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MD-2 Residues Tyrosine 42, Arginine 69, Aspartic Acid 122, and Leucine 125 Provide Species Specificity for Lipid IVₐ

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Lipopolysaccharide (LPS) activates the innate immune response through the Toll-like receptor 4 (TLR4)/MD-2 complex. A synthetic lipid A precursor, lipid IVₐ, induces an innate immune response in mice but not in humans. Both TLR4 and MD-2 are required for the agonist activity of lipid IVₐ in mice, with TLR4 interacting through specific surface charges at the dimerization interface. In this study, we used site-directed mutagenesis to identify the MD-2 residues that determine lipid IVₐ species specificity. A single mutation of murine MD-2 at the dimerization interface near the pocket entrance, E122K, substantially reduced the response to lipid IVₐ. Combining the murine MD-2 E122K with the murine TLR4 K367E/S386K/R434Q mutations completely abolished the response to lipid IVₐ, effectively converting the murine cellular response to a human-like response. In human cells, however, simultaneous mutations of K122E, K125L, Y41F, and R69G on human MD-2 were required to promote a response to lipid IVₐ. Combining the human MD-2 quadruple mutations with the human TLR4 E369K/Q436R mutations completely converted the human MD-2/human TLR4 receptor to a murine-like receptor. Because MD-2 residues 122 and 125 reside at the dimerization interface near the pocket entrance, surface charge differences here directly affect receptor dimerization. In comparison, residues 42 and 69 reside at the MD-2/TLR4 interaction surface opposite the dimerization interface. Surface charge differences there likely affect the binding angle and/or rigidity between MD-2 and TLR4, exerting an indirect influence on receptor dimerization and activation. Thus, surface charge differences at the two MD-2/TLR4 interfaces determine the species-specific activation of lipid IVₐ.

Lipopolysaccharide (LPS), also known as endotoxin, activates the innate immune response during Gram-negative bacterial infection. Lipid A, the active component of LPS, anchors LPS to the outer leaflet of the outer membrane of Gram-negative bacteria. When bacteria divide or die, LPS released into local tissue or the circulation can trigger innate immune recognition (1). Lipid A from most species is highly proinflammatory, although certain lipid A molecules and precursors lack stimulatory power. The synthetic precursor of Escherichia coli lipid A, tetraacylated lipid IVₐ (2) (compound 406), is an agonist in murine cells and a partial agonist in equine cells but is an antagonist in human cells (3).

The Toll-like receptor 4 (TLR4)² and MD-2 complex constitute the essential components of a receptor system for LPS (4, 5). CD14, initially believed to be the LPS receptor, is an enhancing component of the LPS receptor (6). The lack of a transmembrane or an intracellular signaling domain led to speculation about an additional LPS receptor component that actually transduces the LPS signal. TLR4 was identified as the signaling component of the LPS receptor, based on positional cloning in mice that fail to respond to LPS (4, 7) and on the finding that TLR4 knockout cells did not respond to LPS (8). The co-receptor MD-2 is essential for LPS recognition (5), and a single MD-2 point mutation that replaces cysteine 95 with tyrosine (C95Y) completely abolishes LPS responsiveness (9). MD-2 knockout mice, like TLR4 knockout, do not respond to LPS (10). A deficiency in either TLR4 or MD-2 abrogates LPS signaling, whereas a deficiency in CD14 leads to a 100–1000-fold decrease in LPS sensitivity for most proinflammatory genes (e.g. TNF-α and IL1β) and the apparent abolishment of response for others (e.g. IP-10) (11) but does not abolish LPS signaling. The loss of CD14 therefore differs from the loss of TLR4 or MD-2 in that the presence of CD14 sensitizes cells to the presence of LPS whereas TLR4 or MD-2 are absolutely required for LPS responses.

The co-crystal structure of the human TLR4-MD-2-LPS complex revealed that LPS binds to MD-2 through the LPS acyl chains and the MD-2 hydrophobic pocket (12). Five of the six acyl chains are buried inside the hydrophobic pocket. The sixth lies on the surface above the hydrophobic pocket and, along with the MD-2 Phe-126 and Met-85 loops, interacts with the hydrophobic residues on the C-terminal β-strands (β18 – β21) of TLR4 to mediate dimer-dimer assembly of two LPS-ligated TLR4-MD-2 complexes (note: to facilitate an understanding of the data shown in this report, the TLR4, MD-2, LPS molecules in the second TLR4-MD-2-LPS complex will be labeled as TLR4’, MD-2’, LPS’). Hydrogen bonds and ionic interactions are found at the dimerization interface between TLR4, MD-2, and LPS in the co-crystal structure. Surprisingly, the LPS core polysaccharide, which is not required to induce a proinflammatory response, also interacts extensively with TLR4 in the co-crystal structure. Studies with site-directed mutagenesis con-

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² The abbreviations used are: TLR4, Toll-like receptor 4; h, human; m, mouse; PDB, Protein Data Bank.
firmed that Phe-126 on human MD-2 (hMD-2) is essential for receptor dimerization (13) and demonstrated that hydrophobic residues on hMD-2 and human TLR4 (hTLR4) are required for receptor activation (14).

