Lymphocyte predominant cells detect *Moraxella catarrhalis*-derived antigens in nodular lymphocyte-predominant Hodgkin lymphoma

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Nodular lymphocyte-predominant Hodgkin lymphoma (NLPHL) is a rare lymphoma of B-cell origin with frequent expression of functional B-cell receptors (BCRs). Here we report that expression cloning followed by antigen screening identifies DNA-directed RNA polymerase beta’ (RpoC) from *Moraxella catarrhalis* as frequent antigen of BCRs of IgD+ LP cells. Patients show predominance of HLA-DRB1*04/07 and the IgVH genes encode extraordinarily long CDR3s. High-titer, light-chain-restricted anti-RpoC IgG1/κ-type serum-antibodies are additionally found in these patients. RpoC and MID/hag, a superantigen co-expressed by *Moraxella catarrhalis* that is known to activate IgD+ B cells by binding to the Fc domain of IgD, have additive activation effects on the BCR, the NF-κB pathway and the proliferation of IgD+ DEV cells expressing RpoC-specific BCRs. This suggests an additive antigenic and superantigenic stimulation of B cells with RpoC-specific IgD+ BCRs under conditions of a permissive MHC-II haplotype as a model of NLPHL lymphomagenesis, implying future treatment strategies.

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nodular lymphocyte-predominant Hodgkin lymphoma (NLPHL) accounts for 5–16% of all Hodgkin lymphoma (HL) cases, and IgD+ NLPHL represents a distinct clinical subtype, with a strong (>20:1) male predominance. The disease-defining lymphocyte predominant (LP) tumor cells represent only a small proportion of the total tumor infiltrate and are widely outnumbered by reactive cells. LP cells have a late germinal-center B-cell phenotype and are closely related to dense lymphocyte predominant (LP) tumor cells and are closely related to and are widely outnumbered by reactive cells. LP cells have a disease-de

**Results**

**Patients and Ig V gene characteristics.** Functional Ig heavy and light chain genes were successfully amplified from microdissected LP cells from 12 of 22 NLPHL cases of a screening cohort from Germany and Finland, including two composite lymphomas consisting of an NLPHL part (case #7a and #8a) and a diffuse large B-cell lymphoma (DLBCL) part (case #7b and #8b) in the same lymph node. In a validation cohort, composed of only IgD+ NLPHL cases from Switzerland and Sweden, the success rate was 3/5 (#13–#15). The median age of patients with successfully amplified IgV genes was 30 years. Eight patients had IgD+ LP cells (Supplementary Fig. 1), and five of these patients were adolescents (Table 1). Two IgD+ NLPHL samples were obtained from inguinal lymph nodes, but these were relapses. A male predominance was observed among the NLPHL cases (13 of 15). All cases had mutated IgV genes, with mutation frequencies for heavy and light chain IgV genes (VH and VL, respectively) ranging between 0% and 18.0% (average: 8.3% for VH and 4.8% for VL gene segments; Table 2). The complementarity determining region (CDR) 3 of VH region genes isolated from IgD+ LP cells were significantly longer (median: 30 amino acids; mean: 29.95 ± 1.048 [SEM] amino acids; n = 8), compared with the CDR3 of VH1 region genes isolated from IgD− LP cells (median: 17 amino acids; mean: 17.71 ± 1.017 amino acids; n = 7; p < 0.0001, unpaired two-tailed Student’s t-test). Seven of the eight IgD+ NLPHL cases expressed a member of the VH3 family, compared with one of the seven IgD+ NLPHL cases. Furthermore, cases with extraordinarily long CDR3 had characteristic VDJ-rearrangements (frequently D3-3*01-JH6 rearrangements, see Table 2).

**BCRs derived from IgD+ LP cells react with Moraxella spp.** Overall, 6/8 IgD+ NLPHL-derived BCRs (four #3, #6, #9, and #10) from the screening cohort and two #13 and #14) from the validation cohort) reacted against *M. catarrhalis* lysates (Fig. 1a).

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**Table 1 Characteristics of the NLPHL patients included in this study.**

| Case | Gender | Age (year) | Disease status | Localization | LP cells | Reactivity against *M. catarrhalis* RpoC | Reactivity against M. osl Succinate-CoA ligase sub α | HLA-DRB1*04 or HLA-DRB1*07 |
|------|--------|------------|----------------|--------------|----------|----------------------------------------|------------------------------------------------------|----------------------------|
| 1    | m      | 52         | Relapse        | Axillary     | No       | No                                     | No                                                   | No                        |
| 2    | m      | 15         | Relapse        | Supraclavicular | No       | No                                     | No                                                   | No                        |
| 3    | m      | 14         | 2nd relapse    | Cervical     | Yes      | yes                                    | No                                                   | Yes                       |
| 4    | m      | 65         | First manifestation | Cervical | No       | No                                     | No                                                   | Yes                       |
| 5    | f      | 37         | First manifestation | Retropерitoneal | No       | No                                     | No                                                   | No                        |
| 6    | m      | 15         | Relapse        | Cervical     | Yes      | yes                                    | No                                                   | Yes                       |
| 7a   | m      | 51         | 2nd relapse    | Axillary     | No       | No                                     | No                                                   | No                        |
| 7b   | m      | 51         | 2nd relapse    | Axillary     | No       | No                                     | No                                                   | No                        |
| 8a   | m      | 40         | Primary progressive | Abdominal | No       | No                                     | No                                                   | No                        |
| 8b   | b      | 40         | Primary progressive | Abdominal | No       | No                                     | No                                                   | No                        |
| 9    | m      | 42         | Relapse        | Inguinal     | Yes      | Yes                                    | No                                                   | Yes                       |
| 10   | m      | 12         | 2nd relapse    | Inguinal     | Yes      | Yes                                    | No                                                   | Yes                       |
| 11   | m      | 15         | First manifestation | Cervical | Yes      | No                                     | Yes                                                   | Yes                       |
| 12   | m      | 31         | First manifestation | Cervical | No       | No                                     | Yes                                                   | Yes                       |
| 13   | m      | 18         | First manifestation | Cervical | Yes      | Yes                                    | Yes                                                   | Yes                       |
| 14   | m      | 30         | First manifestation | Parotid | Yes      | Yes                                    | No                                                   | Yes                       |
| 15   | f      | 16         | First manifestation | Axillary | Yes      | No                                     | No                                                   | No                        |

