Neisseria meningitidis Lipopolysaccharide Modulates the Specific Humoral Immune Response to Neisserial Porins but Has No Effect on Porin-Induced Upregulation of Costimulatory Ligand B7-2

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The role of lipopolysaccharide (LPS) in the specific humoral response to meningococcal porins was investigated by measuring anti-PorA or -PorB antibody levels in mice immunized with wild-type meningococcal strain H44/76 or with its recently described LPS-negative mutant. Two murine strains were used for these immunizations: C3H/HeJ, which is LPS hyporesponsive, or C3H/HeOuJ, which is LPS responsive. A high level of anti-PorB immunoglobulin G (IgG) response was induced in both strains of mice immunized with either organism. The response induced by the wild-type strain was greater in C3H/HeOuJ mice than in C3H/HeJ mice, while the response induced by the LPS-negative mutant was similar in the two murine strains. Additionally, the anti-PorB response was similar in C3H/HeJ mice immunized with either bacterial strain. In general, the anti-PorA IgG response was lower than the anti-PorB response. These findings indicate that the presence of LPS is not essential for the induction of an antineisserial porin humoral response but can augment such a response. To determine whether LPS has any effect on the B-cell-stimulatory effect of neisserial porins (essential for the adjuvant activity of neisserial porins), B cells from both murine strains were incubated with outer membrane complexes (OMCs) prepared from strain H44/76 and its LPS-negative mutant. OMCs from either meningococcal strain were able to increase the surface expression of the costimulatory ligand B7-2 on B cells from either murine strain. Consistent with previously reported findings, LPS does not significantly affect the ability of neisserial porins to induce the costimulatory ligand B7-2.

In humans, meningococcal disease is caused by *Neisseria meningitidis* belonging to a number of capsular polysaccharide serogroups, including A, B, C, Y, and W-135. The presently available vaccine against *N. meningitidis* is a quadrivalent vaccine composed of capsular polysaccharides from serogroups A, C, Y, and W-135 (18). This preparation does not provide protection against serogroup B strains, which cause approximately one-third of the total cases in the United States and 45 to 80% or more of the cases in Europe (6, 27). Capsular polysaccharide from serogroup B strains mimics the human neuronal cell adhesion molecule (10); hence, the use of group B capsule in a vaccine introduces the risk of autoimmunity. Also, the group B capsular polysaccharide is poorly immunogenic, as indicated by the limited antibody response to the capsule seen in patients' sera after natural infections by the strain (13). Consequently, a number of groups are currently researching the potential of various surface-exposed outer membrane proteins (OMPs) and lipopolysaccharide (LPS) as vaccine candidates (1, 3, 8, 25). LPS, while being reactogenic in the host, has been explored by Steeghs et al. (29) for its potential as an adjuvant (when present in trace amounts) in vaccine preparations.

The potential of neisserial porins PorA and PorB as vaccine candidates and immune adjuvants has been explored by vari-

ous investigators. Porins, which constitute about 60% of the bacterial surface proteins (4), have been shown to be immunogenic without the addition of exogenous adjuvants (36, 39). Moreover, neisserial porin preparations are known to augment the humoral response to otherwise poorly immunogenic substances, e.g., peptides (20, 21), and induce T-cell-dependent immune response for normally T-cell-independent antigens, e.g., polysaccharides (9, 11, 12, 22, 35). In addition, neisserial porins have been used as immunologic adjuvants in a number of varied cases, including noncovalent complexes with malarial peptides (20, 21), group A streptococcal M protein (19), influenza virus hemagglutinin (19), and covalent complexes with multiple bacterial capsular polysaccharides (2, 9, 22, 35). In addition to their use as vaccine adjuvants, the use of neisserial porins as specific antineisserial vaccine candidates has also been investigated (5, 36, 39). Despite these efforts, the effect that LPS may have on the immunogenicity of the major outer membrane porins (PorA and PorB) has never been adequately explored.