We previously demonstrated that ionic interactions at the dimerization interface play an essential role in lipid IV<sub>α</sub> activation (15). Mouse TLR4 (mTLR4) is required for the species-specific activation of lipid IV<sub>α</sub> because, in the presence of mouse MD-2 (mMD-2), one phosphate on lipid IV<sub>α</sub> can interact with a positively charged patch on the opposing mTLR4 (at the dimerization interface) to trigger dimerization. This positively charged patch on mTLR4 is replaced with a negatively charged patch on hTLR4, with the result that human TLR4 does not respond to lipid IV<sub>α</sub> (15).

In this study, we used site-directed mutagenesis to swap surface charges between human and mouse MD-2 to identify residues on MD-2 that account for lipid IV<sub>α</sub> species specificity. We produced five mutations in both murine and human MD-2 at residues 42, 69, 58, 122, and 125 designed to swap surface charges between the two species. We then tested whether these charge changes interconverted the human and mouse phenotypic responses to lipid IV<sub>α</sub>. We found that the E122K mutation was sufficient to abrogate the lipid IV<sub>α</sub> response by murine MD-2 but that the K122E mutation alone was not sufficient to induce a response by human MD-2; simultaneous mutations of K125L, R69G, and Y42F also were required for an hMD-2 response. Furthermore, when the hMD-2 quadruple mutant was introduced to HEK293 cells with the hTLR4 E369K/Q436R double mutant, a full lipid IV<sub>α</sub> response was observed, indicating that the hTLR4-hMD-2 receptor has been converted to a mouse phenotype after these mutations. Conversely, lipid IV<sub>α</sub> inhibited LPS responses when the mMD-2 E122K mutant was introduced to HEK293 cells with the mTLR4 YFP constructs (K367E/S386K/R434Q or K367E/R434Q), or a WT control; (ii) one of the hMD-2 or mMD-2 mutants; (iii) an NF-κB-luciferase plasmid (17); and (iv) the Renilla-luciferase plasmid. The next day, the medium was changed to fresh complete DMEM without serum, and cells were stimulated with the indicated concentrations of LPS/lipid IV<sub>α</sub>. After overnight stimulation, the supernatants were removed, and firefly-luciferase activity was measured in cell lysates. Renilla-luciferase was used for normalization.

For inhibition assays in HEK293 cells, HEK293 cells were plated as described above and transfected with: (i) one of the mMD-2 mutants (E122K or F42Y/G69R/E122K/L125K) or a WT control; (ii) one of the mTLR4 mutants (K367E/R434Q or K367E/S386K/R434Q) or a WT control; (iii) an NF-κB-luciferase reporter construct; and (iv) a Renilla-luciferase reporter construct. The next day, 1000 ng/ml lipid IV<sub>α</sub> was added to selected wells, and after 1 h of incubation, 100 ng/ml LPS was added to the experimental wells. After overnight stimulation, NF-κB-luciferase was measured in cell lysates as described above. Renilla-luciferase was used to normalize NF-κB-luciferase.

RESULTS

Human and Mouse MD-2 Have Different Surface Charges Near the Entrance of the Hydrophobic Pockets—According to our previous model of dimeric mTLR4/mMD-2/lipid IV<sub>α</sub> (Fig. 1) (15), lipid IV<sub>α</sub> packs shallowly in the mMD-2 hydrophobic pocket with the diglucosamine backbone tilted toward the Cys-95–Cys-105 loop opposite the dimerization interface (12, 15). This position lifts the 4′-phosphate of lipid IV<sub>α</sub> up from the hydrophobic pocket so that it can interact with the two positively charged residues, Lys-367 and Arg-434, on the opposing mTLR4 (Fig. 1) to trigger dimerization. (Residues on the second
Mutagenesis Studies Define Species Specificity of MD-2

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TLR4/MD-2/lipid IVₐ complex are labeled with "•" to differentiate from those of the first TLR4/MD-2/lipid IVₐ complex. Hydrophobic interactions, hydrogen bonds, and ionic interactions are indicated by dashed lines and labeled in blue as H8, HB, and IL, respectively. The fourth acyl chain of lipid IVₐ is labeled as L4. Color scheme: mMD-2, blue ribbon; lipid IVₐ, yellow sticks; mTLR4, blue-white ribbon. Residues on mTLR4 a colored in red or magenta and labeled; residues on mMD-2 are colored in green and labeled. The electrostatic surface charges were calculated for hMD-2 and mMD-2 in MoleMol (21), b, surface charges near the hydrophobic pocket entrance of hMD-2 (left) and mMD-2 (right). Color scheme: negatively charged surface, red; positively charged surface, blue; and noncharged surface, white. Surfaces that differ between hMD-2 and mMD-2 are circled in yellow and labeled. Selective surfaces that are common between hMD-2 and mMD-2 are labeled in gray.

FIGURE 2. Electrostatic surface charges are different between hMD-2 and mMD-2 near the hydrophobic pocket entrance. a, zoomed-in view of the dimerization interface of the mTLR4/mMD-2/lipid IVₐ model. Molecules and residues from the second TLR4/MD-2/lipid IVₐ complex are labeled with "•" to differentiate from those of the first TLR4/MD-2/lipid IVₐ complex. Hydrophobic interactions, hydrogen bonds, and ionic interactions are indicated by dashed lines and labeled in blue as HI, HB, and IL respectively. The fourth acyl chain of lipid IVₐ is labeled as L4. Color scheme: mMD-2, blue ribbon; lipid IVₐ, yellow sticks; mTLR4, blue-white ribbon. Residues on mTLR4 a colored in red or magenta and labeled; residues on mMD-2 are colored in green and labeled. The electrostatic surface charges were calculated for hMD-2 and mMD-2 in MoleMol (21), b, surface charges near the hydrophobic pocket entrance of hMD-2 (left) and mMD-2 (right). Color scheme: negatively charged surface, red; positively charged surface, blue; and noncharged surface, white. Surfaces that differ between hMD-2 and mMD-2 are circled in yellow and labeled. Selective surfaces that are common between hMD-2 and mMD-2 are labeled in gray.

