H1N1 hemagglutinin-specific HLA-DQ6-restricted CD4+ T cells can be readily detected in narcolepsy type 1 patients and healthy controls


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ABSTRACT

Following the 2009 H1N1 influenza pandemic, an increased risk of narcolepsy type 1 was observed. Homology between an H1N1 hemagglutinin and two hypocretin sequences has been reported. T cell reactivity to these peptides was assessed in 81 narcolepsy type 1 patients and 19 HLA-DQ6-matched healthy controls. HLA-DQ6-restricted H1N1 hemagglutinin-specific T cell responses were detected in 28.4% of patients and 15.8% of controls. Despite structural homology between HLA-DQ6-hypocretin and -H1N1 peptide complexes, T cell cross-reactivity was not detected. These results indicate that it is unlikely that cross-reactivity between H1N1 hemagglutinin and hypocretin peptides presented by HLA-DQ6 is involved in the development of narcolepsy.

1. Introduction

Narcolepsy type 1 (NT1) is a rare disorder of the regulation of sleep and wakefulness with an incidence of 1 per 100,000 person years and a prevalence ranging between 20 and 50 per 100,000 individuals (Ohayon et al., 2002; Wijnans et al., 2013). The disorder is characterised by five core symptoms: excessive daytime sleepiness, cataplexy, hypnagogic hallucinations, sleep paralysis and disturbed nocturnal sleep. These symptoms arise as a result of the destruction of over 90% of hypocretin (Hcrt)-producing neurons in the lateral hypothalamus (Peyron et al., 2000; Thannickal et al., 2000). Unfortunately, causal treatment of the disorder is not yet available.

In pursuit of the disease mechanism, two findings have shifted the focus of narcolepsy research to the hypothesis that the destruction of Hcrt-producing neurons is caused by an autoimmune process. First, 95% of NT1 patients carry the HLA-DQA1*01:02 / DQB1*06:02 haplotype encoding HLA-DQ6, an HLA-class II molecule expressed on antigen-presenting cells (Juji et al., 1984; Mignot et al., 1997; Tafti et al., 2014), which was later complemented by genome-wide association studies that showed variants within immune system-regulating genes in narcolepsy patients (Faraco et al., 2013; Han et al., 2013; Hor et al., 2010). Second, an increase in the incidence of NT1 has been observed in several European countries after the 2009 H1N1 influenza pandemic, and the subsequent vaccination campaign (Dauvilliers et al., 2013;...
Feltelius et al., 2015; Lind et al., 2014; Partinen et al., 2012). Even though there was no wide-spread vaccination campaign in Asian countries, an increased incidence has also been reported in China (Han et al., 2011). This suggests that NT1 might develop as the result of a cross-reactive anti-viral immune response that leads to the destruction of Hect-producing neurons. More insight in this reaction could pave the way for causal treatment development in NT1 and potentially also prevention of the disease by identifying individuals at-risk.

Research on the auto-immune reaction has focused on two candidate immune cell types that could drive this reaction leading to NT1: cross-reactive B cells and cross-or autoreactive CD4+ T cells. Four studies (Black et al., 2005; Overeen et al., 2006; Tanaka et al., 2006; Van Der Heide et al., 2015) failed to detect autoreactive B cells or auto-antibodies to Hct or Hct-receptors. Another group claimed to have identified autoreactive CD4+ T cells specific for Hct (De La Herran-Arita et al., 2013; De La Herran-Arita et al., 2014), but the article was subsequently retracted. While HLA-DR-restricted Hct-specific T cell responses have recently been described (Latorre et al., 2018), this does not explain the strong link with HLA-DQ6. In short, the molecular mechanism underlying the HLA-DQ6 association remains to be determined.