Bold: IgD+ NLPHL; cases 7 and 8: (a) NLPHL, (b) histological transformation into DLBCL in the same lymph node.
and the *M. catarrhalis* strain ATCC 43617 RO 108 (data not shown), whereas one IgD⁺ NLPHL (#11) reacted with a *M. osloensis* lysate (Fig. 1a, Supplementary Information and Supplementary Fig. 2). No BCRs derived from IgD⁺ NLPHL cases reacted with either *M. catarrhalis* or *M. osloensis*. In Western blots of *M. catarrhalis* lysates, the BCRs derived from IgD⁺ NLPHL cases detected a target antigen of >150 kDa (Fig. 1b, Supplementary Information and Supplementary Figs. 3 and 4). In contrast, the *M. catarrhalis* RpoC monomer has a molecular weight >150 kDa (Fig. 4), which excludes MID/hag as their target. Moreover, the MID/hag protein in Western blots (data not shown). The specificity of MID/hag reactivity against *M. catarrhalis* RpoC was confirmed by ELISA and Western blotting (Fig. 1b, c), demonstrating binding of the BCRs with recombinant RpoC was demonstrated, which could be narrowed down to amino acids 851–865 (Fig. 1d and Supplementary Fig. 5).

IgD⁺ status of NLPHL was significantly associated with reactivity of recombinant Fabs against *M. species* (\(p = 0.007\); Fisher’s exact test) and *M. catarrhalis* RpoC (\(p = 0.0014\); Fisher’s exact test). In contrast to NLPHL, none of the recombinant BCRs derived from 12 DLBCL, 11 primary central nervous system lymphomas, 10 mantle cell lymphomas, and 12 chronic lymphocytic leukemia cases reacted with *M. catarrhalis* RpoC (Supplementary Fig. 6). Additionally, for IgD⁻ NLPHL two autoantigens were identified as targets of BCRs of LP cells (Supplementary Fig. 7). Several representative dot and western blots are shown in supplementary (Supplementary Figs. 16–22).

### Table 2 Ig variable region gene analysis of LP cells.

| Case | LP cells IgD⁺ | VH/VL gene | Homology (%) | Somatic mutation | JH/JL gene | DH gene | length CDR3 (AA) | Junction |
|------|---------------|------------|--------------|-----------------|------------|---------|----------------|----------|
| 1 Neg | VHI-3-01 | 91.3 | Yes | JH₄ᵇ | 20 | CAREVPPIIMWGVGLDFW |
| 2 Neg | VHI-46-01 | 87.9ᵇ | Yes | JH₂ᵇ | 15 | YYYCAEEDGDRIFVDLW |
| 3 Neg | VHI-30-01 | 90.3 | Yes | JH₄ᵇ | 9 | CQKYNQYVPFTV |
| 4 Neg | VH₃-30 | 90.3 | Yes | JH₆ᵇ | 26 | CARVAGAGRNYYWWGWEYFYMDDV |
| 5 Neg | VK-5 | 96 | Yes | JK₁ᵇ | 8 | CQENEYSWVTW |
| 6 Neg | VH₃-07 | 95.5 | Yes | JH₆ᵇ | 26 | CARVLRWGGYSDFWSNYEDYFALDV |
| 7 Neg | VH₃-48 | 90.7 | Yes | JK₂ᵇ | 10 | CQRYSTPPF |
| 8 Neg | VH₃-27 | 87.1 | Yes | JK₃ᵇ | 10 | CQNYTVPLTF |
| 9 Neg | VH₄-59 | 86.4ᵇ | Yes | JH₆ᵇ | 33 | CATVDPTVVEGRTKYYDFWGYGTDQRRYYMDV |
| 10 Neg | VK-27⁻ | 91.6 | Yes | JH₆ᵇ | 22 | CARGKGDVLAFVPNFMDDV |
| 11 Neg | VH₃-11 | 95.5 | Yes | JH₆ᵇ | 30 | CARLSRCAVCLAFGPMYMDV |
| 12 Neg | VK₂⁻ | 99.3 | Yes | JH₆ᵇ | 26 | CARLLEAGVGVGDWGMDDV |
| 13 Neg | VH₃-11 | 95.1 | Yes | JH₆ᵇ | 26 | CARLSRCAVCLAFGPMYMDV |
| 14 Neg | VK₁-37 | 99.3 | Yes | JH₆ᵇ | 16 | CARGKGDVLAFVPNFMDDV |
| 15 Neg | VH₄-31 | 99.2 | Yes | JH₆ᵇ | 17 | CARLSRCAVCLAFGPMYMDV |
| 16 Neg | VK₁-5 | 96 | Yes | JH₆ᵇ | 22 | CARGKGDVLAFVPNFMDDV |

Bold: IgD⁺ NLPHL; all cases had functional IgV genes. For case 15 two functional light chains were amplified. For somatic mutation a threshold of 0.5% was used.