In this study we examined the role of LPS in modulating the immune response to meningococcal PorA and PorB. Experiments were designed to evaluate the immunogenicity of PorA and PorB by immunizing mice with live meningococci or with purified PorA and PorB. The effect of LPS on the humoral response to the meningococcal porins was assessed by comparing the antiporin antibody levels in mice immunized with meningococcal strain H44/76 and its recently isolated isogenic LPS-negative mutant strain (28). This strain is devoid of LPS

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TABLE 1. Anti-PorB response (in μg of IgG/ml) generated against wild-type *N. meningitidis* strain H44/76 and its LPS-negative mutant in LPS-responsive C3H/HeOuJ mice and LPS-unresponsive C3H/HeJ mice^a

Mouse type and day of testing	Results for different regimens				
	PBS	W6	W7	M6	M7
C3H/HeJ					
28	BDL	0.52 $\pm$ 0.69	5.09 $\pm$ 5.58	0.07 $\pm$ 0.1	0.55 $\pm$ 0.44
35	BDL	0.31 $\pm$ 0.49	5.13 $\pm$ 6.77	0.06 $\pm$ 0.09	0.67 $\pm$ 0.53
42	BDL	0.6 $\pm$ 0.8	6.18 $\pm$ 7.55	0.59 $\pm$ 1.05	3.58 $\pm$ 2.87
C3H/HeOuJ					
28	BDL	1.63 $\pm$ 1.39	16.19 $\pm$ 8.08	0.19 $\pm$ 0.33	0.37 $\pm$ 0.25
35	BDL	2.46 $\pm$ 2.01	25.67 $\pm$ 21.95	0.21 $\pm$ 0.26	0.72 $\pm$ 0.74
42	0.06 $\pm$ 0.07	6.49 $\pm$ 5.42	61.48 $\pm$ 48.16	0.82 $\pm$ 0.74	1.86 $\pm$ 1.35

^a W6, 2×10^6 CFU of wild-type H44/76 per dose; W7, 2×10^7 CFU of wild-type H44/76 per dose; M6, 2×10^6 CFU of LPS-negative mutant per dose; M7, 2×10^7 CFU of LPS-negative mutant per dose; BDL, below detectable levels. Values reflect standard deviations for each group of mice ($n = 4$). Mice were immunized on days 0 and 21.

and has amounts of OMPs similar to those possessed by the wild-type parent (28). To further define the role of LPS in modulating the immune response to PorA and PorB, the immunizations were done in an LPS-responsive murine strain, C3H/HeOuJ, and an LPS-hyporesponsive murine strain, C3H/HeJ (24). The role of meningococcal LPS in modulating the potential immunostimulatory effect of PorB was evaluated by measuring the ability of outer membrane complexes (OMCs) prepared from either the wild-type strain or its LPS⁻ mutant, to induce B7-2 expression in naïve murine B cells in vitro.

MATERIALS AND METHODS

Mice. Two isogenic strains of female mice at 6 weeks of age were used for the study and were obtained from the Jackson Laboratory (Bar Harbor, Maine). These were the LPS-responsive strain C3H/HeOuJ and the LPS-hyporesponsive strain C3H/HeJ. The LPS hyporesponsiveness of C3H/HeJ mice is attributed to a defect in the cytoplasmic tail of the LPS signal transducer TLR4 (24).

Bacteria. *N. meningitidis* serogroup B strain H44/76 (B:15:P1.7,16), originally isolated from a patient with meningococcal bacteremia and meningitis from Norway, was used in the study. Its recently isolated LPS-negative isogenic mutant strain was a gift from Peter van der Ley, National Institute of Public Health and the Environment, Bilthoven, The Netherlands (28). This LPS-negative mutant strain is totally devoid of LPS and has amounts of OMPs similar to those held by the wild-type parent (28). The bacteria were grown in gonococcal liquid medium (23) at 37°C with shaking to an optical density at 600 nm of 0.1 to 0.2. The bacteria were then washed with phosphate-buffered saline (PBS) once and were resuspended in PBS at concentrations of 2×10^7 and 2×10^8 cells per ml.

Porins and LPS. PorA and PorB were purified (37) from H44/76 mutant strains H44/76 Δ 3 Δ 4 (15) and H44/76 Δ 1 Δ 4 (14), respectively. These mutant strains allowed purification of the desired porins without contamination from other OMPs. The porins were purified by detergent extraction and column chromatography as described previously (37). Polyacrylamide gel electrophoresis and silver staining (30) (data not shown) demonstrated negligible contamination by other proteins and LPS. Purified LPS from strain H44/76 was kindly provided by Michael Apicella (University of Iowa Medical Center, Iowa City, Iowa).

