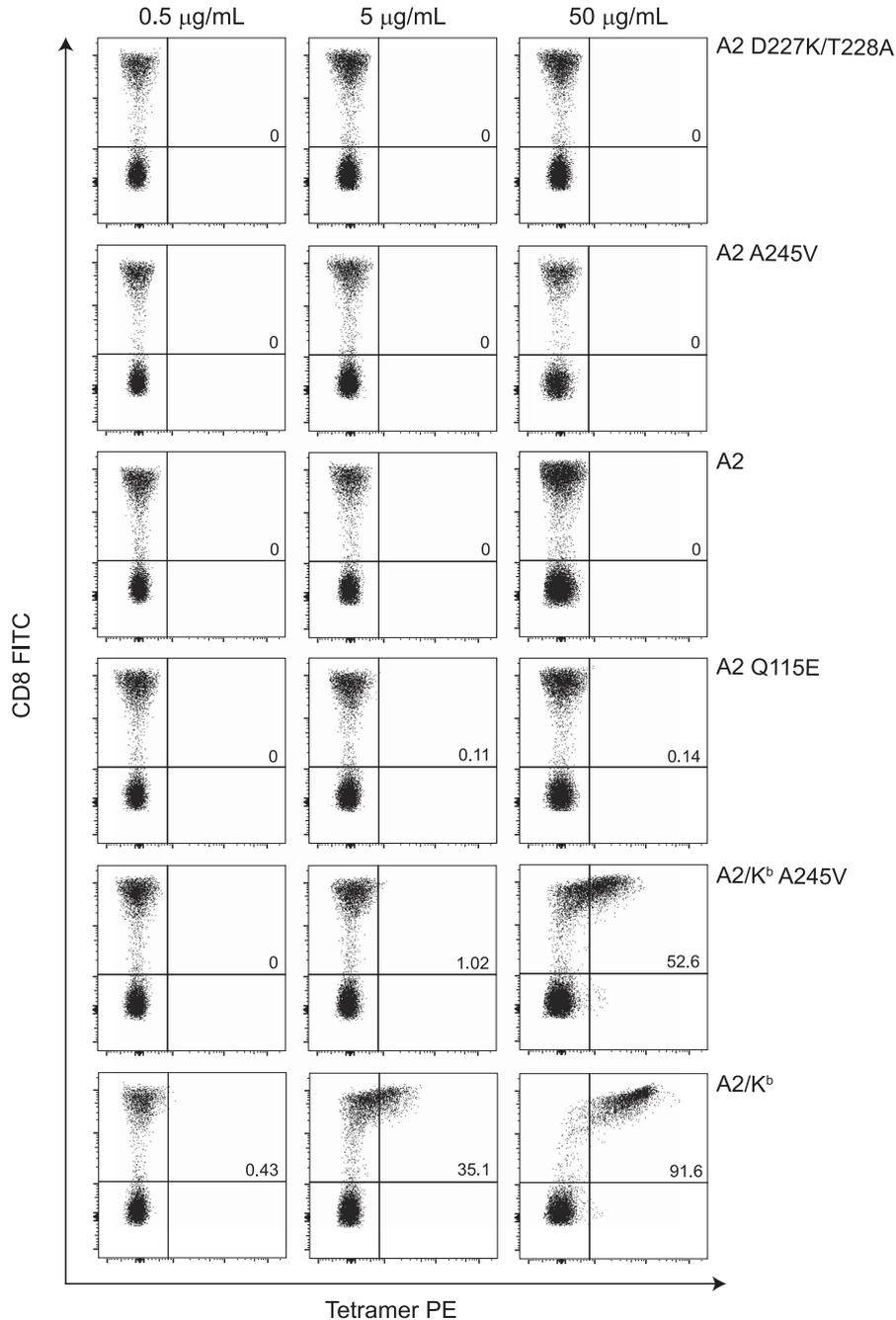


**Figure 3** pMHC binding specificity is compromised at a defined pMHC/CD8 affinity threshold in A2<sup>-</sup> donors.  $1 \times 10^6$  A2<sup>-</sup> PBMCs were stained with ViViD and the indicated ELAGIGILTV tetramer (A2 D227K/T228A, A2 A245V, A2, A2 Q115E, A2/K<sup>b</sup> A245V or A2/K<sup>b</sup>) at 0.5, 5 or  $50 \mu\text{g ml}^{-1}$ , followed by a panel of lineage-specific monoclonal antibodies as described in the Methods section. Plots are gated on live, CD3<sup>+</sup> populations. Data were acquired using a FACSCantoII flow cytometer and analyzed with FlowJo software version 10.6. Values shown in the upper right quadrant indicate % tetramer<sup>+</sup> CD8<sup>+</sup> T cells.