**Insertion in FR3 (AGAAT).**

**With deletion of 3 nt in CDR2.**

**Restriction to certain MHC II classes in IgD⁺ NLPHL.** Seven of the eight IgD⁺ NLPHL patients, including all six cases with an RpoC-specific BCR, had HLA-DRB1*04 or HLA-DRB1*07 haplotypes (Table 3). The presence of HLA-DRB1*04 or HLA-DRB1*07 was significantly associated with reactivity against *Moraxella* species (\(p = 0.0256\); two-tailed Fisher’s exact test), and with reactivity against *M. catarrhalis* RpoC (\(p = 0.044\); two-tailed Fisher’s exact test). For *M. catarrhalis* RpoC five t-cell epitopes, with high SYFPEITHI scores, were predicted for HLA-DRB1*04, and six epitopes were predicted for HLA-DRB1*07 (Supplementary Table 2), suggesting that these haplotypes can provide cognate follicular T-cell help for RpoC-specific B cells.

**NLPHL patients show high-titer anti-RpoC-serum antibodies.** Serum antibodies against *M. catarrhalis* RpoC were detected in 2/2 patients with IgD⁺ RpoC-specific BCRs within the screening cohort, at a titer of 1:3200, which belonged to the IgG1/k subclass.
(Fig. 1e). High-titer, anti-\textit{M. catarrhalis}-RpoC antibodies were found in 20/98 NLPHL patients enrolled in clinical trials conducted by the German Hodgkin Study Group (GHSG) (Fig. 2a), which is representative of the general population of NLPHL patients. All anti-\textit{M. catarrhalis}-RpoC antibodies were of IgG class and predominantly of the IgG1 subclass (Fig. 2b), thus probably not related to the IgG+ LP cell clone. However, in each patient with serum antibodies against RpoC, these were light chain restricted (Fig. 2b), indicating a clonal origin and presumably a relation to the initiating event of NLPHL. The titers ranged from 1:800 to 1:3,200 (Fig. 2c). When applying a titer higher than 1:400 as cut off for positivity, no healthy control or patient with cHL or THRLBCL was positive. High titer (>1:400) serum antibodies against \textit{M. catarrhalis} RpoC were associated with NLPHL ($p < 0.0001$; Fisher’s exact test). Low-titer RpoC-antibodies were detected in the serum of 9/188 healthy controls (Supplementary Fig. 8) and in 10/100 patients with classical HL (Fig. 2d), with maximum titers of 1:200 (Fig. 2c, Supplementary Figs. 9 and 10).
Table 3 MHC alleles of NLPHL.

| Case | HLA-A | HLA-B | HLA-DRB1 | HLA-DQ B1 | HLA-DQA1 |
|------|-------|-------|----------|-----------|---------|
| 1    | A*11/A*24 | B*44/B*51 | DRB1*01:01/DRB1*11:01 | DQB1*03:01/05:01 | DQA1*05:01 |
| 2    | A*01/A*02 | B*40/B*49 | DRB1*01:01/DRB1*11:02 | DQB1*03:19/05:01 | DQA1*05:01 |
| 3    | A*03/A*32 | B*44/B*51 | DRB1*04:01/DRB1*11:01 | DQB1*03:01/03:02 | DQA1*03:01 |
| 4    | A*02/A*31 | B*18/B*56 | DRB1*04:01/DRB1*15:01 | DQB1*06:02/03:02 | DQA1*02:01 |
| 5    | A*03/A*32 | B*15/B*47 | DRB1*11:01/DRB1*11:01 | DQB1*03:01/03:02 | DQA1*03:01 |
| 6    | A*30/A*32 | B*13/B*35 | DRB1*04:07/DRB1*07:01 | DQB1*02:01/01:01 | DQA1*02:01 |
| 7    | A*01/A*02 | B*08/B*08 | DRB1*11:01/DRB1*15:01 | DQB1*06:02/03:01 | DQA1*02:01 |
| 8    | A*02/A*33 | B*14/B*35 | DRB1*02:01/DRB1*12:01 | DQB1*03:01/03:05 | DQA1*01:02 |
| 9    | A*01/A*11 | B*35/B*44 | DRB1*04:01/DRB1*08:01 | DQB1*04:02/01:01 | DQA1*03:01 |
| 10   | A*02/A*25 | B*44/B*18 | DRB1*04:01/DRB1*14 | DQB1*03:01/05:05 | DQA1*04:04 |
| 11   | A*02/A*02 | B*07/B*50 | DRB1*07/DRB1*07 | DQB1*02/01:02 | DQA1*02:01 |
| 12   | A*01/A*03 | B*35/B*58 | DRB1*01:01/DRB1*04:01 | DQB1*03:02/01:01 | DQA1*01:05 |
| 13   | A*01/A*02 | B*08/B*44 | DRB1*03:01/DRB1*07:01 | DQB1*02:01/01:01 | DQA1*01:02 |
| 14   | A*02/A*11 | B*07/B*35 | DRB1*07:01/DRB1*13:02 | DQB1*03:02/02:04 | DQA1*02:01 |
| 15   | A*02/A*31 | B*40/B*57 | DRB1*07:01/DRB1*07:01 | DQB1*03:01/03:03 | DQA1*02:01 |