Immunization of mice. Mice ($n = 4$) were immunized subcutaneously with 2×10^6 or 2×10^7 bacteria of either the wild-type strain H44/76 or its LPS-negative isogenic mutant in 100 μl of PBS. Control mice were given 100 μl of PBS. The mice were immunized at days 0 and 21, and sera were obtained every 7 days, ending on day 42. In a separate experiment, following the same immunization regimen, mice were given 10 μg of purified PorA or PorB formed into proteosomes (36).

ELISA. The concentrations of anti-PorA- and anti-PorB-specific immunoglobulin G (IgG) present in the immune and nonimmune murine sera were determined by quantitative enzyme-linked immunosorbent assay (ELISA) as described previously (36). Briefly, flat-bottomed 96-well plates were coated overnight at room temperature with 100 μl of a 2- $\mu\text{g}/\text{ml}$ solution of purified PorA or PorB in carbonate-bicarbonate buffer (pH 9.6). IgG concentrations were measured for each individual murine serum. The ELISA plate contents were

developed by using the chromogenic substrate for alkaline phosphatase (Sigma Diagnostics Inc., St. Louis, Mo.). The concentrations of porin-specific IgG antibodies in serum samples were calculated by extrapolation from standard IgG log-log-transformed titration curves run in parallel. Anti-LPS IgG titers were determined by performing an ELISA similar to that described above, except that the plates were coated with 100 μl of a 10- $\mu\text{g}/\text{ml}$ solution of purified LPS in sodium barbital buffer (pH 4.6).

Preparation of OMCs. *N. meningitidis* cultures were grown to an optical density at 600 nm of 0.8. The cells were suspended in PBS, and OMCs were prepared according to the method described by van der Ley et al. (31). Briefly, meningococci were inactivated at 56°C for 30 min and were lysed by resuspending in 10 mM Tris (pH 8.0) followed by sonication. Cell debris was removed by centrifuging at 10,000 $\times g$. OMCs were obtained from the supernatant by subsequent centrifugation at 50,000 $\times g$. The OMCs were then treated with 1% sodium laurylsarcosinate to remove cytoplasmic membrane proteins bound to the OMCs. The protein content of the OMCs was determined by using the bicinchoninic acid protein assay reagent (Pierce Chemical Co.) as per the manufacturer's protocol. Bovine serum albumin was used as a standard.

In vitro stimulation of naïve B cells. Naïve B cells were isolated from the spleens of C3H/HeJ and C3H/HeOuJ mice according to the standard protocol (38). Briefly, a single-cell suspension of the spleen tissue was obtained by passing through a fine wire mesh, followed by the lysis of red blood cells (0.15 M Tris-buffered NH₄Cl). T cells were removed by T-cell-specific antibody-mediated complement lysis. Other nonspecific cells were removed by passage through a Sephadex G-10 column followed by a Ficoll gradient separation. The B cells, at a concentration of 5×10^6 cells/ml, were incubated for 24 h at 37°C and 5% CO₂ in the presence of 10 μg of OMCs (quantitated with respect to their protein content)/ml prepared from either strain H44/76 or its LPS⁻ mutant. Negative (incubated with medium alone) and positive (incubated with purified PorA and PorB proteins formed into proteosomes at a concentration of 10 $\mu\text{g}/\text{ml}$) controls were run in parallel. The cells were then probed with rat anti-mouse antibodies and were conjugated with fluorescein isothiocyanate to determine the level of cell surface expression of B7-1 and B7-2 cell surface markers by flow cytometry analysis (7). All the antibody conjugates for flow cytometry analysis were obtained from Caltag Laboratories (Burlingame, Calif.).

RESULTS

Immunogenicity of strain H44/76 and its isogenic LPS-negative mutant. Anti-PorA, anti-PorB, and anti-LPS IgG levels were measured by ELISA in sera from C3H/HeJ and C3H/HeOuJ mice after immunization with meningococcal strain H44/76 or its LPS-negative mutant. The anti-PorB IgG levels were greater in C3H/HeOuJ mice than in C3H/HeJ mice (Table 1). The wild-type strain H44/76 evoked an anti-PorB response about 30 to 40 times higher than that evoked by the LPS-negative mutant strain in the C3H/HeOuJ mice (Table 1). The difference in the anti-PorB response was, however, not as pronounced when the LPS-hyporesponsive mice were immu-