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Mutagenesis Studies Define Species Specificity of MD-2

Mutations K122E and K125L Increased the Human MD-2 Response to Lipid IVₐ—We next examined whether E122K was sufficient to convert hMD-2-mTLR4 from a lipid IVₐ nonresponder to a responder. The single mutants K58N and K125L were used as controls, and the effects were measured as described. LPS responsiveness was not significantly affected by these mutations (Fig. 3c), indicating that they did not disrupt the structural motif essential for LPS signaling. In comparison, E122K substantially reduced lipid IVₐ responsiveness (Fig. 3b), indicating that Glu-122 at the pocket entrance is essential for receptor dimerization (13, 14) are conserved between the two species (12). In addition, mMD-2 has the hydrophobic Leu-125 in place of Lys-125 in hMD-2 (Fig. 2a), which likely enhanced hydrophobic interactions between mMD-2 and mTLR4 at the dimerization interface. Similarly, hydrogen bonds between Arg-434’ on mTLR4 and the hydroxyl group on the acyl chain of lipid IVₐ (Fig. 2a) contributed to the stabilization of the mTLR4/mMD-2/lipid IVₐ dimer.

Comparison of the electrostatic surface charges for hMD-2 and mMD-2 (13, 18) revealed differences near the entrance of the hydrophobic pockets (Fig. 2b). Human MD-2 has positively charged Arg-90 and Lys-122 at the hydrophobic pocket entrance, whereas mMD-2 has positively charged Arg-90 but negatively charged Glu-122 at the pocket entrance. Human MD-2 has positively charged Lys-125 at the dimerization interface close to the pocket entrance, whereas mMD-2 has hydrophobic Leu-125 at this position. A little further away from the pocket entrance, hMD-2 has positively charged Lys-58 on the β4 strand that has been implicated in lipid IVₐ discrimination (19), whereas mMD-2 has negatively charged Asn-58 at this position. Because the acyl chains of LPS bind to the hydrophobic pocket, and the diglucosamine backbone of LPS sits next to the pocket entrance (12, 13), modifications of MD-2 surface charges at residues 122, 125, and 58 likely affect lipid binding and directly influence lipid IVₐ species specificity.

E122K Mutation on mMD-2 Nearly Eliminated Lipid IVₐ Responsiveness—To determine whether any of these surface charge differences alter the response to lipid IVₐ, we engineered MD-2 mutants that swapped surface charges between the human and murine analogs. The effects of these mutations were measured with the luciferase assay.

N58K, E122K and L125K mutants were created by site-directed mutagenesis from WT mMD-2 expressed in the pEFOB vector. These single substitutions from the native mouse residues to their human counterparts did not affect LPS signaling (Fig. 3a), suggesting that these mutations did not disrupt the structural motif essential for LPS signaling. In comparison, E122K substantially reduced lipid IVₐ responsiveness (Fig. 3b), indicating that Glu-122 at the pocket entrance is essential for mMD-2 to respond to lipid IVₐ.

Human and Murine MD-2 Have Different Surface Charges at the A Patch That Physically Associates with TLR4 in the Monomeric MD-2-TLR4 Complex—In the absence of ligand, MD-2 forms a high-affinity complex with TLR4 through interactions.
Mutagenesis Studies Define Species Specificity of MD-2

FIGURE 3. Glu-122 and Leu-125 on mMD-2 are essential for lipid IVα responsiveness. HD293 cells were transiently transfected with: (i) one of hMD-2 (a and b) or mMD-2 (c and d) single mutants near the hydrophobic pocket entrance; (ii) mTLR4 WT construct; (iii) a NF-κB luciferase reporter construct; and (iv) a Renilla-luciferase reporter construct. The next day, cells were stimulated with 1000 ng/ml, 100 ng/ml, 10 ng/ml, or 0 ng/ml LPS (a and c) or lipid IVα (b and d) overnight. Supernatants were then removed, and NF-κB-luciferase was measured in cell lysates. The luciferase shown has been normalized by Renilla-luciferase. The data shown are representative of one experiment that was repeated a total of four times.

at the A and B patches (Figs. 1 and 4, a and b) (12, 13). The A patch had more interactions in the human complex (Fig. 4a), whereas the B patch had more interactions in the mouse complex (Fig. 4b). Because a stable TLR4:MD-2 complex is still observed in the absence of intact B patch interactions (13), the A patch interactions between MD-2 and TLR4 likely play a dominant role in the formation of TLR4:MD-2 complex. Surface features at the B patch were quite similar between human and mouse MD-2 (supplemental Fig. 1a) and between human and mouse TLR4 (supplemental Fig. 1b). It is likely that the differences are a secondary effect of different A patch interactions between the two species.