Based on the increased incidence of NT1 after the H1N1 influenza pandemic mentioned above, we aimed to assess whether H1N1 influenza reactive CD4+ T cells are present in NT1 patients. A secondary aim was to assess whether these H1N1 influenza specific CD4+ T cells cross-react with Hct. We determined the crystal structure of one earlier identified H1N1 hemagglutinin peptide and two Hct peptides bound to the disease-predisposing HLA-DQ6 molecules to assess structural homology. Subsequently, we stimulated peripheral blood mononuclear cells with these peptides to generate specific T cell lines and clones. We then performed proliferation tests on these clones to assess both H1N1- and Hct-reactivity and assess HLA-DQ6 restriction, cross-reactivity and T cell receptor sequence of these clones.

2. Materials and methods

2.1. Subjects

Between March 2014 and June 2016, we included all consecutive narcolepsy type 1 patients after informed consent, recruited from the sleep clinic of the department of Neurology, Leiden University Medical Center and the Sleep-Wake Centre of Stichting Epilepsie Instellingen Nederland (SEIN), Heemstede. All patients were diagnosed with narcolepsy type 1 according to the International Classification of Sleep Disorders (ICSD-3; (American Academy of Sleep Medicine, 2014)). Symptom onset in all patients was after the 2009 H1N1 pandemic. Healthy controls were included in the same time period as the narcolepsy type 1 patients and matched for HLA and gender.

2.2. Hct-1 measurements

CSF samples were drawn for Hct-1 measurement in 34 narcolepsy type 1 patients. Hypocretin-1 concentrations were measured in duplicate with an 

2

hypocretin-1 radioimmunoassay (Phoenix Pharmaceuticals, Mountain View, CA, USA). This assay has an intra-assay variability of < 5% and a detection limit of 50 pg/mL. To adjust for inter-assay variability, Stanford reference CSF samples were included in the assay (Ripley et al., 2001; Mignot et al., 2002).

2.3. Peptides

All peptides used were produced at the Peptide Synthesis Facility of the Department of Immunohematology and Blood Transfusions of the Leiden University Medical Center. Two Hct peptides, Hct56-68 and Hct67-99, and one 2009 H1N1 influenza A hemagglutinin (H1N1-HA) peptide, H1N1-HA275-287, were selected based on sequence similarity between these peptides and those described in the aforementioned retracted article (De La Herran-Arita et al., 2013; De La Herran-Arita et al., 2014). All peptide sequences can be found in Supplemental Table 1.

For follow-up experiments, we used processed Hct peptides: two truncated peptides lacking the first 4 residues (including histidines on position 59 and 90 of Hct56-68 and Hct67-99, respectively), thereby increasing homology between H1N1-HA275-287 and the Hct peptides. Additionally, the histidine residue on position 59 of the first Hct peptide (Hct56-68) was replaced by an o xo-histidine or alanine residue rendering the two peptides more homologous to H1N1-HA275-287.

Soluble complexes of HLA-DQ6 containing the peptides H1N1-HA275-287, Hct56-68 and Hct67-99 were produced essentially as described previously for HLA-DQ2 (Henderson et al., 2007; Petersen et al., 2014). Briefly, the αβ-heterodimer of the HLA-DQ6 extracellular domain was expressed in Hi5 insect cells, with each peptide linked to the N-terminus of the HLA-DQ6 β-chain. The C-terminus of the constructs contained an enterokinase cleavable Fos/Jun zippers, and, at the C terminus of the β-chain, a BirA biotinylation sequence followed by a His10-Tag. The complexes were purified via dialfiltration, metal affinity, size exclusion and ion exchange chromatography. For crystallisation experiments the Fos/Jun zippers were removed by enterokinase cleavage and ion exchange chromatography.