TABLE 2. Anti-PorA response (μg of IgG/ml) generated against wild-type *N. meningitidis* strain H44/76 and its LPS-negative mutant in LPS-responsive C3H/HeOuJ mice and LPS-unresponsive C3H/HeJ mice^a

Mouse type and day of testing	Results ($\pm$ SD) for different regimens				
	PBS	W6	W7	M6	M7
C3H/HeJ					
28	BDL	BDL	BDL	0.03 ± 0.03	0.26 ± 0.27
35	BDL	BDL	BDL	BDL	0.87 ± 1.1
42	BDL	BDL	BDL	0.07 ± 0.07	2.24 ± 2.36
C3H/HeOuJ					
28	BDL	BDL	BDL	BDL	0.23 ± 0.27
35	BDL	BDL	BDL	0.06 ± 0.08	0.57 ± 0.51
42	BDL	BDL	0.05 ± 0.04	0.21 ± 0.39	1.71 ± 1.22

^a W6, 2×10^6 CFU of wild-type H44/76 per dose; W7, 2×10^7 CFU of wild-type H44/76 per dose; M6, 2×10^6 CFU of LPS-negative mutant per dose; M7, 2×10^7 CFU of LPS-negative mutant per dose; BDL, below detectable limit. For end-group, $n = 4$. Mice were immunized on days 0 and 21.

nized with either bacterial strain. In addition, as elaborated in Table 1, even though the anti-PorB response was lower in C3H/HeJ mice than in C3H/HeOuJ mice, it was still significant, reaching a maximum concentration of about $6 \mu\text{g/ml}$. Furthermore, the LPS-negative bacterial strain evoked a very similar anti-PorB response in the two murine strains. The maximum anti-PorA IgG level attained in mice sera was $2.2 \mu\text{g/ml}$ (Table 2). Interestingly, a detectable anti-PorA response was obtained only in mice immunized with 10^7 CFU of the LPS⁻ mutant strain per dose and was comparable in the two strains of mice.

When intact meningococci were given, PorB was more immunogenic than PorA, as indicated by anti-PorB IgG levels that were higher than anti-PorA IgG levels (Tables 1 and 2). Since the anti-PorB response of mice might be modulated by the presence of LPS on the bacterial surface and by the ability of mice to immunologically respond to LPS, anti-LPS IgG levels were determined. An anti-LPS IgG response was seen only in the LPS-responsive C3H/HeOuJ mice immunized with the higher dose (10^7 CFU/dose) of wild-type strain H44/76 (data not shown). No detectable anti-LPS IgG antibodies were seen in sera from C3H/HeOuJ mice immunized with the LPS⁻ bacterial strain or in the sera from the LPS hyporesponsive strain of mice immunized with either bacterial strain.

Immunogenicity of purified PorA and PorB. As mentioned in the preceding paragraph, both PorA and PorB were found to be immunogenic when the mice were immunized with live cultures of *N. meningitidis*, albeit to different extents. Additionally, variations seen in the IgG response due to modulation by LPS (either at the host level or at the inoculum level) were different for the two proteins. In order to determine if these differences were due to the relative abundance or availability of the two proteins to the immune system or due to their inherently different immunogenicity, mice were immunized with purified PorA or PorB formed into proteosomes (36) and the levels of anti-PorA and anti-PorB IgG were determined by ELISA. Anti-PorA IgG levels were comparable to anti-PorB IgG levels in sera from the two strains of mice, C3H/HeJ and C3H/HeOuJ, when they were immunized with purified PorA or PorB (Table 3). However, the anti-PorA and anti-PorB IgG levels in sera from C3H/HeOuJ mice immunized with either porin were about 10-fold higher than in sera from C3H/HeJ mice. These levels were about twofold higher than the maxi-

mum IgG concentrations achieved against PorB in C3H/HeOuJ mice immunized with 2×10^7 CFU of live cultures of the wild-type bacterial strain per dose. To determine if anti-LPS IgG, which could have been generated against any trace amounts of LPS contaminating the porin preparations, was induced, an ELISA against purified LPS was carried out. No anti-LPS IgG antibodies were detected in sera from either of the two mice strains immunized with either of the purified porins (data not shown).