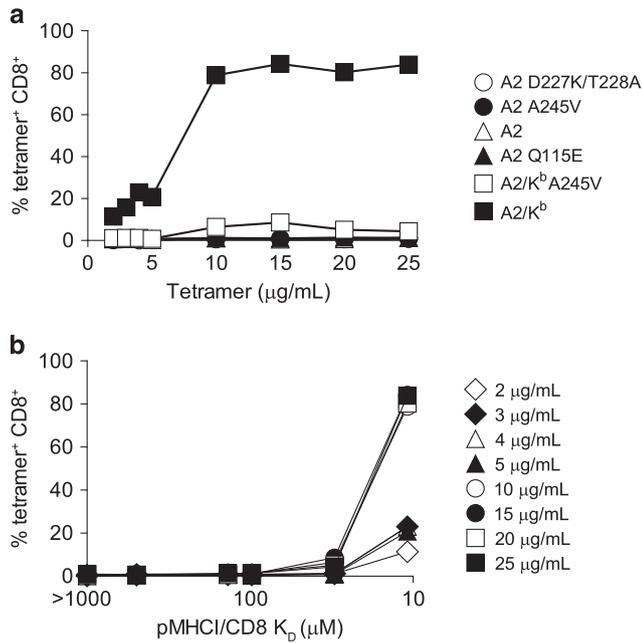
A2 D227K/T228A, A2 A245V, A2 and A2 Q115E tetramers up to a concentration of  $50 \mu\text{g ml}^{-1}$  (Figure 4). Similarly, no background staining was detected with the A2/K<sup>b</sup> A245V tetramer at 0.5 and  $5 \mu\text{g ml}^{-1}$ . Reactivity was apparent with the same reagent at  $50 \mu\text{g ml}^{-1}$ , however, exceeding the levels observed in comparable experiments with A2<sup>-</sup> PBMCs. The A2/K<sup>b</sup> tetramer was again largely nonspecific, although this effect was not obvious at  $0.5 \mu\text{g ml}^{-1}$ .

To consolidate these findings, we performed analogous experiments across a broader range of tetramer concentrations using PBMCs from a different A2<sup>+</sup> donor (Figure 5a). Again, no loss of specificity was detected with the A2 D227K/T228A, A2 A245V, A2 or A2 Q115E

tetramers up to a concentration of  $25 \mu\text{g ml}^{-1}$ . The A2/K<sup>b</sup> A245V tetramer was also highly specific at  $\leq 5 \mu\text{g ml}^{-1}$ , but modest reactivity was observed with the same reagent at  $> 5 \mu\text{g ml}^{-1}$ . Considerable background staining was apparent with the A2/K<sup>b</sup> tetramer. To clarify these data, we plotted nonspecific staining as a function of tetramer concentration versus pMHC/CD8 affinity (Figure 5b) and used non-parametric tests to examine the impact of these variables on tetramer binding at the cell surface (Figure 6). Our analyses revealed that loss of tetramer specificity does not occur gradually with incremental increases in the strength of the pMHC/CD8 interaction. Instead, the specificity of pMHC engagement is is



**Figure 4** pMHC binding specificity is compromised at a defined pMHC/CD8 affinity threshold in A2<sup>+</sup> donors.  $1 \times 10^6$  A2<sup>+</sup> PBMCs were stained and analyzed as described in the legend for Figure 3. Values shown in the upper right quadrant indicate % tetramer<sup>+</sup> CD8<sup>+</sup> T cells.



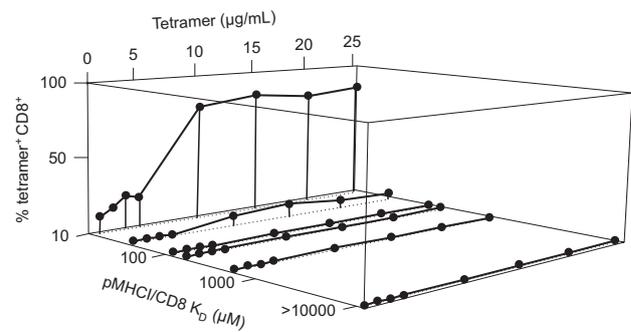
**Figure 5** Detailed analysis of pMHC binding specificity across a range of pMHC/CD8 affinities in an A2<sup>+</sup> donor. (a)  $1 \times 10^6$  A2<sup>+</sup> PBMCs were stained and analyzed as described in the legend for Figure 3, with the exception that each tetramer was used at 2, 3, 4, 5, 10, 15, 20 or 25  $\mu\text{g ml}^{-1}$ . (b) The same data shown as % tetramer<sup>+</sup> CD8<sup>+</sup> T cells versus pMHC/CD8 affinity.