Fig. 2 Serological responses against RpoC of M. catarrhalis in NLPHL, cHL, and THRBCL. a Sera of patients with NLPHL (diluted 1:100) were tested for antibodies against RpoC of M. catarrhalis. b Analysis of Ig classes (left), IgG subclasses (middle), and light chains (right) of serum-antibodies against RpoC of M. catarrhalis in patients with NLPHL. The anti-RpoC antibodies were exclusively of the IgG class, mostly IgG1, and showed light chain restriction. c Titers of anti-RpoC antibodies in seropositive patients with NLPHL. The curves represent OD at 490 nm of different serum dilutions. Patients with NLPHL had titers between 1:800 and 1:3200. d Sera of patients with cHL (diluted 1:100) were tested for antibodies against RpoC of M. catarrhalis. e Seropositive patients with cHL had RpoC-antibody titers of up to 1:1200. f PFS and OS of patients with NLPHL with and without RpoC-antibodies. No significant difference was observed for PFS (p = 0.13, Log-Rank-test) and OS (p = 0.26, Log-Rank-test). g Sera of patients with THRBCL (diluted 1:100) were tested for antibodies against RpoC, but all patients with THRBCL were seronegative for RpoC-antibodies. Serum of a seropositive NLPHL patient served as positive control. h Scatter blot for comparison of RpoC-antibodies in sera of patients with NLPHL, cHL, or THRBCL, and healthy controls. Data in a and d are representative of three independent experiments, data in b, c, e, g, and h are representative of two independent experiments.

RpoC-antibody-seropositive NLPHL patients (n = 20) did not differ in their clinical characteristics (age, gender, stage, site of manifestation, progression-free, and overall survival) from RpoC-antibody-seronegative NLPHL patients (Fig. 2f and data not shown). Unfortunately, the IgD-status was not available for this cohort. In the sera from 50 patients with THRBCL, which represents a closely related entity to NLPHL, no RpoC-antibodies were found (Fig. 2g). Summarizing, anti-RpoC-antibodies were
frequently found in NLPHL patients, but not in patients with related lymphomas or healthy controls (Fig. 2h).

**RpoC and MID/hag induce additive stimulation.** Since we hypothesized that specific stimulation of the LP cell BCR by RpoC contributes to the lymphomagenesis of IgD+ NLPHL, patient-derived RpoC-specific BCRs were functionally investigated. At baseline, neither recombinant *M. catarrhalis* RpoC nor MID/hag resulted in increased proliferation of the IgD+ DEV cell line, which is the only available NLPHL cell line (not shown). Similar results were observed for DEV cells stably expressing transfected BCRs without reactivity against RpoC. In contrast, RpoC stimulation resulted in the significantly increased proliferation of DEV cells that stably expressed RpoC-reactive IgD+ BCRs (Fig. 3a, b). Likewise, when MID/hag fragments 2/3 or 3 were applied by itself, already a significantly increased proliferation rate was observed (Supplementary Fig. 11). However, proliferation was further increased by the costimulation with RpoC and the MID/hag fragments 2 and 3, which contain the IgD-binding region (amino acids 920–1200) (Fig. 3a–c and Supplementary Fig. 11). This additive effect of MID/hag stimulation was not observed when DEV cells were transfected with an RpoC-reactive BCR of the IgG or IgM subtype (Fig. 3a, b). Accordingly, RpoC and MID/hag stimulation resulted in the strong activation of the BCR-signaling pathway, as determined by phosphorylation of key BCR-signaling factors (pTyr525/526 spleen tyrosine kinase [SYK], pTyr96 B-cell linker [BLNK], pTyr759 phosphoinositide-specific phospholipase C [PLC]γ2, and pTyr223 Bruton’s tyrosine kinase [BTK]) in DEV cells that stably expressed RpoC-reactive IgD+ BCRs (Fig. 3c). The activation of the BCR pathway was associated with a significant increase in MYC expression (Fig. 3c).

Additionally, the NF-κB pathway was activated after stimulation with RpoC and MID/hag (Supplementary Fig. 12). Activation was also shown by flow cytometric analysis of cytoplasmic calcium levels in DEV cells that stably expressed RpoC-reactive IgD+ BCRs by an increase in the intracellular calcium levels after incubation with *M. catarrhalis* RpoC, which could be further increased by coinoculation with RpoC and MID/hag, but was not induced by a control antigen (MAZ, Supplementary Fig. 13).

**Antigen/drug conjugates target RpoC-reactive LP cells.** By using a synthetic FITC-conjugated RpoC peptide, which contained the binding epitope, the binding and internalization of RpoC into DEV cells that stably expressed RpoC-reactive BCRs could be measured using flow cytometry (Fig. 3d). In a LDH release assay, RpoC conjugated to a truncated form of *Pseudomonas aeruginosa* exotoxin A (RpoC/EtaA), was found to be cytotoxic against the DEV cell line that stably expressed RpoC-specific BCRs but had no effects on non-transfected DEV cells or on DEV cells that expressed BCRs specific for antigens other than RpoC (Fig. 3e). As shown by a trypan blue exclusion assay, 50% of the NLPHL cells expressing an RpoC-specific BCR died within 48 h after incubation with RpoC/EtaA (Supplementary Fig. 14). In support of these results, an increase in the number of apoptotic cells was detected by an AnnexinV/propidium iodide assay (Fig. 3f).