Immunostimulatory activity of OMCs from strain H44/76 and its isogenic LPS-negative mutant. PorB from *N. meningitidis* is known to have immunostimulatory activity. PorB can activate B cells and induce the surface expression of the co-stimulatory B7-2 molecules (38). This effect is related to the porins' adjuvanticity in conjugate vaccines (22). In order to determine if the presence of LPS can modulate this function of PorB, purified splenic naïve B cells were incubated in vitro with OMCs prepared from either of the bacterial strains (wild-type H44/76 and its LPS-negative mutant). The level of expression of B7-2 cell surface molecules was determined in B cells isolated from the LPS-responsive mice strain C3H/HeOuJ. In parallel, B cells prepared from the LPS-hyporesponsive C3H/HeJ mice were also studied. The B cells, after stimulation, were also probed for the presence of another costimulatory cell surface molecule, B7-1. The expression of B7-2 on B cells from

TABLE 3. Anti-PorA and anti-PorB responses (in μg of IgG/ml) generated against purified PorA and PorB in LPS-responsive C3H/HeOuJ mice and LPS-unresponsive C3H/HeJ mice^a

Mouse type and day of testing	Results ($\pm$ SD) for PBS or porin treatment		
	PBS	PorA	PorB
C3H/HeJ			
28	BDL	11.6 ± 7.27	14.15 ± 13.85
35	BDL	10.14 ± 6.38	18.07 ± 15.73
42	BDL	9.9 ± 3.7	17.02 ± 14.79
C3H/HeOuJ			
28	BDL	72.03 ± 49.02	62.67 ± 35.26
35	BDL	114.21 ± 70.68	196 ± 82.23
42	BDL	130.62 ± 56.47	109.2 ± 35.86

^a BDL, below detectable limit. Mice ($n = 4$ per group) were immunized on days 0 and 21. For immunizations $10 \mu\text{g}$ of purified porins (in the form of proteosomes)/ml was used.

FIG. 1. In vitro stimulation of naïve B cells from C3H/HeOuJ mice and C3H/HeJ mice. B cells were incubated for 24 h with OMCs from wild-type strain H44/76 (dotted line) and its LPS⁻ mutant (solid line), and B7-1 and B7-2 surface expression was compared with results from medium-incubated cells (filled histogram). (A) Analysis of inducible expression of costimulatory cell surface molecule B7-2. (B) Analysis of the level of expression of the B7-1 cell surface molecule. Both analyses were performed by flow cytometry.

C3H/HeJ mice was induced to similar extents by incubation with OMCs prepared from either bacterial strain (Fig. 1A). However, B7-2 on B cells from C3H/HeOuJ mice was induced to slightly higher levels by OMCs from the wild-type strain H44/76 than by OMCs from the LPS⁻ mutant strain (Fig. 1A). The levels of B7-1 cell surface marker, however, did not show a significant difference after stimulation with OMCs from the two bacterial strains in B cells isolated from either murine strain (Fig. 1B). These results are consistent with previous data presented after use of purified porins (38), which was repeated as control for this study. The surface expression of B7-2 on B cells from either strain of mice, stimulated with 10 μ g of purified PorB protein/ml in the form of proteosomes, was elevated to a level similar to that obtained after stimulation with OMCs prepared from the two bacterial strains. Purified PorA (10 μ g/ml) did not induce B7-2 surface expression to the levels induced by PorB in B cells isolated from mice belonging to either of the two murine strains. Levels of expression of B7-1 cell surface marker on B cells isolated from the two murine strains remained unchanged upon stimulation by either PorA or PorB (data not shown).

DISCUSSION

The purpose of this study was to examine the immunogenicity of PorA and PorB meningococcal porins in conjunction with LPS in order to evaluate their potential as vaccine candidates and to determine the necessity of LPS for the induction of antiporin immune responses. Both the porins and LPS have been investigated individually as plausible antineisserial vaccine candidates in the past (5, 25, 32, 37, 38). Results from the current study revealed that the presence of LPS in conjunction with PorB on the bacterial cell surface affects the anti-PorB humoral immune response mounted by mice. However, it is important to note that the presence of LPS is not essential for evoking an anti-Por response, as demonstrated by the elevated levels of anti-PorB IgG in mice immunized with the LPS-negative mutant (>3 μ g/ml) (Table 2). This is consistent with the initial observation made in *Salmonella enterica* serovar Typhosa regarding the ability of LPS to function as an adjuvant (16). An immunomodulatory role of LPS on the anti-PorA humoral response evoked by OMCs from *N. meningitidis* was observed by Steeghs et al. (29), especially with regard to the

generation of bactericidal anti-PorA antibodies. However, they did not investigate the anti-PorB response, accounting for their conclusion that LPS is essential for an antiporin humoral response, which we have demonstrated is not necessarily the case.