compromised beyond a certain pMHC/CD8 affinity threshold, epitomized by the A2/K<sup>b</sup> A245V ( $K_D \sim 27 \mu\text{M}$ ) and A2/K<sup>b</sup> ( $K_D \sim 11 \mu\text{M}$ ) tetramers.

**T-cell activation specificity is compromised at a defined pMHC/CD8 affinity threshold**

CD8<sup>+</sup> T-cell activation is exquisitely sensitive, requiring  $< 10$  pMHC molecules for full calcium release and mature synapse formation.<sup>35</sup> As a consequence, effector functions can be elicited at cognate pMHC concentrations well below those necessary for detectable tetramer binding.<sup>36</sup> To determine the pMHC/CD8 affinity at which activation specificity is lost, we used a panel of Hmy.2 C1R (C1R) B cells transduced to express A2 D227K/T228A, A2 A245V, A2, A2 Q115E, A2/K<sup>b</sup> A245V or A2/K<sup>b</sup> at equivalent surface densities. Nonspecific activation as a function of pMHC/CD8 affinity was initially tested using the LC13 and SB10 CD8<sup>+</sup> T-cell clones, which are neither restricted by nor alloreactive against A2.<sup>37,38</sup> After overnight stimulation, nonspecific macrophage inflammatory protein-1 $\beta$  release was only observed in the presence of A2/K<sup>b</sup> C1R B cells (Figure 7a). Similar results were obtained with the A2-restricted CD8<sup>+</sup> T-cell clone MEL187.c5 (Figure 7b).

To confirm these findings with a different effector read-out, we used the same panel of C1R B cells in standard chromium release assays with the MEL187.c5 CD8<sup>+</sup> T-cell clone to measure peptide-independent cytotoxicity (Figure 7c). The A2 D227K/T228A, A2 A245V, A2 and A2 Q115E C1R B-cell targets remained largely intact throughout the experiment. Similarly, there was no detectable short-term killing of A2/K<sup>b</sup> A245V C1R B cells. Marginal nonspecific lysis was apparent with the same targets after prolonged incubation, however, consistent with a subtle time-dependent effect triggering the release of cytolytic enzymes. The A2/K<sup>b</sup> C1R B-cell targets were killed in substantial numbers over time. Collectively, these data mirror the



**Figure 6** pMHC binding specificity is a function of tetramer concentration and pMHC/CD8 affinity. The percentage of tetramer<sup>+</sup> CD8<sup>+</sup> T cells varies with tetramer concentration ( $P = 4.4 \times 10^{-3}$ ; Friedman test). Modest to strong evidence was found for individual MHC1 mutants (A2 D227K/T228A:  $P = 1.6 \times 10^{-2}$ ; A2 A245V:  $P = 1.4 \times 10^{-1}$ ; A2:  $P = 1.4 \times 10^{-1}$ ; A2 Q115E:  $P = 1 \times 10^{-2}$ ; A2/K<sup>b</sup> A245V:  $P = 5.4 \times 10^{-2}$ ; A2/K<sup>b</sup>:  $P = 8.8 \times 10^{-4}$ ; Jonckheere–Terpstra test for increasing dependence on tetramer concentration). There was strong evidence for an effect of pMHC/CD8 affinity on tetramer staining ( $P = 3 \times 10^{-7}$ ; Friedman test), although this was not apparent when data for the two lowest  $K_D$  values were excluded ( $P = 1.7 \times 10^{-1}$ ; Friedman test). Tetramer staining was strongly dependent on the  $K_D$  of the pMHC/CD8 interaction ( $P < 10^{-7}$ ; Jonckheere–Terpstra test for increasing dependence on  $K_D$ ). The virtual absence of staining at pMHC/CD8 affinities  $> 27 \mu\text{M}$  suggests that a value within this order of magnitude behaves as a threshold.