2.4. Crystallisation, data collection, structure determination and refinement

Peptide-HLA-DQ6 complexes were crystallised at 20°C via the hanging drop vapor diffusion method using equal volumes of mother liquor and protein solution at 10 mg/mL in a buffer containing 10 mM Tris (pH 8) and 150 mM NaCl. HLA-DQ6-Hct56-68 and HLA-DQ6- Hct67-99 were crystallised with mother liquor containing 16–20% PEG4000, 0.1 M NaOAc pH 4.5–5.0, and HLA-DQ6- H1N1-HA275-287 was crystallised with 23% PEG4000, 0.2 M NaCl, 0.1 M HEPES pH 7. Prior to data collection the crystals were cryoprotected in mother liquor supplemented with 20% glycerol, or 20% ethylene glycol in the case of HLA-DQ6- Hct67-99, and flash frozen in liquid N2. X-ray diffraction data was collected at the mx2 beamline of the Australian Synchrotron using a ADSC Q315r detector and data processing was carried out with XDS (Kabsch, 2010) and Scala (Evans, 2006). The crystal structures were solved by molecular replacement in Phaser (McCoy et al., 2007) using a published HLA-DQ6 structure (PDB code 1UVQ) as search model. The structural models were refined by iterative rounds of model building in Coot (Emsley et al., 2010) and restrained refinement in Phenix (Adams et al., 2010). For further details on data collection and refinement statistics, see Table 1.

2.5. Peripheral blood mononuclear cell (PBMC) isolation

Blood was drawn from all patients and healthy controls. PBMCs were extracted using Ficoll-Paque (GE Healthcare, Chicago, USA) gradient reagent. The first experiments were performed on fresh PBMCs, but in the remainder the isolated PBMCs were subsequently frozen in 10% dimethyl sulfoxide (DMSO; Sigma Aldrich, Saint Louis, USA) in fetal calf serum (FCS; Sigma Aldrich, Saint Louis, USA). These samples were stored until use in liquid nitrogen vessels.

2.6. Antigen-specific T cell lines

After isolating or thawing of PBMCs of narcolepsy type 1 patients and healthy controls, 1 × 10⁸ cells were put into culture in Iscove's Modified Dulbecco's Medium (IMDM; Lonza, Basel, Switzerland) supplemented with l-glutamine (Thermo Fisher, Waltham, USA), 10% (pooled) human serum (NHS) and a mixture of the H1N1-HA275-287, Hct56-68 and Hct67-99 peptides. After every 5 days r-interleukin 2 (20 U/mL final concentration; IL-2; Novartis, Basel, Switzerland) and interleukin 15 (10 ng/mL final concentration, IL-15; R&D, Minneapolis,
USA) were added to each culture (Kooij-Winkelhaar and Koning, 2015).

2.7. Peptide-specific T cell clone generation

Peptide-specific T cell clones (TCCs) were generated from T cell lines specific for H1N1-HA275-287 from 3 narcolepsy patients by limiting dilution in culture medium containing 10^6 irradiated feeder cells/mL, 20 U/mL rIL-2, 10 ng/mL IL-15 and 1 µg/mL PHA (“feeder mix”; Remel, Lenexa, USA). The cells were stimulated with 20 U/mL rIL-2 and 10 ng/mL in 10% human serum/IMDM after 5 days. After 10 days, growing wells were transferred to 24-well plates and cultured in feeder mix until a confluent layer of cells was formed. For the T cell lines of 9 narcolepsy patients, streptavidin-PE-HLA-DQ6-H1N1-HA275-287 and streptavidin-PE-HLA-DQ6-HLA-A281,68 and HLA-DQ6-281,68 tetramers were used to directly stain HLA-H1N1-HA275-287, HLA-DQ6,281,68, and HLA-DQ6-281,68-specific T cells. Tetramers were produced essentially as described (Ooi et al., 2017). These tetramer-positive CD4+ T cells were sorted by flow cytometry on a FACS-Aria III instrument (BD Biosciences) and expanded as described above. Clones were subsequently generated from the identified H1N1-HA275-287-specific and/or HLA-DQ6-281,68 or HLA-DQ6-281,68-specific T cell lines, as described previously (Kooij-Winkelhaar and Koning, 2015). All T cell lines used for TCC generation were derived from frozen narcolepsy patient samples.