**Autoantigenic targets of BCRs derived from IgD− LP cells.** Two autoantigens, human ribosomal protein S27a (RPS27a, for NLPHL #1, AA1-AA95) and human pyruvate carboxylase (for NLPHL #5, AA1030-AA1178), were identified as antigenic targets of the BCRs of two individual IgD− NLPHL cases. Reactivity of the respective Fabs was confirmed by ELISA using recombinantly expressed RPS27 and pyruvate carboxylase with C-terminal FLAG-tag expressed in HEK293 cells (Supplementary Fig. 7A, B). ELISAs with different fragments of pyruvate carboxylase revealed AA1111–AA1177 as the binding region of the recombinant Fab of patient #5 (Supplementary Fig. 7C). When comparing the identified antigens from the patients with autoreactive NLPHL-BCRs with those of healthy controls by Western-blot no obvious difference was detectable (Supplementary Fig. 7D). However, when comparing them by isoelectric focusing (IEF) a different electric charge of pyruvate carboxylase exclusively in patient #5 was observed (Supplementary Fig. 7E). This different electric charge was not altered after treatment with alkaline phosphatase (Supplementary Fig. 7F), but recombinant biotinylated pretreatment ahead of IEF resulted in the disappearance of the different electric charge, confirming a differential biotinyla tion of pyruvate carboxylase of patient #5 (Supplementary Fig. 7G). The hypobiotinylated pyruvate carboxylase might contribute to its immunogenicity in patient #5. Autoreactive BCRs contributing to lymphomagenesis by chronic stimulation due to alternative secondary modifications have previously been described in MGUS, Waldenström macroglobulinemia, multiple myeloma, and primary central nervous system lymphoma. Pyruvate carboxylase is a highly conserved gene, and has been identified as an antigen recognized by BCRs of CLL.

**Discussion**

Here, we describe a distinct subtype of NLPHL, with IgD+ LP cells, characteristically long IgVH CDR3s (median 30 amino acids), a high frequency of IgV gene mutations, and characteristic VDJ-recombination. IgD+ NLPHL previously defined a unique clinical NLPHL subset, which primarily affected the cervical lymph nodes of male adolescents. Our results provide evidence that chronic antigenic stimulation by a common bacterium contributes to lymphomagenesis in NLPHL. Antigens produced by *M. catarrhalis* or *M. osloensis* were specifically recognized by recombinant BCRs derived from 7/8 NLPHL cases with IgD+ LP cells. Further analysis identified *M. catarrhalis* RpoC as the specific antigen for six *M. catarrhalis*-reactive BCRs and SUCLG1 as specific antigen for the single *M. osloensis*-reactive BCR. *M. catarrhalis*-derived RpoC bound specifically to the antigen-binding sites of IgD+ NLPHL-derived BCRs, which were specific for *Moraxella*, with no cross-reactivity against >200 pathogens, including various bacterial, fungal, parasitic, and viral pathogens. Likewise, BCRs from 45 B-NHLs, including DLBCL, primary central nervous system lymphoma, mantle cell lymphoma, and chronic lymphocytic leukemia, did neither bind to the *M. catarrhalis* lysate nor to RpoC. The presence of high-titer *M. catarrhalis*-RpoC antibodies in NLPHL serum samples suggests generally an adaptive humoral immune response against *M. catarrhalis*. The fact that these antibodies were predominantly of the IgG1 subclass and in addition light chain restricted, suggests a clonal B-cell expansion apart from the LP cell clone, that underwent class switch recombination and plasmocytic differentiation. These findings suggest that naive IgD+ B cells become activated in an adaptive humoral immune response against *M. catarrhalis* and represent the precursors of LP cells.

*M. catarrhalis* is a widespread, Gram-negative bacterium that causes recurrent airway infections and otitis media. *M. catarrhalis* additionally expresses the IgD-binding protein MID/hag, a bacterial autotransporter that binds specifically to the IgD Fc region and activates IgD+ B cells in a superantigenic manner. Of interest, the outer membrane vesicles of *M. catarrhalis* contain both MID/hag and RpoC and activate B cells, suggesting that *M. catarrhalis* can stimulate IgD+ LP cells in an additive manner, through RpoC binding to the antigen-binding region and through MID/hag binding to the Fc region of the BCR. This result implies the combined antigenic and
Fig. 3 Costimulation of different types of LP cells by RpoC and MID/hag.  

**a** Tetrazolium proliferation assay with the transfected DEV cells expressing recombinant BCRs with different RpoC-reactive Fab fragments and Fc fragments of either IgD or IgG class. Stimulation with RpoC resulted in significant proliferation, and costimulation with MID/hag fragments 2 and 3 resulted in strong further increase of proliferation in cell lines expressing BCR of IgD class, e.g. transfected DEV expressing IgD+ BCR #3 stimulated by rec. human SLP2 vs. rec. M. catarrhalis RpoC; p < 0.00001 (DF = 32, q = 17.99); DEV expressing IgG+ BCR #3 stimulated by rec. human SLP2 vs. rec. M. catarrhalis RpoC and MID/hag 2&3: p < 0.00001 (DF = 32, q = 46.22). **b** In a Tetrazolium assay stimulation with RpoC resulted in increase of proliferation in DEV cells expressing RpoC-reactive BCRs, but not in DEV cells expressing non-RpoC-reactive BCRs. In IgD+ DEV cells with RpoC-reactive BCR incubation with MID/hag 2 and 3 resulted in a significant increase of proliferation, whereas costimulation with MID/Hag fragments 2 and 3 and the control antigen SLP2 had no additive effect. DEV expressing IgD+ BCR #6 stimulated by rec. human SLP2 vs. rec. M. catarrhalis RpoC and RpoC/ETA; adjusted p < 0.00001 (DF = 56, q = 7.321) and DEV expressing IgD+ BCR #6 stimulated by rec. M. catarrhalis RpoC and MID/hag 2&3 vs. DEV expressing IgM+ BCR #2: p < 0.00001 (DF = 56, q = 29.44). Values in **a** and **b** are mean ± SEM. Two-way ANOVA with Tukey’s multiple comparisons were performed, **p** ≤ 0.01, ***p** ≤ 0.001, ****p** ≤ 0.0001. Experiments were independently repeated three times.  