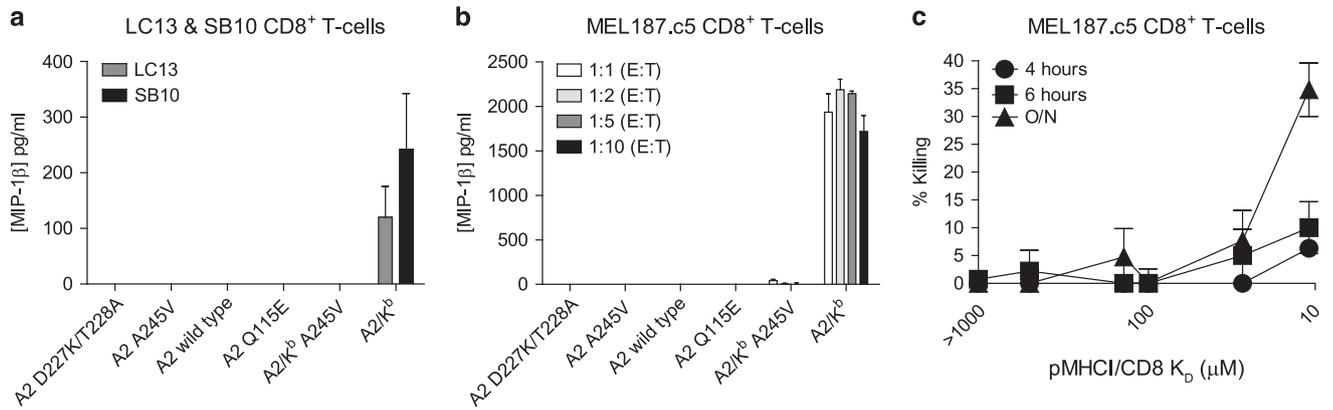
corresponding tetramer staining patterns and indicate that CD8<sup>+</sup> T-cell activation specificity is maintained below a defined pMHC/CD8 affinity threshold ( $K_D \sim 27 \mu\text{M}$ ).

**DISCUSSION**

Despite an extremely weak interaction with MHC1 (average  $K_D \sim 145 \mu\text{M}$ ), the CD8 co-receptor mediates profound biological effects that enhance the sensitivity of TCR-driven activation in response to cognate antigen.<sup>12,39</sup> A small increment in pMHC/CD8 affinity can further amplify the functional consequences of this interaction, increasing antigen sensitivity in responding CD8<sup>+</sup> T cells by up to 100-fold.<sup>26</sup> These observations suggest a possible translational role for affinity-enhanced CD8 molecules.<sup>27</sup> For example, the introduction of such modified co-receptors together with tumour-specific TCRs may facilitate the activation of engineered T cells in the presence of naturally expressed cancer antigens, compensating both for low-affinity TCR/pMHC interactions and low-density cognate pMHC expression on the target cell surface. However, excessive increases in the strength of the pMHC/CD8 interaction ( $K_D \sim 11 \mu\text{M}$ ) lead to nonspecific T-cell activation.<sup>28</sup> It is therefore important to define the optimal affinity at which CD8 co-receptor engagement enhances pMHC recognition without compromising the specificity of antigen-specific CD8<sup>+</sup> T cells.

In this study, we used a panel of MHC1 molecules spanning a range of CD8-binding affinities to delineate the impact of variable pMHC/CD8 interactions on the specificity of TCR-mediated antigen recognition. Surface plasmon resonance studies confirmed that none of these mutations affect the TCR/pMHC1-binding platform. Tetrameric pMHC1 complex engagement at the cell surface was enhanced in a stepwise manner with increasing pMHC/CD8 affinities. In contrast, the specificity of pMHC1 binding and T-cell activation was compromised at a defined pMHC/CD8 affinity threshold ( $K_D \sim 27 \mu\text{M}$ ).

Biophysical studies have shown that the murine pMHC/CD8 interaction (average  $K_D \sim 49 \mu\text{M}$ ) is considerably stronger than the