2.8. Flow cytometry

Peptide-specific T cell lines generated from one patient were incubated for 30 min with 11 antibodies for surface staining and subsequently acquired on an LSRII instrument (BD Biosciences). Fluorochrome-labelled antibodies directed against CD3 (clone UCHT1), CD4 (clone SK3), CD5 (clone L17F12), CD7 (clone M-T701), CD14 (clone MAPP9), CD27 (clone M-T271), CD28 (clone CD28.2), CD45RA (clone L48) and IgG1 (clone MOPC-21) were from BD Biosciences (San Jose, California, USA), anti-CD8 (clone 3B5) was from Invitrogen (Bleiswijk, the Netherlands) and anti-CD45 (clone HI30) from eBioscience (San Diego, California, USA). Results were analysed using FlowJo V.10 software (Schmitz et al., 2016).

2.9. T cell proliferation assay and assays for assessing HLA-DQ6 restriction

Proliferation assays were performed on T cell lines and TCCs in triplicate in 150 µL IMDM supplemented with 10% human serum in 96-well, flat-bottom plates (Corning Life Sciences, Tewksbury, USA) using 1 × 10^5 T cells stimulated with 1 × 10^5 irradiated HLA-DQA1*01:02/DQB1*06:02 (HLA-DQ6)-matched allogeneic PBMCs (3000 RAD) in the presence or absence of either H1N1-HA275-287 or HLA-DQ6,281,68 and HLA-DQ6,281,68 (10 µg/mL). In HLA-restriction experiments, the HLA-DQA1*01:02/DQB1*06:02-matched allogeneic PBMCs were replaced by PBMCs expressing either HLA-DQA1*03:01/DQB1*03:02 (HLA-DQ8; no association with narcolepsy), HLA-DQA1*01:02/DQB1*06:03 (less frequently found in narcolepsy compared to healthy controls (Tafli et al., 2014)) or a mix of HLA-DQA1*01:02/DQB1*06:02 and HLA-DQA1*01:02/DQB1*06:03. Triplicate wells containing 10^5 T cells supplemented with 20 U/mL rIL-2 and 10 ng/mL IL-15 functioned as a positive control. After 48 h at 37 °C, cultures were pulsed with 10 µCi/mL of [H]thymidine and harvested 18 h later. Proliferation was measured using a MicroBeta MicroPlate Counter (PerkinElmer, Waltham, MA, USA). A positive response was defined as a stimulation index (SI) of 3 (defined as the mean count in the wells with peptides divided by the mean count in the wells without peptide) (Kooij-Winkelhaar and Koning, 2015). Additionally, to confirm HLA restriction of the T cell lines, blocking experiments were performed in which either anti-HLA-class I (W6/32), anti-HLA-DR (B7/21), anti-HLA-DQ (SPV-L3) or anti-HLA-DR (B8.12.2) monoclonal antibodies (mAbs; locally produced) were added to the initial assay.
2.10. T cell receptor (TCR) sequencing

TRAV, TRBV and CDR3 gene segment sequences of H1N1-HA275-287-specific TCCs were amplified using PCR and a set of specifically designed primers. PCR products rendered in this way were cloned into a Promega pGEM-T Easy vector and subsequently sequenced. The TRAV and TRBV gene usage and CDR3 sequences for all generated clones were determined using IMGT/V-QUEST (Brochet et al., 2008).

2.11. Statistical analysis

Differences at baseline in participant characteristics were calculated with Student's t-tests and Pearson's chi-square test. Pearson's chi-square test was also used for comparing T cell proliferation in narcolepsy patients as compared to healthy controls. Differences between conditions in the HLA blocking experiments were calculated by one-way ANOVA with a Bonferroni post hoc analysis. Differences between P-values below 0.05 were deemed significant. Bonferroni corrections were executed when needed. All analyses were conducted using the IBM SPSS Statistics 23 software package.