**c** Activation of the BCR-signaling pathway. Representative Western blot analysis of the BCR signaling pathway shows a strong activation by RpoC and even stronger by coinucubation with RpoC and MID/hag in DEV cells transfected to express an RpoC-reactive IgD+ BCR. The incubation with RpoC, RpoC/Mid/Hag, or anti-IgM/IgD antibody results in the upregulation of the activated isoforms pTyr525/526 SYK, pTyr96 BLNK, pTyr759 PLCγ2, and pTyr223 BTK and induced overexpression of MYC.  

**d** Binding and internalization of RpoC/FITC into LP cells. RpoC/FITC bound to DEV cells transfected to express recombinant BCR of case #6 with RpoC-reactivity, but not to DEV cells transfected to express recombinant BCR of case #5. After 60 min internalization of RpoC/FITC into DEV cells with the RpoC-specific BCR #6 was observed. Control CD30/FITC neither bound to DEV cells nor was internalized.  

**e** Dose-dependent cytotoxic effects by ETA toxin-conjugated RpoC dependent on expression of RpoC-reactive BCRs on LP cells. Specific cytotoxicity evoked by RpoC/ETA was observed in the DEV cell line expressing the RpoC-reactive BCR of patient #3 (left), but not in the one expressing the autoreactive BCR of patient #5 (right).  

**f** Apoptosis induced by ETA toxin-conjugated RpoC dependent on expression of RpoC-reactive BCRs on LP cells. Characterization of DEV cells stably transfected to express IgG+ recombinant BCRs with (above, from case #3) or without (below, from case #8a) reactivity to M. catarrhalis RpoC by Annexin-V/FITC and propidium iodide staining after 24 h cultivation in the presence of RpoC/ETA, MAZ/ETA, or RpoC/ETA together with MID/hag. RpoC/ETA induced specifically apoptosis in the DEV cell line with RpoC-reactive BCR. Data in **a**–**c** and **f** are representative of three independent experiments, data of **d** and **e** are representative of two independent experiments.
superantigenic stimulation of RpoC-reactive BCRs, which is supported by our in vitro model using the DEV cell line to express IgD\(^+\) patient-derived RpoC-specific BCRs. The RpoC-induced increase in proliferation was only observed in DEV cells transfected with RpoC-reactive BCRs. The combination of RpoC and MID/hag fragments that contained the IgD-binding domain resulted in the strong and additive BCR pathway activation and proliferative effects in DEV cells that expressed RpoC-reactive IgD\(^+\) BCRs.

A potential role for superantigen-driven germinal center reactions in the generation of highly mutated IgV regions in so-called IgD-only B cells has previously been proposed\(^{30}\). The high mutation load in IgVH genes isolated from IgD\(^+\) NLPHL patients identifies a germinal center origin for the respective LP cells, which would require cognate T-cell help. This is supported by the presence of “permissive” HLA-DRB1*04/*07 haplotypes. Indeed, several high-affinity T-cell epitopes are predicted for these haplotypes, suggesting that these BCRs can provide cognate follicular T-cell help for RpoC-specific BCRs. Thus, in addition to the two \textit{M. catarrhalis}-derived stimuli, a third stimulus may be provided in respective individuals by antigen-specific CD4\(^+\) T-helper cells, resulting in the extensive proliferation of B cells with a specificity for \textit{M. catarrhalis} RpoC. During germinal center reactions, the chronically stimulated B cells likely acquire transforming events, resulting in the development of the malignant clone\(^4\). Because all RpoC-reactive BCRs derived from LP cells were IgD\(^+\), the additional stimulation by the MID/hag protein is likely to be essential for the pathogenetic role played by \textit{M. catarrhalis} in this scenario, as this finding indicates that the LP precursor cells are selected to retain IgD expression\(^{31–33}\). Contributions to lymphomagenesis from the chronic stimulation by T helper cells that have been activated by infectious pathogens or autoantigens have been demonstrated for some other lymphomas\(^{32–34}\). However, with the exception of hepatitis C virus, the target antigens of the BCRs from these lymphomas have either not been defined or have been shown to be autoantigens, and a combined antigen-specific and superantigenic stimulation, as has been identified here for NLPHL, has never been reported.

In contrast with NLPHL, no RpoC-antibodies were observed in the sera of a cohort of 50 THRLBCL patients. THRLBCL is an aggressive B-cell lymphoma that is closely related to NLPHL. Transformations of NLPHL into THRLBCL-like cases have been observed. However, the lack of RpoC-antibodies in THRLBCL patients suggests a different pathogenetic mechanism than that observed for the \textit{Moraxella}-induced NLPHL subtype. Furthermore, NLPHL cases that are \textit{Moraxella} sp.-induced do not present with a THRLBCL-like morphology. Given recent reports from retrospective analyses regarding less intensive treatments and active surveillance strategies for NLPHL\(^{35}\), the results of the present study might further raise discussions regarding how to treat this \textit{Moraxella} sp.-induced NLPHL subgroup, in particular. These results raise the question of whether antibiotic treatment...
and/or vaccination strategies could be used to prevent relapses of Moraxella sp.-induced NLPHL. Finally, the shared, specific BCR antigen found in IgD+ LP cell could be therapeutically exploited as the targeting moiety for different therapeutic formats, such as antigen/toxin conjugates, bispecific CD3 or CD16 constructs or CAR-T cells, resulting in the selective delivery of a therapeutic payload to RpoC-reactive B cells and leaving other B cells unaffected.

