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TLT2 Potentiates Neutrophil Antibacterial Activity and Chemotaxis in Response to G Protein-Coupled Receptor-Mediated Signaling

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Receptors encoded within the Trem locus have been shown to play an important role in modulating the cellular response to pattern recognition receptor signaling. TREM-like transcript 2 (TLT2) is a member of the Trem locus that is conserved in mouse and human. TLT2 exhibits a unique expression pattern in that it is expressed on cells of the myeloid and lymphoid lineage, suggesting that it plays a role in both innate and adaptive immunity. In this work, studies reveal that TLT2 plays an important role in potentiating neutrophil antibacterial activity and chemotaxis. TLT2 ligation enhances the neutrophil response to the formylated peptide FMLF, leading to increased reactive oxygen species production, degranulation, and chemotaxis. Moreover, TLT2 has the ability to specifically potentiate neutrophil activation and chemotaxis in response to a range of agonists that bind to G protein-coupled receptors, as it does not potentiate the response of cells to growth factor receptor-, Fc receptor-, or TLR-mediated signaling. Finally, TLT2 ligation potentiates the recruitment of neutrophils to sites of inflammation in vivo. These findings reveal a novel functional role for TLT2 that involves potentiation of neutrophil responses to G protein-coupled receptor signaling. Thus, TLT2 appears to play an important role in enhancing the innate immune response via a novel molecular mechanism. The Journal of Immunology, 2011, 187: 2346–2355.

Cells of the innate immune system rely on a range of receptors to detect and respond to pathogens. The direct recognition of pathogens or products of cellular stress by pattern recognition receptors (PRRs) such as the TLRs and the NOD-like receptors are well characterized (1, 2). Additionally, other families of receptors serve to modulate the response of immune cells to signals derived from PRRs, including those encoded within the Trem locus (3). Receptors encoded within the Trem locus are expressed by a wide range of innate immune cells, including neutrophils, monocytes, macrophages, microglia, osteoclasts, and dendritic cells, as well as megakaryocytes and platelets (4). TREM-like transcript 2 (TLT2) is a type 1 transmembrane receptor, with a single extracellular Ig domain followed by a serine/threonine-rich membrane-proximal segment, and a short cytoplasmic tail following a single transmembrane domain. Unlike other TREM family members, murine TLT2 does not possess an obvious signaling motif within its 39-aa cytoplasmic tail, nor does it possess charged amino acids in the transmembrane domain, suggesting that it does not interact with prominent adaptor proteins such as DAP12, FcRγ, or TIRAP. In mice, TLT2 has been shown to be expressed on B cells, macrophages, and neutrophils, and thus, is the only member of the TREM locus to be expressed by cells of both the innate and adaptive immune systems (5).

TREM-1, the most well-characterized TREM protein, is the only TREM family member other than TLT2 that is expressed on neutrophils. TREM-1 ligation mediates increased production of inflammatory cytokines, chemokines, lactoferrin, reactive oxygen species (ROS), and myeloperoxidase (MPO) (6). Functional studies have found that TREM-1 cross-linking induces only a modest increase in specific antibacterial activities, whereas it predominately acts in a synergistic fashion to amplify the inflammatory response in conjunction with TLR and NOD-like receptor signaling (7, 8). Ligation of TREM-1 in concert with LPS stimulation potentiates cytokine secretion more than either stimulus alone. Thus, TREM-1 modulates immune cell function by effectively amplifying the magnitude of the response to signals delivered via PRRs. TREM-2 is expressed on a variety of cell types, including monocytes, macrophages, osteoclasts, bone marrow-derived dendritic cells, immature dendritic cells, and microglia (9, 10). TREM-2 has recently emerged as an important negative regulator of autoimmunity and appears to exert an anti-inflammatory activity on microglia and macrophages. Thus, TREM family members appear to predominantly function as modulatory proteins that control innate immune cell function in response to other stimuli.

TLT2, like TREM-1, is highly expressed on neutrophils, and its expression is upregulated in response to inflammatory conditions in vivo (5). However, the functional role of this receptor on cells of the innate immune system has not been described. Because the TREM-1 and TREM-2 receptors have been shown to modulate the functional response of cells to signals derived from PRRs, it was of interest to determine whether engagement of the TLT2 receptor would also modulate neutrophil function in response to signals derived from receptors involved in the induction of, or response to, inflammatory conditions. In this study, agonistic mAbs against TLT2 were used to demonstrate that ligation of TLT2 on neu-
trophils potentiates the respiratory burst and degranulation in response to FMLF and C5a, as well as the chemotactic response to several chemokines. The chemokines MIP-2 and KC, the complement component C5a, and the bacterial product FMLF all signal via G protein-coupled receptors (GPCRs). These receptors contain seven membrane-spanning helices that undergo conformational changes upon ligand binding, which in turn transduces a signal via activation of heterotrimeric G proteins. GPCRs make up a large family of proteins with broad functions in biological systems. In the context of innate immunity, signals delivered via GPCRs influence many aspects of neutrophil function, including promoting the production of ROS and the release of antimicrobial mediators, as well as chemotaxis (11). The finding that TLT2 regulates neutrophil function by potentiating the response to agonists that signal via GPCR-dependent pathways represents a novel mechanism whereby antibacterial responses and recruitment of phagocytic cells to sites of infection and inflammation are enhanced.