Interestingly, the anti-PorB response observed in this study is much higher than the anti-PorA response in sera from mice immunized with whole bacteria, which is a pattern similar to that observed in patients with meningococcal disease (14, 15, 17). On the other hand, the anti-PorA and anti-PorB IgG levels obtained in mice immunized with purified porins were very similar. These results could be explained by the presence of higher amounts of PorB than of PorA on the bacterial cell surface (26) and/or by PorB's possible immunodominance over PorA when the two proteins are present together on intact meningococci. However, when outer membrane vesicle vaccines are used, the immunogenicity of PorA has been shown to be much greater than that of PorB (33, 34), possibly due to an alteration in the structure of PorB during the synthesis of the outer membrane vesicle vaccine, diminishing its immunogenicity.

The augmentation of the antiporin immune response by LPS appears not to be due to an alteration in the stoichiometric presentation of the porins. This was demonstrated by the following findings: (i) anti-PorB IgG levels induced by either the wild-type or LPS-negative meningococcal strain were similar in the LPS hyporesponsive C3H/HeJ mice, and (ii) the anti-PorB IgG levels induced by the wild-type H44/76 strain were 10-fold higher in LPS-responsive C3H/HeOuJ mice's sera than in sera from the LPS-hyporesponsive mice. The effect on immune response due to an altered structure of PorB discussed in point ii can be ruled out because the observed IgG concentrations against the LPS-positive strain are similar to those against the LPS⁻ mutant in mice that do not respond to LPS.

In the present study we also demonstrate that the expression of B7-2 on the surface of B cells stimulated by PorB does not require the presence of LPS (Fig. 1). Stimulation of B cells isolated from either C3H/HeJ or C3H/HeOuJ mice with OMC preparations from either of the two bacterial strains induces similar levels of B7-2 expression. Inducible B7-2 levels are slightly higher in C3H/HeOuJ B cells incubated with OMCs from the wild-type bacterial strain. This result is consistent with a previously reported observation (38) that PorB by itself is able to induce the expression of costimulatory B7-2 molecules in B cells isolated from either the C3H/HeJ or the C3H/HeOuJ mice. Also, this induction of B7-2 molecules by PorB in B cells from either murine strain is not significantly affected by the presence of trace amounts of LPS. Here we observe that the presence of LPS in amounts that naturally coexist with PorB on bacterial cell surfaces does not modulate the immunopotentiating effect of PorB (as deduced from the expression of similar levels of B7-2 on B cells isolated from either murine strain when incubated with OMCs prepared from the two bacterial strains).