A delicate interaction network was observed at the A patch of both the human (Fig. 4c) and mouse (Fig. 4d) TLR4:MD-2 complexes in the co-crystal structures (PDB codes 3FXI and 2Z64) (12, 13). Positive residues Arg-68 and Lys-109, which are conserved between hMD-2 and mMD-2, were involved in extensive hydrogen bonds and ionic interactions with neighboring TLR4 residues at the A patch of the human and mouse complexes (Fig. 4, c and d). An extra hydrogen bond was found in the human complex between the hydroxyl group of Tyr-42 on hMD-2 and the carboxyl oxygen of Phe-42 on hTLR4 (Fig. 4c). This hydrogen bond was absent in the mouse complex because mMD-2 has Phe-42 that lacks the hydroxyl group on the aromatic ring (Fig. 4d). Because Tyr-42 resides on the β3 strand of MD-2 (Fig. 4a), this extra hydrogen bond between hMD-2 and hTLR4 likely helps to orient the overall conformation of the human complex. For example, it may modify the tilt angle and/or rigidity between hMD-2 and hTLR4 to disfavor dimerization so that extra forces are required to trigger dimerization.

Human and murine MD-2 also differ in electrostatic surface charges at the A patch (Fig. 4e). Aside from positively charged Arg-68 and Lys-109 present in both species, the hMD-2 surface also contains positively charged Arg-69 and the amino group of Tyr-42. In mMD-2, Arg-69 is replaced with the noncharged Gly-69, and Tyr-42 is replaced with the more hydrophobic Phe-42, whose amino group does not lie on the surface. Thus, hMD-2 is more positively charged than mMD-2 at the A patch. Consistently, hTLR4 is more negatively charged at the A patch than mTLR4 (supplemental Fig. 1c). Because A patch interactions between MD-2 and TLR4 are mainly ionic (Fig. 4, c and d), the increased positive charges on hMD-2 likely result in a hMD-2:hTLR4 complex that is more tightly bound at the A patch. Thus, a major difference between hMD-2 and mMD-2 at the A patch arises from two residues, 69 and 42, which permit additional interactions within the human MD-2:TLR4 complex that may affect binding angle and/or rigidity between hMD-2 and hTLR4 to disfavor dimerization in the absence of strong agonists such as E. coli LPS.

Mutations R69G and Y42F Increased Human MD-2 Response to Lipid IVα.—To determine whether residues 69 and 42 play a role in lipid IVα discrimination, we swapped charges at these residues between hMD-2 and mMD-2 and measured the effects on LPS/lipid IVα stimulation as described. Although the F42Y and G69R mutations on mMD-2 did not affect LPS (Fig. 5a) or lipid IVα signaling (Fig. 5b), the reverse mutations (R69G and Y42F) on hMD-2 substantially increased lipid IVα responsiveness (Fig. 5d), indicating that additional interactions at the A patch resulting from Tyr-42 and Arg-69 impaired lipid IVα responsiveness. Thus, lipid IVα activation of MD-2 is influenced by interactions at both the dimerization interface and the opposite A patch, which physically associates MD-2 with TLR4.

Mutations of Y42F, R69G, K122E, and K125L, in Combination, Converted the Human MD-2 Nonresponse to Lipid IVα to the Full Mouse-like Response.—To examine whether mutations at the dimerization interface and the A patch have a cumulative effect on lipid IVα signaling, we engineered hMD-2 double mutants that contain pairwise combinations of the five mutations. All mutants retained their ability to respond to LPS (supplemental Fig. 2a), indicating that the structural motifs essential for LPS responsiveness are intact in these mutants. However, the magnitudes of the responses were different: hMD-2 responded to lipid IVα with double mutants containing either K122E or R69G, but the response was higher in the double mutant R69G/K122E (supplemental Fig. 2b). This confirms that although Y42F and K125L play a role in responding to lipid IVα, K122E and R69G are required for a complete LPS-mimetic activity of lipid IVα.

High order mutants that contain three or four of the five mutations were further engineered by site-directed mutagenesis. Similar to other hMD-2 mutants, the LPS responsiveness remained similar after these mutations (supplemental Fig. 3a), suggesting that these mutations did not disrupt the structural motif essential for LPS signaling. However, the lipid IVα responses were dependent on the
Mutagenesis Studies Define Species Specificity of MD-2

Lipid IV<sub>A</sub> Activated the Mutant hTLR4 (E369K/Q436R)–hMD-2 (Y42F/R69G/K122E/K125L) Complex—We previously demonstrated that, in the presence of mMD-2, hTLR4 gained lipid IV<sub>A</sub> responsiveness after the E369K/Q436R mutation or the E369K/K388S/Q436R mutation (15). To test whether the combined mutations of hTLR4 and hMD-2 could convert the human LPS receptor into a mouse phenotype, we co-transfected the hMD-2 mutant (Y42F/R69G/K122E/K125L) with one of the hTLR4 mutants (E369K/Q436R or E369K/K388S/Q436R) and measured responsiveness to lipid IV<sub>A</sub> stimulation. Gain of hydrophobic surface from the K125L mutation near the dimerization surface (12) and loss of positive charges at the A patch from the R69G and Y42F mutations also are required to convert the mTLR4–hMD-2 complex from a lipid IV<sub>Α</sub> nonresponder to a lipid IV<sub>Α</sub> responder. Thus, interactions at the dimerization interface and at the A patch that physically associates MD-2 with TLR4 cumulatively determine the role of MD-2 in the species-specific activation of lipid IV<sub>A</sub>.