**Figure 7** CD8<sup>+</sup> T-cell activation specificity is compromised at a defined pMHC/CD8 affinity threshold. (a)  $3 \times 10^4$  clonal SB10 or LC13 CD8<sup>+</sup> T cells were incubated overnight with  $6 \times 10^4$  C1R B cells expressing A2 D227K/T228A, A2 A245V, A2, A2 Q115E, A2/K<sup>b</sup> A245V or A2/K<sup>b</sup>. Supernatants were collected and assayed for macrophage inflammatory protein (MIP)-1 $\beta$  by enzyme-linked immunosorbent assay (ELISA). Data are shown corrected for background production of MIP-1 $\beta$ . (b)  $3 \times 10^4$  clonal MEL187.c5 CD8<sup>+</sup> T cells were incubated overnight at the indicated E:T ratios with C1R B cells expressing A2 D227K/T228A, A2 A245V, A2, A2 Q115E, A2/K<sup>b</sup> A245V or A2/K<sup>b</sup>. Supernatants were collected and assayed for macrophage inflammatory protein (MIP)-1 $\beta$  by ELISA. Data are shown corrected for background production of MIP-1 $\beta$ . (c)  $1 \times 10^4$  clonal MEL187.c5 CD8<sup>+</sup> T cells were incubated with  $2 \times 10^3$  C1R B cells expressing A2 D227K/T228A, A2 A245V, A2, A2 Q115E, A2/K<sup>b</sup> A245V or A2/K<sup>b</sup> in standard chromium release assays as described in the Methods section. Data are shown as % killing versus pMHC/CD8 affinity. Error bars represent s.d.

human pMHC/CD8 interaction (average  $K_D \sim 145 \mu\text{M}$ ).<sup>21,25</sup> This peculiar feature of mice may act to enhance T-cell cross-reactivity, allowing a size-limited repertoire to provide effective coverage against a common universe of pMHC antigens.<sup>40</sup> It is also notable that the affinity of the murine pMHC/CD8 interaction lies just below the specificity threshold defined in this study ( $K_D \sim 27 \mu\text{M}$ ). A conserved optimum may therefore dictate the evolutionary limits of co-receptor binding within a functional mammalian immune system.

The data presented here suggest the existence of an affinity window that potentially enables optimization of the pMHC/CD8 interaction for therapeutic purposes without nonspecific T-cell activation. However, it is important to note that CD8<sup>+</sup> T cells are naturally cross-reactive and that this phenomenon is controlled to some extent by the CD8 co-receptor.<sup>41–43</sup> It will therefore be important to examine this effect in more detail to avoid potentially dangerous off-target reactivity.<sup>44,45</sup> Nonetheless, the maintenance of CD8<sup>+</sup> T-cell specificity below a supranormal pMHC/CD8 affinity threshold offers an exciting opportunity to enhance the therapeutic efficacy of adoptive cell transfer irrespective of antigen specificity.

## METHODS

### Cells

The following CD8<sup>+</sup> T-cell clones were used in this study: (i) MEL2 and MEL187.c5, specific for the Melan-A-derived epitope ELAGIGILTV (residues 26–35) restricted by HLA A\*0201 (A2); (ii) LC13, specific for the Epstein–Barr virus EBNA3A-derived epitope FLRGRAYGL (residues 339–347) restricted by HLA B\*0801;<sup>37</sup> and (iii) SB10, specific for the cytomegalovirus pp65-derived epitope CPSQEPMSIYVY (residues 103–114) restricted by HLA B\*3508.<sup>38</sup> Clones were maintained in RPMI 1640 containing  $100 \text{ U ml}^{-1}$  penicillin,  $100 \text{ mg ml}^{-1}$  streptomycin,  $2 \text{ mM}$  L-glutamine and 10% heat-inactivated fetal calf serum (R10; all components from Life Technologies, Carlsbad, CA, USA), supplemented with 2.5% Cellkines (Helvetica Healthcare, Geneva, Switzerland),  $200 \text{ IU ml}^{-1}$  interleukin-2 and  $25 \text{ ng ml}^{-1}$  interleukin-15 (both PeproTech, Rocky Hill, NJ, USA). Healthy donor PBMCs were isolated by standard density gradient centrifugation using Ficoll-Hypaque (GE Healthcare, Chicago, IL, USA). C1R B cells expressing full-length A2 and variants thereof were generated and maintained as described previously.<sup>26</sup>