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REFERENCES

- Andersson, J., O. S. Sjöberg, and G. Mollen. 1972. Induction of immunoglobulin and antibody synthesis in vitro by lipopolysaccharides. *Eur. J. Immunol.* 2:349.
- Benz, R. 1994. Permeation of hydrophilic solutes through mitochondrial outer membranes: review on mitochondrial porins. *Biochim. Biophys. Acta* 1197:167-196.
- Bjune, G., E. A. Hoiby, J. K. Gronnesby, O. Arnesen, J. H. Fredriksen, A. Halstensen, E. Holten, A.-K. Lindbak, H. Nøkleby, E. Rosenquist, L. K. Solberg, O. Closs, J. Eng, L. O. Froholm, A. Lystad, L. S. Bakkevig, and B. Hareide. 1991. Effect of outer membrane vesicle vaccine against group B meningococcal disease in Norway. *Lancet* 338:1093-1096.
- Blake, M. S., and E. C. Gotschlich. 1986. Functional and immunological properties of pathogenic neisserial surface proteins, p. 377-400. In M. Inouye (ed.), *Bacterial outer membranes as model systems*. John Wiley & Sons, Inc., New York, N.Y.
- Blake, M. S., and L. M. Wetzler. 1995. Vaccines for gonorrhea: where are we on the curve? *Trends Microbiol.* 3:469-474.
- Centers for Disease Control and Prevention. 1999. Summary of notifiable diseases, United States, 1998. *Morb. Mortal. Wkly. Rep.* 47:ii-92.
- Coligan, J. E., A. M. Kruisbeek, D. H. Margulies, E. M. Shevach, and W. Strober (ed.). 1994. *Current protocols in immunology*, p. 5.0.1-5.8.8. John Wiley & Sons, Inc., New York, N.Y.
- Diaz, R. J., and I. M. Outschorn. 1994. Current status of meningococcal group B vaccine candidates: capsular or noncapsular? *Clin. Microbiol. Rev.* 7:559-575.
- Donnelly, J. J., R. R. Deck, and M. A. Liu. 1990. Immunogenicity of a *Haemophilus influenzae* polysaccharide-*Neisseria meningitidis* outer membrane protein vaccine. *J. Immunol.* 145:3071-3079.
- Finne, J., M. Leinonen, and P. H. Makela. 1983. Antigenic similarities between brain components and bacteria causing meningitis. Implications for vaccine development and pathogenesis. *Lancet* ii:355-357.
- Fusco, P. C., F. Michon, M. Laude-Sharp, C. A. Minetti, C. H. Huang, I. Heron, and M. S. Blake. 1998. Preclinical studies on a recombinant group B meningococcal porin as a carrier for a novel *Haemophilus influenzae* type b conjugate vaccine. *Vaccine* 16:1842-1849.
- Fusco, P. C., F. Michon, J. Y. Tai, and M. S. Blake. 1997. Preclinical evaluation of a novel group B meningococcal conjugate vaccine that elicits bactericidal activity in both mice and nonhuman primates. *J. Infect. Dis.* 175:364-372.
- Griffiss, J. M., R. Yamasaki, M. Estabrook, and J. J. Kim. 1991. Meningococcal molecular mimicry and the search for an ideal vaccine. *Trans. R. Soc. Trop. Med. Hyg.* 85(Suppl. 1):32-36.
- Guttormsen, H. K., L. M. Wetzler, and A. Naess. 1993. Humoral immune response to the class 3 outer membrane protein during the course of meningococcal disease. *Infect. Immun.* 61:4734-4742.
- Guttormsen, H. K., L. M. Wetzler, and C. O. Solberg. 1994. Humoral immune response to class 1 outer membrane protein during the course of meningococcal disease. *Infect. Immun.* 62:1437-1443.
- Johnson, A. G., G. Gaines, and M. Landy. 1956. Studies on the O antigen of *Salmonella typhosa*: V. Enhancement of antibody response to protein antigen by the purified lipopolysaccharide. *J. Exp. Med.* 103:225-230.
- Lehmann, A. K., A. Halstensen, I. S. Aaberge, J. Holst, T. E. Michaelsen, S. Sornes, L. M. Wetzler, and H. Guttormsen. 1999. Human opsonins induced during meningococcal disease recognize outer membrane proteins PorA and PorB. *Infect. Immun.* 67:2552-2560.
- Lepow, M. L., J. Beeler, M. Randolph, J. S. Samuelson, and W. A. Hankins. 1986. Reactogenicity and immunogenicity of a quadrivalent combined meningococcal polysaccharide vaccine in children. *J. Infect. Dis.* 154:1033-1036.
- Lowell, G. H. 1990. Proteosomes, hydrophobic anchors, iscoms, and liposomes for improved presentation of peptides and protein vaccines, p. 141-160. In G. C. Woodrow and M. M. Levine (ed.), *New generation vaccines*. Marcel Dekker, Inc., New York, N.Y.
- Lowell, G. H., W. R. Ballou, L. F. Smith, R. A. Wirtz, W. D. Zollinger, and W. T. Hockmeyer. 1988. Proteosome-lipopeptide vaccines: enhancement of immunogenicity for malaria CS peptides. *Science* 240:800-802.
- Lowell, G. H., L. F. Smith, R. C. Seid, and W. D. Zollinger. 1988. Peptides bound to proteosomes via hydrophobic feet become highly immunogenic without adjuvant. *J. Exp. Med.* 167:658-663.
- Mackinnon, F. G., Y. Ho, M. S. Blake, F. Michon, A. Chandraker, M. H. Sayegh, and L. M. Wetzler. 1999. The role of B/T costimulatory signals in the immunopotentiating activity of neisserial porin. *J. Infect. Dis.* 180:755-761.
- Morse, S. A., S. Stein, and J. Hines. 1974. Glucose metabolism in *Neisseria gonorrhoeae*. *J. Bacteriol.* 120:707-714.
- Poltorak, A., X. He, I. Smirnova, M. Y. Liu, C. V. Huffel, X. Du, D. Birdwell, E. Alejos, M. Silva, C. Galanos, M. Freudenberg, P. Ricciardi-Castagnoli, B. Layton, and B. Beutler. 1998. Defective LPS signaling in C3H/HeJ and