Two hMD-2 mutants, R69G/K122E and Y42F/R69G/K122E/K125L, were compared directly with the WT hMD-2 construct for responsiveness to LPS (Fig. 6a) or lipid IV<sub>A</sub> (Fig. 6b). As the number of mutations increased, the responsiveness to lipid IV<sub>A</sub> increased. Conversely, when the reverse mutations were introduced to mMD-2 in combination, the lipid IV<sub>A</sub> responsiveness was reduced after the G69R/E122K and F42Y/G69R/E122K/L125K mutations (Fig. 6d), whereas LPS responsiveness remained unchanged (Fig. 6c). (The full list of mMD-2 mutants is shown in Supplemental Figs. 4 and 5.) These results confirm that the four residue differences between hMD-2 and mMD-2, i.e. Tyr-42/Phe-42, Arg-69/Gly-69, Lys-122/Glu-122, and Lys-125/Leu-125, all contribute to lipid IV<sub>A</sub> discrimination.

In summary, by swapping surface charges between hMD-2 and mMD-2, we demonstrated that Glu-122 is required for mMD-2 to respond to lipid IV<sub>A</sub>. Therefore, negative charges conveyed by Glu-122 at the pocket entrance are essential for mMD-2 to respond positively to lipid IV<sub>A</sub> stimulation. However, gain of negative charges at the pocket entrance alone (from the K122E mutation) are not sufficient to confer full response to hMD-2 against lipid IV<sub>A</sub> stimulation. Gain of hydrophobic surface from the K125L mutation near the dimerization surface (12) and loss of positive charges at the A patch from the R69G and Y42F mutations also are required to convert the mTLR4–hMD-2 complex from a lipid IV<sub>A</sub> nonresponder to a lipid IV<sub>A</sub> responder. Thus, interactions at the dimerization interface and at the A patch that physically associates MD-2 with TLR4 cumulatively determine the role of MD-2 in the species-specific activation of lipid IV<sub>A</sub>.

**FIGURE 4.** Electrostatic surface charges are different between hMD-2 and mMD-2 at the A patch that physically associates with TLR4. The monomeric TLR4–MD-2 complexes subtracted from the co-crystal structures (PDB codes 2Z64 and 3FXI) (12, 13) are shown in a and b. The hMD-2/hTLR4 interfaces (a) and mMD-2/mTLR4 interfaces (b) are colored in green, and the hMD-2/mTLR4 interfaces (b) are colored in yellow. The A and B patches are circled and labeled as A and B, respectively, in a and b. The β3, β4, and β7 strands on MD-2 are labeled. Zoomed-in views of the A patch interactions are shown in c for the human complex, and d for the mouse complex. Residues involved in MD-2/TLR4 interactions are shown as green sticks in c for the human complex and yellow sticks in d for the mouse complex. Hydrogen bonds and ionic interactions are shown in dashed lines in c and d, with the distances labeled. Color scheme: hTLR4, pink ribbon; hMD-2, brown; mTLR4, white ribbon; mMD-2, blue ribbon. The electrostatic surface charges at the A patch are shown in e. Negatively charged surface, red; positively charged surface, blue; noncharged surface, white. Surfaces that differ between hMD-2 and mMD-2 are circled in yellow, with the residues labeled in black in e. Surfaces that are common between hMD-2 and mMD-2 are labeled in gray in e.
The LPS response in all of the mutant hTLR4/hMD-2 complexes was approximately half of the response of the WT human complex (Fig. 7a), indicating that some surface features essential for an optimal LPS response were lost in the hTLR4/hMD-2 complexes after these mutations were introduced. However, the lipid IVa response in the mutants was high and dose-dependent, unlike the WT hTLR4/hMD-2 complex that did not respond to lipid IVa (Fig. 7b). These results suggest that the charge reversals at the dimerization interface of hTLR4 and the pocket entrance and at the A patch of hMD-2 are sufficient to convert the human LPS receptor response to a mouse phenotype. All four mutations on hMD-2 must be required because use of the hMD-2 double mutant (R69G/K122E) along with the hTLR4 mutant did not restore lipid IVa activity. The next day, supernatants were removed, and NF-κB luciferase activity was measured in cell lysates. The luciferase shown has been normalized by Renilla-luciferase. The data shown are representative of one experiment that was repeated a total of four times.

The LPS response in all of the mutant hTLR4/hMD-2 complexes was approximately half of the response of the WT human complex (Fig. 7a), indicating that some surface features essential for an optimal LPS response were lost in the hTLR4/hMD-2 complexes after these mutations were introduced. However, the lipid IVa response in the mutants was high and dose-dependent, unlike the WT hTLR4/hMD-2 complex that did not respond to lipid IVa (Fig. 7b). These results suggest that the charge reversals at the dimerization interface of hTLR4 and the pocket entrance and at the A patch of hMD-2 are sufficient to convert the human LPS receptor response to a mouse phenotype. All four mutations on hMD-2 must be required because use of the hMD-2 double mutant (R69G/K122E) along with the hTLR4 mutant did not restore lipid IVa response. Thus, the negative surface of hTLR4 at the dimerization interface, and the more positively charged surface on hMD-2 at the pocket entrance and at the A patch, determine the roles of hTLR4 and hMD-2 in the species-specific activation of lipid IVa.