3. Results

3.1. Patient characteristics

We included 81 narcolepsy type 1 patients and 19 healthy controls. Patient characteristics are shown in Table 2. Notably, all narcolepsy type 1 patients except one were HLA-DQA1*01:02/DQB1*06:02 (HLA-DQ6) positive. Thirty-four patients had undergone a lumbar puncture for Hcrt-1 measurement; all had Hcrt-1 values in the cerebrospinal fluid that were below the cut-off value of 110 pg/mL based on the ICSD-3 criteria for narcolepsy type 1. Narcolepsy type 1 patients were younger than healthy controls, but the distribution of males and females was comparable between the two groups.

3.2. H1N1-HA275-287, Hcrt56-68 and Hcrt87-99 presented by HLA-DQ6 show structural homology

Based on earlier described peptides of H1N1-HA and hypocretin that are able to bind HLA-DQ6 (De La Herran-Arita et al., 2013, 2014), we investigated the possibility of mimicking between H1N1-HA and Hcrt peptides in the context of HLA-DQ6 presentation. We crystallized and determined the crystal structures of H1N1-HA275-287, Hcrt56-68 and Hcrt87-99 presented by HLA-DQ6 at resolutions of 1.7 Å, 2.0 Å and 1.95 Å, respectively (Fig. 1). Alignment of the structures revealed that the two Hcrt peptides - HLA-DQ6 complexes, HLA-DQ6-Hcrt56-68 and HLA-DQ6-Hcrt87-99, were nearly indistinguishable in terms of peptide backbone positioning (Cα rmsd < 0.1 Å), peptide sidechain conformations and HLA substructure surrounding the peptide. Compared to the two Hcrt complexes, the H1N1-HA275-287 peptide was bound to HLA-DQ6 in the expected homologous register and with overall similar backbone positioning (Cα rmsd < 0.35 Å) and sidechain conformations. Within the 9-mer core of the bound peptides, the most notable differences were observed in the exposed positions p2 and p8 of the peptides (p2-histidine and p8-threonine in the Hcrt complexes, and p2-alanine and p8-soleucine in the H1N1-HA complex). In addition to the differences in peptide sidechains, we observed a difference in the β-chain helix, which was positioned closer to the peptide in the H1N1-HA complex when compared to the two Hcrt complexes. This homology prompted us to determine whether this could also lead to T cell cross-reactivity to the H1N1-HA and hypocretin peptides in functional experiments.

3.3. HLA-DQ6-H1N1-HA275-287-specific CD4+ T cells are readily detectable in narcolepsy type 1 patients and healthy controls, but do not cross-react with HLA-DQ6-Hcrt56-68 or -Hcrt87-99

T cell lines were generated from PBMCs of narcolepsy type 1 patients and healthy controls by co-culture with a pool of the H1N1-HA275-287, Hcrt56-68 and Hcrt87-99 peptides for 5 days followed by expansion in culture medium containing IL-2 and IL-15. Subsequently, the specificity of these T cell lines against the H1N1-HA275-287 peptide was determined by co-culture of the T cell lines with irradiated HLA-DQ6 positive allogeneic PBMCs in the presence or absence of the H1N1-HA275-287 peptide. Specific proliferation was measured by determining the incorporation of 3H-thymidine after three days of culture. Proliferation was defined as a stimulation index equal or higher to 3. All T cell lines proliferated in the positive control condition which reinforced our earlier conclusion based on visual assessing T cell lines that they were in good condition. In 28.4% (23/81) of narcolepsy type 1 patients and 15.8% (3/19) of healthy controls, an H1N1-HA275-287 specific T cell proliferative response was observed (Fig. 2). To assess the specificity of the T cell lines against the Hcrt peptides, they were also stimulated with the Hcrt56-68 and Hcrt87-99 peptides. No reactivity to Hcrt56-68 or Hcrt87-99 was observed in T cell lines of either narcolepsy type 1 patients or controls (Fig. 2), indicating the absence of cross-reactivity of H1N1-HA275-287 specific T cells with Hcrt56-68 and Hcrt87-99 in the context of HLA-DQ6. FACS analysis was performed on 13 HLA-DQ6-H1N1-HA275-287 specific T cell lines. Analyses revealed a dominance of CD4+ T cells in these T cell lines (Fig. 3).