- C57BL/10ScCr mice: mutations in Tlr4 gene. *Science* **282**:2085–2088.
25. Poolman, J. T. 1995. Development of a meningococcal vaccine. *Infect. Agents Dis.* **4**:13–28.
 26. Poolman, J. T., and H. C. Zanen. 1980. Detection of antibody activity in human sera against meningococcal cell wall antigens using a gel-immunoradio-assay (GIRA). *FEMS Microbiol. Lett.* **7**:293–296.
 27. Scholten, R. J., H. A. Bijlmer, J. T. Poolman, B. Kuipers, D. A. Caugant, L. Van Alphen, J. Dankert, and H. A. Valkenburg. 1993. Meningococcal disease in The Netherlands, 1958–1990: a steady increase in the incidence since 1982 partially caused by new serotypes and subtypes of *Neisseria meningitidis*. *Clin. Infect. Dis.* **16**:237–246.
 28. Steeghs, L., R. den Hartog, A. den Boer, B. Zomer, P. Roholl, and P. van der Ley. 1998. Meningitis bacterium is viable without endotoxin. *Nature* **392**:449–450.
 29. Steeghs, L., B. Kuipers, H. J. Hamstra, G. Kersten, L. Van Alphen, and P. van der Ley. 1999. Immunogenicity of outer membrane proteins in a lipopolysaccharide-deficient mutant of *Neisseria meningitidis*: influence of adjuvants on the immune response. *Infect. Immun.* **67**:4988–4993.
 30. Tsai, C. M., and C. E. Frasch. 1982. A sensitive silver stain for detecting lipopolysaccharides in polyacrylamide gels. *Anal. Biochem.* **119**:115–119.
 31. van der Ley, P., J. E. Heckels, M. Virji, P. Hoogerhout, and J. T. Poolman. 1991. Topology of outer membrane porins in pathogenic *Neisseria* spp. *Infect. Immun.* **59**:2963–2971.
 32. Verheul, A. F., H. Snippe, and J. T. Poolman. 1993. Meningococcal lipopolysaccharides: virulence factor and potential vaccine component. *Microbiol. Rev.* **57**:34–49.
 33. Wedge, E., and L. O. Froholm. 1986. Human antibody response to a group B serotype 2a meningococcal vaccine determined by immunoblotting. *Infect. Immun.* **51**:571–578.
 34. Wedge, E., E. A. Hoiby, E. Rosenqvist, and G. Bjune. 1998. Immune responses against major outer membrane antigens of *Neisseria meningitidis* in vaccinees and controls who contracted meningococcal disease during the Norwegian serogroup B protection trial. *Infect. Immun.* **66**:3223–3231.
 35. Wetzler, L. M. 1994. Immunopotentiating ability of neisserial major outer membrane proteins. Use as an adjuvant for poorly immunogenic substances and potential use in vaccines. *Ann. N. Y. Acad. Sci.* **730**:367–370.
 36. Wetzler, L. M., M. S. Blake, K. Barry, and E. C. Gotschlich. 1992. Gonococcal porin vaccine evaluation: comparison of Por proteosomes, liposomes and blebs isolated from *rmp* deletion mutants. *J. Infect. Dis.* **166**:551–555.
 37. Wetzler, L. M., M. S. Blake, and E. C. Gotschlich. 1988. Characterization and specificity of antibodies to protein I of *Neisseria gonorrhoeae* produced by injection with various protein I-adjuvant preparations. *J. Exp. Med.* **168**:1883–1897.
 38. Wetzler, L. M., Y. Ho, and H. Reiser. 1996. Neisserial porins induce B lymphocytes to express costimulatory B7–2 molecules and to proliferate. *J. Exp. Med.* **183**:1151–1159.
 39. Zollinger, W. D. 1990. New and improved vaccines against meningococcal disease, p. 325–348. *In* G. C. Woodrow and M. M. Levine (ed.), *New generation vaccines*. Marcel Dekker, Inc., New York, N.Y.

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