Lipid IVa Inhibited LPS Responses in the Mutant mTLR4 (K367E/S386K/R434Q)/H18528 mMD-2 (E122K) Complex—As described above, by grafting positively charged residues to hTLR4 and negatively charged or noncharged residues to hMD-2, we converted the hTLR4/hMD-2 complex to a murine phenotype. All four mutations on hMD-2 must be required because use of the hMD-2 double mutant (R69G/K122E) along with the hTLR4 mutant did not restore lipid IVa response. Thus, the negative surface of hTLR4 at the dimerization interface, and the more positively charged surface on hMD-2 at the pocket entrance and at the A patch, determine the roles of hTLR4 and hMD-2 in the species-specific activation of lipid IVa.

F24Y/G69R/E122K/L125K) and tested the lipid IVa responsiveness.

LPS activated all combinations of mutant mTLR4/mMD-2 complexes (Fig. 8, black bars), indicating that the four mutant combinations maintained the structural features required for LPS signaling. In contrast, lipid IVa did not activate the mutant mTLR4/mMD-2 complexes (Fig. 8, open bars), indicating that the loss of positive charge at the dimerization interface of mTLR4 and the loss of negative charge at the hydrophobic pocket entrance of mMD-2 prevented the normal murine lipid IVa response. Furthermore, when lipid IVa was incubated with the cells prior to LPS stimulation, lipid IVa blocked LPS signaling (Fig. 8, gray bars). This result suggests that the charge reversals were sufficient to convert the mouse receptor to a human phenotype. Thus, positive charges at the dimerization interface of mTLR4 and negative charges at the pocket entrance of mMD-2 define the roles of mTLR4 and mMD-2 in the species-specific activation of lipid IVa.
DISCUSSION

Lipid IVα is an agonist in rodent cells but an antagonist in human cells (15). Both mTLR4 and mMD-2 are required for the LPS-mimetic activity of lipid IVA (15). The essential role of mTLR4 in lipid IVA activation arises from its unique surface charges at the dimerization interface (15). In this study, we used site-directed mutagenesis to demonstrate that the species specificity of MD-2 recognition of lipid IVA is determined by surface charge differences at two specific areas: residues 122 and 125 near the hydrophobic pocket entrance, and residues 42 and 69 at the A patch opposite the dimerization interface (Fig. 9).

The roles of residues 122 and 125 in lipid IVA activation are easy to understand. Because residue 122 resides at the hydrophobic pocket entrance, its surface charge can directly influence lipid IVA binding. The side chain of Glu-122 (from mMD-2) carries strong negative charges that would repulse the similarly negatively charged phosphate on lipid IVA to raise the $4^{\prime}\$-phosphate (Fig. 2a). This change in orientation would permit ionic interactions between the $4^{\prime}\$-phosphate on lipid IVA and the positively charged patch on mTLR4 to trigger receptor dimerization. When murine Glu-122 was mutated to its human counterpart Lys-122, the positively charged side chain of Lys-122 attracted the negatively charged $4^{\prime}\$-phosphate on lipid IVA, forcing lipid IVA down where it could not interact with the positively charged patch on mTLR4 to trigger dimerization and reducing lipid...
IV$_A$ responsiveness. Because WT hMD-2 naturally has Lys-122 at this position, lipid IV$_A$ does not activate proinflammatory responses when hMD-2 is present. However, gain of negative charges at the entrance of the hMD-2 hydrophobic pocket alone (by K122E mutation) were not sufficient to convert hMD-2 into a mouse phenotype. Loss of positive charges at the dimerization interface (K125L mutation), and at the A patch (R69G and Y41F mutations) (Fig. 9) were also required for a strong proinflammatory responses to lipid IV$_A$.

Leu-125 likely affects lipid IV$_A$ activation through a direct effect on receptor dimerization (Fig. 9). Leu-125 sits on the Phe-126 loop, which is essential for receptor dimerization (13, 14). However, Phe-126 does not directly bridge dimerization in the hTLR4-hMD-2-LPS co-crystal structure (12); it actually folds back toward hMD-2 to accommodate the extra acyl chain of LPS that lies on hMD-2 surface in the co-crystal structure (12). Extensive hydrophobic interactions are observed among the extra acyl chain of LPS, hydrophobic residues on hMD-2 (Phe-126, Ile-124, Leu-87, Met-85, and Val-82), and hydrophobic residues on hTLR4 (Phe-440, Leu-444, and Phe-463) at the dimerization interface. Another interpretation, however, is that hydrophobic residues on MD-2 and TLR4 at the dimerization interface form a hydrophobic pocket to fit in the extra acyl chain of LPS lying on hMD-2 surface. Whether this extra acyl chain simply has a volume effect or actually plays a functional role is not known.

This scenario is changed in the case of lipid IV$_A$ activation by the mTLR4-mMD-2 complex. Although mTLR4 has the same hydrophobic residues (Phe-438’, Leu-442’, and Phe-461’) at the dimerization interface as hTLR4 (Phe-440’, Leu-444’, and Phe-463’) hMD-2 has hydrophobic Leu-125 in place of positively charged Lys-125 on hMD-2, whereas lipid IV$_A$ has four acyl chains instead of six in LPS. Therefore, the hydrophobicity of the mMD-2 Phe-126 loop is increased, but lipid hydrophobicity is decreased. Leu-125 can coordinate with Phe-126 and Ile-124 on mMD-2 to interact with Met-417’, Phe-438’, Leu-442’, and Phe-461’ on mTLR4 through hydrophobic interactions (Fig. 2a), partially compensating for the reduced hydrophobic interactions due to the loss of two acyl chains in lipid IV$_A$.