3.4. T cell reactivity to H1N1-HA275-287 is HLA-DQ6-restricted

T cell clones (TCCs) were generated from the H1N1-HA275-287 reactive T cell lines of 12 narcolepsy type 1 patients by either limiting dilution (in T cell lines of 3 narcolepsy type 1 patients) or isolation using streptavidin-PE-HLA-DQ6-H1N1-HA275-287 tetramers (in T cell lines of 9 narcolepsy type 1 patients) and tested for reactivity against H1N1-HA275-287. In TCCs generated from all H1N1-HA275-287 specific CD4+ T cell lines, H1N1-HA275-287 specific clonal T cell responses were found (Table 3).

To assess HLA-DQ6 restriction, T cell proliferation experiments were performed with irradiated allogeneic PBMCs of different haplotypes: HLA-DQA1*01:02/DQB1*06:03, HLA-DQA1*03:01/DQB1*03:02 (HLA-DQ8) or a mix of HLA-DQA1*01:02/DQB1*06:02 and HLA-DQA1*01:02/DQB1*06:03 next to those expressing HLA-DQA1*01:02/DQB1*06:02. T cell proliferation was only observed in the presence of HLA-DQ6-expressing PBMCs and the H1N1-HA275-287 peptide. Furthermore, when T cell proliferation experiments were performed with irradiated allogeneic PBMCs expressing HLA-DQ6, an anti-HLA-DQ mAb was able to block T cell proliferation of the generated TCCs. An anti-HLA-class I mAb blocked T cell proliferation considerably less effectively, whereas anti-HLA-DR and -DP mAbs did not affect T cell proliferation (Fig. 4A-B). These experiments confirm that the detected H1N1-HA275-287 specific CD4+ T cell proliferation is HLA-DQ6-restricted.
3.5. The HLA-DQ6-H1N1-HA_{275-287} specific T cell receptor repertoire in narcolepsy type 1 patients and healthy controls shows no biased expression

Recent reports describe a bias in TCR sequences for recognition of peptide-HLA complexes in CD4+ T cell mediated diseases (Qiao et al., 2014; Petersen et al., 2014). Since we were not able to show significant differences between percentages of narcolepsy type 1 patients and controls with HLA-DQ6-H1N1-HA_{275-287}-specific T cells, we searched for differences in the T cell repertoire used by narcolepsy type 1 patients and controls to mount immune responses to this antigen. TCRs expressed by 20 H1N1-HA_{275-287}-specific TCCs from 4 narcolepsy type 1 patients and 4 H1N1-HA_{275-287}-specific TCCs from 2 healthy controls were sequenced (Table 4). 18 TCR sequences were identified in TCCs of narcolepsy type 1 patients; 4 different TCR sequences in TCCs of healthy controls. There was expansion of some clones within a given patient, but these likely arose during the culturing process, with some T cell clones responding better to peptide hence expanding at a greater rate than others subsequently skewing the representative pool. Nevertheless, although only a small sample size was interrogated, no evidence for a biased TRAV, TRBV or CDR3 sequence motif was observed across unrelated individuals with narcolepsy type 1 or in healthy controls.

4. Discussion

HLA-DQ6-H1N1-HA peptide-specific CD4+ T cell responses were readily detected in both narcolepsy type 1 patients and healthy controls, with a higher proportion in the narcolepsy type 1 group. We did not detect HLA-DQ6-Hcrt peptide-specific T cell responses. Our experiments do not support the hypothesis that these Hcrt peptides are implicated in cross-reactivity leading to Hcrt-producing neuronal destruction and, thereby, to narcolepsy type 1.