**Methods**

**Study samples.** The study was approved by the local ethics committees of the Universities in Frankfurt and Homburg. Frozen tissue sections of NLPHL specimens from the Deutsche Studiergruppe (DSG) of Pathology, Goethe University Hospital, Frankfurt/Main, Germany, from the Department of Pathology, Tampere University, Tampere, Finland, from the Department of Pathology, CHUV Lausanne, Switzerland, and from the Department of Pathology, Uppsala University Hospital, Sweden, were analyzed. Informed consent of the patients was obtained in accordance with the Declaration of Helsinki. Sera of patients with NLPHL and sera of healthy controls were obtained at the medical school Homburg/Saar, Germany. Moreover, sera of patients with cHL or NLPHL were obtained from the HD13 (ISRCTN63474366), HD14 (ISRCTN04761296), HD15 (ISRCTN32443041), HD16 (NCT00736320), HD17 (NCT01355800) and HD18 (NCT00155354) trials of the German Hodgkin Study Group (GHSG) as control and validation cohort.

Furthermore, sera of patients with cHL or NLPHL were obtained from the HD13 (ISRCTN63474366), HD14 (ISRCTN04761296), HD15 (ISRCTN32443041), HD16 (NCT00736320), HD17 (NCT01355800) and HD18 (NCT00155354) trials of the German Hodgkin Study Group (GHSG) as control and validation cohort.

**Laser microdissection and IgV region gene PCR.** Single, clearly identifiable LP cells were microdissected with an ultraviolet laser (PALM microdissection system, Zeiss Axiovert 200M microscope), pooled in groups of 30 cells and resuspended in 18 µl 1x PCR buffer and digested with 2 µl of proteinase K (Roche, Grenzach, Germany) at 55 °C for 4 h, followed by enzyme inactivation at 95 °C for 10 min. The LP cell lysates were subjected to two rounds of Vc-c, Vc-α, Vc-δ and Vc-λ specific PCR amplifications (30 and 44 cycles in the first and second round of PCR, respectively) using IgV family-specific primers and J primer mixes, and Expand high fidelity PCR kit (Roche) as described by Küppers et al.

**Expression of recombinant BCRs.** The amplified IgV region genes were sequenced and analyzed with IMGT-V-Quest for functionality, V, D and J segment usage and indications for somatic mutations. If both a functional heavy and light chain variable region gene was amplified, the IgV region genes were cloned into TOPO Zero-Blunt vector (Invitrogen Life Technologies, Darmstadt, Germany). IgV gene fragments were re-extended at the 5’ and 3’ ends according to the proper immunoglobulin germline genes. Complete IgV gene fragments were inserted via ApaLI and XhoI for IgVc or IgVc, in front of a κ-constant or λ-constant region gene, respectively, and of Vcβ and BclI for Vcβ in front of a γ-constant region gene into a modified pCES-1 vector for expression of the Fab fragments.

Fabs were expressed and purified.

**Antigen screening.** To screen for potential reactivity of Fabs against bacterial antigens, heat-inactivated lysates of 13 different bacterial strains or patient isolates including M. catarrhalis, M. osloensis, M. nonliquefaciens, Streptococcus pneumoniae, Streptococcus pyogenes, Haemophilus influenzae, Staphylococcus aureus, coagulase-negative Staphylococci, Klebsiella pneumoniae, Enterobacter aerogenes, Escherichia coli, Acinetobacter baumannii, Neisseria sp., as well as DNA from M. catarrhalis and osloensis isolated from a patient, were provided by the Institute of Medical Microbiology and Hygiene of the University of Saarland, Homburg/ Saar, Germany. Inactivated lysates of M. catarrhalis strain ATCC 43617 RO 108 and lysates of Bartonella henselae strain Marseille (Bartonella henselae A positive), respectively, were provided by the Institute of Medical Microbiology and Infection Control of the Hospital of the Goethe University Hospital, Frankfurt/Main (Supplementary Table 3), were spotted onto PVDF membranes each with a dose of 10 µg. The dot blots of bacterial lysates were blocked in 10% (w/v) non-fat dry milk powder in TBST [TBS, 0.1% (v/v) Tween 20] at 4 °C overnight. Washes twice in TBST and incubated for 1 h with the individual Fabs, each at a concentration of 10 µg/ml. Following three 30-min TBST washes and subsequent incubation for 1 h at room temperature with biotinylated goat anti-human heavy and light chain Fab antibody (Dianova, 109-065-088) at a dilution of 1:5000 (v/v) the arrays and blots were incubated for 10 min at room temperature with Strep-POX (1:5000) in 2% (w/v) milk/TBST and binding was detected using the ECL system (Amersham Pharmacia, Freiburg, Germany).