### pMHC tetramer staining and flow cytometry

Soluble pMHC tetramers were produced as described previously.<sup>17</sup> For A2 typing,  $1 \times 10^6$  PBMCs were stained with  $\alpha\text{A2-FITC}$  (clone BB7.2; Serotec, Oxford, UK) for 30 min at 4 °C. For pMHC tetramer staining,  $1 \times 10^6$  PBMCs were resuspended in phosphate-buffered saline and stained with LIVE/DEAD Fixable Violet (ViViD; Life Technologies) for 5 min at room temperature. After washing in phosphate-buffered saline, cells were stained with tetramer-PE (A2 wild type and variants thereof) at the indicated concentrations for 20 min at 37 °C. The following mouse anti-human monoclonal antibodies were then added for 20 min at 4 °C:  $\alpha\text{CD3-PerCP}$  (clone SK7; BioLegend, San Diego, CA, USA);  $\alpha\text{CD4-FITC}$  (clone VIT4; Miltenyi Biotec, Bergisch Gladbach, Germany);  $\alpha\text{CD8-APC}$  (clone HIT8a; BD Pharmingen, San Diego, CA, USA);  $\alpha\text{CD14-Pacific Blue}$  (clone HCD14; BioLegend); and  $\alpha\text{CD19-Pacific Blue}$  (clone HIB19; BioLegend). Cells were washed twice in phosphate-buffered saline after staining and  $5 \times 10^4$  events per condition were acquired using a FACSCantoII flow cytometer (BD Biosciences, San Jose, CA, USA). Data were analyzed with FlowJo software version 10.6 (TreeStar Inc., Ashland, OR, USA).

### Macrophage inflammatory protein-1 $\beta$ enzyme-linked immunosorbent assay

Clonal CD8<sup>+</sup> T-cells were incubated with C1R B cells expressing full-length A2 or variants thereof at different effector-to-target (E:T) ratios as indicated. Supernatants were collected after 18 h and assayed for macrophage inflammatory protein-1 $\beta$  by enzyme-linked immunosorbent assay according to the manufacturer's instructions (R&D Systems, Minneapolis, MN, USA).

### Chromium release assay

Target C1R B cells ( $1 \times 10^6$ ) were loaded with  $^{51}\text{Cr}$  ( $30 \mu\text{Ci}$ ) for 1 h and plated in triplicate at  $2 \times 10^3$  cells per well in R10. Clonal CD8<sup>+</sup> T cells were then applied at an E:T ratio of 5:1 in a final volume of 150  $\mu\text{l}$ . Target cells incubated alone were used to calculate spontaneous release. Total release was measured via the addition of Triton X-100 (Sigma-Aldrich, St Louis, MO, USA). Supernatants were collected after 4, 6 or 18 h at 37 °C and mixed with OptiPhase Supermix Scintillation Cocktail (150  $\mu\text{l}$  per well; PerkinElmer Life Sciences, Waltham, MA, USA).  $^{51}\text{Cr}$  content was measured using a MicroBeta Counter (PerkinElmer Life Sciences). Specific lysis (%) was calculated according to the following formula: (experimental release – spontaneous release/total release – spontaneous release)  $\times 100$ .

## Surface plasmon resonance

Soluble TCRs and CD8 $\alpha\alpha$  were produced as described previously.<sup>22,46</sup> Binding analysis was performed using a BIAcore 3000 (GE Healthcare) equipped with a CM5 sensor chip. Between 200 and 400 response units of biotinylated pMHC were immobilized to streptavidin, which was chemically linked to the chip surface. The pMHC was injected at a slow flow rate (10  $\mu\text{l min}^{-1}$ ) to ensure uniform distribution on the chip surface. Combined with the small amount of pMHC bound to the chip surface, this reduced the likelihood of off-rate limiting mass transfer effects. Soluble MEL5 TCR and CD8 $\alpha\alpha$  were purified and concentrated to 100 and 150  $\mu\text{M}$ , respectively, on the day of analysis to reduce the likelihood of aggregation affecting the results. For equilibrium analysis, eight serial dilutions of analyte were carefully prepared in triplicate for each sample and injected over the relevant sensor chips at 25 °C. Soluble MEL5 TCR or CD8 $\alpha\alpha$  were injected over the chip surface at a flow rate of 30  $\mu\text{l min}^{-1}$ . Results were analyzed using BIAevaluation 3.1 (GE Healthcare), Microsoft Excel (Microsoft, Redmond, WA, USA) and Origin 6.1 (OriginLab, Northampton, MA, USA). The equilibrium binding constant ( $K_D$ ) values were calculated using a nonlinear curve fit ( $y = [P]x/[P_2+x]$ ).

## Statistical analysis

The dependence of nonspecific CD8<sup>+</sup> T-cell staining intensity on tetramer concentration and the  $K_D$  of the pMHC/CD8 interaction was assessed using the Friedman test for one-way effects and the Jonckheere–Terpstra test for the dependent variable increasing with the treatment variable.<sup>47</sup>

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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