The HLA-DQ6-H1N1-HA peptide-specific TCCs did show some, but
Table 3
H1N1-HA275-287-specificity of the generated T cell clones (TCCs). All subjects are narcolepsy type 1 patients.

<table>
<thead>
<tr>
<th>Subject number</th>
<th>H1N1 vaccination</th>
<th>TCCs tested</th>
<th>H1N1-HA275-287-specific TCCs</th>
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<tbody>
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</tr>
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</table>

a TCC generation using limiting dilution instead of tetramer sorting.

no extensive clustering of T cell receptor sequences in narcolepsy type 1 patients. Larger studies would be required to determine if the H1N1-specific TCR repertoire in NT1 patients differs from controls.

Our findings add to those of others in the field who did show antibody-mediated reactivity to H1N1- HA in narcolepsy type 1 patients. Several groups found H1N1-HA specific antibodies in narcolepsy type 1 patients (Lind et al., 2017; Lind et al., 2014), but H1N1-HA specific T cells have not been described. The lack of reactivity to Hcrt peptides was reported in studies focusing on autoantibodies (Black et al., 2005) and CD4+ T cells (Ramberger et al., 2017; Kornum et al., 2017). HLA-DR-restricted Hcrt-specific T cell responses have recently been described (Latorre et al., 2018), but that study does not explain the strong link with HLA-DQ6. Interestingly, one other study (Ramberger et al., 2017) reported reactivity to Hcrt-peptide pools in a small minority of narcolepsy type 1 patients, although the peptides used differed from the ones in the current study.

Moreover, in our current study we focused on H1N1-HA and Hcrt peptides that display sequence homology, which does not rule out that other H1N1 peptides are involved. Another possibility is that the key differences between the peptides, a histidine residue at position 59 and 90 of the Hcrt56-68 and Hcrt57-90 peptides, respectively, as compared with an alanine residue in the corresponding position in the H1N1-HA275-287 peptide, may prevent cross-reactive responses. We therefore also tested substitution variants of the Hcrt-peptides in which the histidine residues were replaced by an alanine, but we observed no cross-reactivity to these peptides as well, making it unlikely that post-translational modification of Hcrt-peptides underlies cross-reactivity (results not shown). In future studies we will therefore be testing T cell responses to peptide pools representing the H1N1 proote and preprohypocretin.

One of the limitations in our study is that we have not been able to distinguish between narcolepsy type 1 patients and healthy controls that have actually encountered the H1N1 influenza virus and those who have not. We could therefore not be sure whether different exposure to the virus explains the lack of differences in H1N1-HA peptide-specific T cell responses between narcolepsy patients and healthy controls. However, T cell mediated cross-protective immunity generated by previous H1N1 infections was found to be common in the population (Miller et al., 2010).
Another limitation in our study is that we are performing our experiments in blood, while the actual destruction of Hert-producing neurons is taking place at the other side of the blood-brain barrier. It was recently described that T cell composition in cerebrospinal fluid differed between narcolepsy type 1 patients and healthy controls (Moresco et al., 2018). Repeating our experiments in cerebrospinal fluid would therefore be a better environment to test for cross-reactive T cells.