The roles of Gly-69 and Phe-41 in lipid IV$_A$ activation are likely to be indirect: these residues reside at the A patch opposite the dimerization interface (Fig. 9) and in the mTLR4-mMD-2 co-crystal structure, neither one is involved directly in the A patch interaction with mTLR4 (Fig. 4d) (13, 15). However, Gly-69 and Phe-41 are next to the two positively charged residues on mMD-2 (Arg-68 and Lys-109) that interact extensively with mTLR4 at the A patch of the mouse complex (Fig. 4d) (13). A similar interaction network was observed between hMD-2 and hTLR4 at the A patch in the hTLR4-hMD-2-LPS co-crystal structure (Fig. 4c) (12). Unlike F41 on mMD-2 that does not participate in the A patch interaction, Tyr-41 on hMD-2 is directly involved in hydrogen bonds with Glu-42 from hTLR4. Arg-69, on the other hand, sits next to Arg-68 on the same loop (Fig. 4c). Because both Arg-69 and Arg-68 are positively charged, the electrorepulsive forces between them will force the two side chains apart, pushing Arg-68 closer to Glu-42 on hTLR4 and freeing room for Tyr-41 on hMD-2 to interact with Glu-42 on hTLR4 through hydrogen bonds. Because Tyr-41 resides on a separate loop connected to the β3 strand instead of the β7 strand containing Arg-68, the gain of a hydrogen bond at this position likely has a global orientation effect on hMD-2 that requires extra forces to trigger receptor dimerization. Because lipid IV$_A$ has only four acyl chains and does not have the core polysaccharide, it cannot activate the LPS receptor in the presence of hMD-2.

In fact, we suspected that the A patch residues on MD-2 would play a role in lipid IV$_A$ discrimination because the relative orientations of hMD-2 and hTLR4 are different in the inhibitor-bound state (13) and the agonist-bound state (12). Prior to publication of the hTLR4-hMD-2-LPS co-crystal structure (PDB code 3FXI), Lee and co-workers had published the co-crystal structure of the TV3-hMD-2-Eritoran complex (PDB code 2Z6S), which has the TLR4-hagfish fusion protein in place of intact ectodomain of hTLR4 (13). Both hMD-2 and the N-terminal 200 residues of hTLR4 are present in both crystal structures. However, when the two co-crystal structures are aligned on those hTLR4 N-terminal residues, the relative orientations of hMD-2 are different (supplemental Fig. 6). The hydrophobic pocket of MD-2 is tilted 6.7 Å (8.5°) farther away from TLR4 in inhibitor-bound TV3-hMD-2-Eritoran than it is in agonist-bound hTLR4-hMD-2-LPS. It is likely that LPS binding triggered a global orientation event between hMD-2 and hTLR4 to facilitate receptor dimerization, due to the strong hydrophobic interactions at the dimerization interface from the extra acyl chain. Although we cannot exclude the possibility that the different tilt angles between the two crystal structures merely result from the replacement of hTLR4 with TV3 in the inhibitor-bound state, the observation that charge mutation of the MD-2 A patch affects lipid IV$_A$ activation strongly argues against this possibility.

Lipid IV$_A$ is a partial agonist in equine cells (19). However, similar to human MD-2, equine MD-2 has the positively charged Arg-122 at the hydrophobic pocket entrance. Therefore, repulsive forces cannot be generated at the pocket entrance between Arg-122 and the lipid IV$_A$ phosphate to lift lipid IV$_A$ up. However, equine MD-2 has Ser-42 instead of murine Phe-42 or human Tyr-42 at the A patch. This substitution from aromatic residue to serine removes not only the hydrogen bond involving the hydroxyl group on Tyr-42 in the human receptor complex, but also any potential hydrophobic interactions with the aromatic ring in both human and mouse receptor. Consequently, the relative binding angle/rigidity between equine MD-2 and equine TLR4 could be substantially different from the other two species. Hence, lipid IV$_A$ functions as a partial agonist in the presence of equine TLR4-MD-2 receptor.

A practical application of our finding here, however, is to extend this knowledge to the understanding of receptor polymorphisms. Species-specific recognition of lipid IV$_A$ by the mouse and human TLR4-MD-2 receptor can be interpreted as two extreme cases of receptor polymorphism resulting in either complete activation or complete inhibition. Charge variation at a single residue can alter the response to lipid IV$_A$ stimulation. Single nucleotide polymorphisms at TLR4 residues 299 and 399 reportedly decrease the proinflammatory response to LPS stimulation (20). Because these residues do not directly affect recep-
Mutagenesis Studies Define Species Specificity of MD-2

tor dimerization (supplemental Fig. 7), these single nucleotide polymorphisms may alter the relative binding angle/rigidity of the TLR4/MD-2 complex so that receptor dimerization is not as easily triggered by LPS cross-linking.

In conclusion, we used site-directed mutagenesis studies to demonstrate that induced changes in the three major forces at the dimerization interface, ionic interactions, hydrogen bonds, and hydrophobic interactions, contribute significantly to receptor function and explain the species specificity of LPS-binding responses. Different lipid A analogs that vary in acyl chain length or composition, or phosphate composition of the diglucosamine backbone, likely have different balances among the stabilizing forces at the dimerization interface that affect receptor dimerization and activation.