To extend the screening for infectious antigens, the recombinant NLPHL-Fabs were screened together with recombinant Fabs of different B-cell neoplasias at concentrations of 1, 10, and 20 µg/ml on an infectious disease epitope microarray (PEPterCHIP; Heidelberg, Germany) consisting of 3760 database-derived B-cell epitopes from 190 pathogens, including 113 viruses, 41 bacteria, 10 parasites, 1 and 1 pathogenic fungus. Goat anti-human IgG (H + L) conjugated to DyLight800 (1:5000) was used as secondary antibody and incubated for 45 min at room temperature. As a scanner the LI-COR Odyssey Imaging System was used with a scanning offset of 0.65 mm, a resolution of 21 µm and scanning intensities of 77/7 (red = 700 nm/green = 800 nm). Data quantification was followed by removal of spots with a deviation of more than 40%. Screening, scanning, and data analysis was performed by PEPterPRINT GmbH in Heidelberg, Germany.

**Generation of DEV cells expressing recombinant BCRs.** The only existing NLPHL cell line (DEV) was cultured at 37 °C in an atmosphere containing 5% CO2 in 5% of the culture medium. As a control for NLPHL, we used a recombinant human protein with a pRTS expression vector with an IgV region heavy chain and constant regions Cγ1–Cγ4, Cγ1–Cγ4, or Cα1–Cα4 with membrane coding exons TM1 and TM2 for
and of IgD, IgG, or IgM class, 1 × 10^6 cells were incubated with no antigen, followed by biotinylated Anti-His antibody (Qiagen, 34660, Hilden, Germany) (1:500) followed by biotinylated streptavidin (Qiagen, 016-110-084) (1:500) each for 20 min at 4 °C with washing steps in between (Supplementary Fig. 15). BCR and NF-κB pathway activation and proliferation assay. For Western blot analysis of the BCR pathway activation of transfected DEV cells either expressing a BCR reacting against M. catarrhalis RpoC or a different antigen, respectively, and of IgD, IgG, or IgM class, 1 × 10^6 cells were incubated with no antigen, recombinant RpoC at 5 µg/ml, RpoC and MAD/hag (both at 0.5 µg/ml) or RpoC and MID/hag fragment 2&3, MAZ at 5 µg/ml and the DEV cell line transfected to express RpoC-reactive surface BCR of the IgD class, as well as 10% Triton X-100. LDH was measured according to the protocol of the LDH assay kit (Roche, Mannheim, Germany). ELISA read out was done using a Victor II apparatus (PerkinElmer, Rodgau, Germany). For the analysis of the direct cytotoxic effects of the immunotoxins were measured by trypan blue assays at 0, 24, and 48 h.

HLa typing. HLA-typing of class I and II human leukocyte antigens (HLA) was performed for all patients with IgD+ LP cells by sequence-based typing (Labor Thiele, Kaiserslautern, Germany).

Analysis of binding and internalization. To analyze binding to and internalization of RpoC into DEV cells transfected to express RpoC-reactive BCRs, a synthetic RpoC peptide consisting of the amino acid sequence VAAKDVVNADGDVVF14201. Transfected DEV cells either expressing IgD+ BCRs with reactivity against RpoC or against a different antigen were resuspended in calcium-free and magnesium-free phosphate-buffered saline, and loaded with Fluo-4 AM dye (final concentration 2 μM, Invitrogen, Karlsruhe, Germany) for 30 min at room temperature. Antigen was added followed by flow cytometry of the cells. Ionomycin (10 ng/μl, Sigma-Aldrich, 407952) was used as a positive control for the analysis of calcium release from internal stores. Intracellular calcium levels were repeatedly analyzed immediately after adding the antigen to the dye-loaded cells. To exclude cell debris DEV cell line was gated for relatively high FSC and low SSC. EZ4U FACS Canto. In addition, the effects of the immunotoxins were measured by flow cytometry using the BD FACS Canto and either the original DEV cell line or DEV cell lines transfected to express LP cell-derived BCR, which contain His6 tags. Cells were incubated with murine anti-His antibody (Qiagen, 34660, Hilden, Germany) (1:500) followed by biotinylated anti-murine antibody (1:200) and PE-labeled streptavidin (Qiagen, 016-110-084) (1:500) each for 20 min at 4 °C with washing steps in between (Supplementary Fig. 15).

BCR and NF-κB pathway activation and proliferation assay. For Western blot analysis of the BCR pathway activation of transfected DEV cells either expressing a BCR reacting against M. catarrhalis RpoC or a different antigen, respectively, and of IgD, IgG, or IgM class, 1 × 10^6 cells were incubated with no antigen, recombinant RpoC at 5 µg/ml, RpoC and MAD/hag (both at 0.5 µg/ml) or RpoC and MID/hag fragment 2&3, MAZ at 5 µg/ml and the DEV cell line transfected to express RpoC-reactive surface BCR of the IgD class, as well as 10% Triton X-100. LDH was measured according to the protocol of the LDH assay kit (Roche, Mannheim, Germany). ELISA read out was done using a Victor II apparatus (PerkinElmer, Rodgau, Germany). For the analysis of the direct cytotoxic effects of the immunotoxins were measured by trypan blue assays at 0, 24, and 48 h.

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Data availability

All relevant data are available in the Article, Supplementary Information or from the corresponding author upon reasonable request.

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Author contributions
L.T., S.H.: design of study, performing experiments, data analysis, and writing manuscript; N.F.; E.G., M.K.; M.A.W.; F.N.; performing experiments and data analysis; S.K.; R.M.B., A.N., L.v.M., V.A.J.K., M.V., C.S., L.d.L., A.E., D.A.E: supplied essential material, interpretation of data, R.K., K.-D.P., M.-L.H., M.P.: design of study, interpretation of data, and revision of manuscript.

Competing interests
The authors declare no competing interests.

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