Additionally, detecting proliferation of a small immune subset that could have driven the destruction of the approximately 80,000 Hert-producing neurons (Thannickal et al., 2000) in a vast number of non-proliferating immune cells is technically difficult. The procedure used for peptide-specific TCC generation was also used in previous studies for the isolation of HLA-DQ-restricted gluten-specific T cell clones from patients with celiac disease in which we have determined the affinity of such T cells for the cognate HLA-DQ-gluten complexes. We observed that in cell-free assays the affinity values for some of these HLA-DQ-gluten specific TGRs were comparable with affinity values observed for microbial or non-self TCR–pMHC-II interactions, while others exhibited affinity values in line with those of low-affinity autoreactive TCR–pMHC complexes (Petersen et al., 2014). In cellular assays similar substantial differences were observed (Broughton et al., 2012). Therefore, this indicates that our method allows the identification of both high- and low-affinity T cell clones. However, we cannot exclude the possibility that with our technique we missed the detection of very low frequency T cells. The T cell library method that was performed in a recent publication on T cell reactivity to Hert (Latorre et al., 2018) would be an interesting technique to screen for these low frequency clones. Other novel approaches, such as mass cytometry, to address this rare immune subset problem are emerging with techniques that can isolate disease-specific immune subsets with unprecedented detail (Van Unen et al., 2017). Repeating our experiments with only those subsets that are specific for narcolepsy type 1, would significantly increase the odds of identifying rare cross-reactive immune cells in narcolepsy type 1 patients should they exist.

![Graph showing the effect of H1N1-HA275-287 on T cell response in narcolepsy type 1 patients.](image)

**Fig. 4.** A H1N1-HA275-287 dose-dependent T cell response in a narcolepsy type 1 patient T cell clone (patient number 50, TCC 87) is found only in proliferation experiments performed with irradiated PBMCs that are HLA-DQA1*01:02/DQB1*06:02 (HLA-DQ6)-positive. Experiments were performed in triplicate wells. Significant differences relative to proliferation experiments with irradiated HLA-DQA8 (HLA-DQA1*03:01/DQB1*03:02)-positive PBMCs. B. Anti-HLA-DQ mAb blocks T cell proliferation of the generated TCCs. An anti-HLA-class I mAb blocked T cell proliferation considerably less effectively, whereas anti-HLA-DR and –DP mAbs did not affect T cell proliferation.

* p < .05, ** p < .01, *** p < .001;

mAb = monoclonal antibody; PBMCs = peripheral blood mononuclear cells; TCC = T cell clone.
Table 4
T cell receptor sequences of 24 (20 narcolepsy type 1 patient, 4 healthy control) H1N1-NA2009-specific T cell clones (TCCs). Green and red values indicate receptor segments that are shared between TCCs of >1 narcolepsy type 1 patient or healthy control.

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A = alanine; C = cysteine; CDR3 = complementarity-determining region 3; D = aspartic acid; E = glutamic acid; F = phenylalanine; G = glycine; H = histidine; I = isoleucine; K = lysine; L = leucine; M = methionine; N = asparagine; P = proline; Q = glutamine; R = arginine; S = serine; T = threonine; TRAI = T-cell receptor alpha joining segment; TRAV = T-cell receptor alpha variable segment; TRBD = T-cell receptor beta diversity segment; TRBJ = T-cell receptor beta joining segment; TRBV = T-cell receptor beta variable segment; V = valine; W = tryptophan; Y = tyrosine.

5. Conclusions
We identified HLA-DQ6-restricted H1N1-NA peptide-specific T cell responses in a subset of narcolepsy type 1 patients and healthy controls. We did not find HLA-DQ6-H1N1-NA peptide-specific T cells cross-reactive to Hcrt-2 peptides. These results indicate that it is unlikely that cross-reactivity between H1N1-NA and Hcrt-2 peptides presented by HLA-DQ6 is involved in the development of narcolepsy.

Conflicts of interests
The authors confirm no conflict of interest to disclose.

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We thank Allan Thompson for T cell receptor analyses. We thank Ms. Kai Lee Loh for technical assistance. Crystallography was undertaken at the mx2 beamline at the Australian Synchrotron, part of ANSTO. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Supplementary data
Supplementary data to this article can be found online at https://doi.org/10.1016/j.jneuroim.2019.04.009.

References
American Academy of Sleep Medicine, 2014. International Classification of Sleep Disorders. American Academy of Sleep Medicine, Darien, IL.