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MD-2 Residues Tyrosine 42, Arginine 69, Aspartic Acid 122, and Leucine 125 Provide Species Specificity for Lipid IV A
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SI Figure legend

SI Figure 1. The electrostatic surface charges are similar between hMD-2 and mMD-2 at the B patch, and between hTLR4 and mTLR4 at both the A and B patches. Electrostatic surface charges were calculated for hMD-2, mMD-2, hTLR4, and mTLR4 in MolMol (1). Surface charges of hMD-2 (left) and mMD-2 (right) at the B-patch are shown in (a), surfaces charges of hTLR4 (left) and mTLR4 (right) at the B patch are shown in (b), and surfaces charges of hTLR4 (left) and mTLR4 (right) at the A patch are shown in (c). The A and B patches are circled and labeled. Red for negatively charged surface, blue for positively charged surface, and white for non-charged surface.

SI Figure 2. The hMD-2 double mutant, R69G_K122E, gained most lipid IVₐ responsiveness among all double mutants. HEK293 cells were transiently transfected with: 1) one of the ten hMD-2 double mutants; 2) mTLR4 wild type construct; 3) a NF-κB-luciferase reporter construct; 4) a renilla-luciferase reporter construct. After overnight transfection, cells were stimulated with 1000 ng/ml, 100 ng/ml, 10 ng/ml, or 0 ng/ml of LPS (a) or lipid IVₐ (b) overnight. Supernatants were then removed, and NF-κB-luciferase was measured in cell lysates. The luciferase shown has been normalized by renilla-luciferase. Data are one representative figure of three replicates.

SI Figure 3. The hMD-2 quadruple mutant, Y42F_R69G_K122E_K125L, gained most lipid IVₐ responsiveness among all mutants. The high-order hMD-2 mutants were transiently transfected with wild type mTLR4 and reporter constructs overnight, and stimulated with decreasing concentrations of LPS (a) or lipid IVₐ (b) as described in SI
Fig. 2. The next day, supernatants were removed, and NF-κB-luciferase was measured in cell lysates. The luciferase shown has been normalized by renilla-luciferase. One representative data from three replicates are shown in the figure.

SI Figure 4. The mMD-2 double mutants that contain the E122K mutation lost most of the lipid IV$_A$ responsiveness. The ten mMD-2 double mutants were transiently transfected with mTLR4 to HEK293 cells, along with an NF-$\kappa$B luciferase reporter construct and renilla-luciferase reporter construct. After overnight transfection, cells were stimulated with 1000 ng/ml, 100 ng/ml, 10 ng/ml, or 0 ng/ml lipid IV$_A$ (a) or LPS (b). The next day, supernatants were removed, and NF-κB-luciferase was measured in cell lysates. The luciferase shown has been normalized by renilla-luciferase. Data are one representative figure of three repeating experiments.

SI Figure 5. The high-order mMD-2 mutants that contain the E122K mutations lost most of the lipid IV$_A$ responsiveness. The triple and quadruple mutants that contain both E122K and L125K mutations were transiently transfected with mTLR4 to HEK293 cells, along with an NF-$\kappa$B luciferase reporter construct and renilla-luciferase reporter construct. After overnight transfection, cells were stimulated with 1000 ng/ml, 100 ng/ml, 10 ng/ml, or 0 ng/ml lipid IV$_A$ (a) or LPS (b). The next day, supernatants were removed, and NF-κB-luciferase was measured in cell lysates. The luciferase shown has been normalized by renilla-luciferase. Data are one representative figure of three repeating experiments.
SI Figure 6. The hydrophobic pocket of hMD-2 is tilted away from TLR4 in the Eritoran-bound state vs. the LPS-bound state. The co-crystal structures of TV3/hMD-2/Eritoran (PDB ID: 2Z65) (2) and hTLR4/hMD-2/LPS (PDB ID: 3FXI) (3) were aligned on the N-terminal 200 residues of hTLR4. The tilt angle and distance of hMD-2 in the two structures are labeled. Color scheme: hTLR4 in 3FXI (pink), hMD-2 in 3FXI (brown); TV3 in 2Z65 (light yellow), hMD-2 in 2Z65 (green).

SI Figure 7. I299 and L399 in the hTLR4/hMD-2/LPS co-crystal structure. The hTLR4/hMD-2/LPS co-crystal structure (PDB ID: 3FXI) (3) was shown in two perpendicular views. The single polymorphism residues (SNPs) of I299 and L399 are shown as black spheres and labeled. Color scheme: hTLR4 (light pink), hMD-2 (hot pink), LPS (cyan); hTLR4’ (wheat), hMD-2’ (magenta), LPS’ (green).
SI References:


Meng et al, SI Figure 5

(a) Lipid IVa stimulation

Nf-κB-luciferase (fold of activation)

Lipid IVa

mMD-2 mutants

WT F42Y E122K L125K N58K E122K G69R E122K L125K F42Y G69R E122K L125K F42Y N58K E122K L125K

(b) LPS stimulation

Nf-κB-luciferase (fold of activation)

LPS

mMD-2 mutants

WT F42Y E122K L125K N58K E122K G69R E122K L125K F42Y G69R E122K L125K F42Y N58K E122K L125K