Materials and Methods

Isolation of mouse neutrophils

C57BL/6 mice 8–10 wk of age were used for isolation of bone marrow cells from the tibias and femurs. All mice were housed in specific pathogen-free conditions in University of Alabama animal facilities, and all procedures were approved by an institutional review committee. The bone marrow was passed through 25- and 20-gauge needles (BD Biosciences, Franklin Lakes, NJ) to generate a single-cell suspension in 1× HBSS (136 mM NaCl, 5.55 mM glucose, 5.36 mM KCl, 4.16 mM NaHCO3, 1.66 mM KH2PO4, 0.338 mM Na2HPO4 [pH 7.2]). RBCs were lysed by incubation in ACK (0.15 M NH4Cl, 0.1 mM NaHCO3, 0.1 mM EDTA [pH 7.2]) for 5 min on ice. Monocytes were then separated by density sedimentation using a Percoll (Amersham, Piscataway, NJ) gradient (60/80%) in 1× HBSS centrifuged at room temperature at 1500 rpm for 25 min. The cells at the 60/80 interface, which was comprised of >95% neutrophils as assayed by flow cytometry, were collected, counted with a hemocytometer, and resuspended in media at appropriate concentrations. The media used in all experiments was RPMI 1640, supplemented with penicillin/streptomycin, sodium pyruvate, 2-ME, L-glutamine, and 5% FBS. Anti-CD11b FITC (BD Pharmingen, San Diego, CA), anti–Gr-1 PE, and anti–Gr-1 allophycocyanin mAbs (Southern Biotechnology Associates, Birmingham, AL) were used to determine the purity of isolated neutrophils.

Respiratory burst assay

The anti-TLT2 mAbs 1H4 and 1C5 were generated, as previously described (5), and were prepared under LPS-free conditions. The Ab preparations used in these studies were subjected to the limulus amebocyte lysate test, and were demonstrated to contain no detectable endotoxin (limit of detection is 0.03 EU/ml). Where indicated, Abs were biotinylated using EZ-Link NHS-LC-biotin (Pierce, Rockford, IL). Following isolation, 1×106 purified neutrophils in 1 ml RPMI 1640 were incubated with anti-TLT2 mAb, isotype control mAb, or LPS, or were left untreated for 10 min prior to the addition of triggering stimuli. After the indicated period of time, the neutrophils were then stained for the surface markers CD11b and Gr-1. Degranulation was measured by a specific increase in the cell surface expression of CD11b.

Phagocytosis assay

A total of 5×10⁶ 2.0-μm biotinylated polystyrene beads (Polysciences, Warrington, PA) was incubated with a 1:100 dilution of streptavidin-FITC (BioSource International, Carlsbad, CA) in 100 μl PBS for 15 min at room temperature in the dark. The beads were then washed three times with 1× PBS. Subsequently, 50% of the FITC-labeled beads were incubated at room temperature with mouse serum containing anti-FITC Abs for 30 min in the dark. The FITC-specific antisera was generated by immunizing C57BL/6 mice with FITC-conjugated protein Ag, after which serum was harvested on day 10. After opsonization with the antisera, the beads were washed three times with 1× PBS and warmed to 37°C prior to addition to neutrophils. Neutrophils (1×10⁶ cells/sample) in 500 μl RPMI 1640 were preincubated with the indicated stimuli for 10 min. A total of 1×10⁶ fluorescent beads was then introduced to the cell suspensions, followed by a 15-min incubation. Trypan blue was added to quench extracellular FITC fluorescence, and phagocytosis of the beads was assayed by flow cytometry.

Chemotaxis assay

Neutrophil chemotaxis was assayed using 3.0-μm, 6.5-mm transwell inserts (Costar, Corning, NY) placed in 24-well cell culture plates. A total of 1×10⁶ neutrophils was placed in 100 μl RPMI 1640 in the upper chamber, and the chemotactic factors, FMLF, MIP-2, KC, IL-8, C5a, or GM-CSF, were added at the indicated concentrations to 600 μl in the bottom chamber. The migration was quantitated by the addition of the chemotactic agent alone. The chemotactic factors, FMLF, MIP-2, KC, MIP-2, and GM-CSF, and human rIL-8 were added to the upper chamber with the neutrophils at specified concentrations, and the samples were incubated for 60 min at 37°C in a humidity-controlled incubator under 5% CO2. Migrating neutrophils were removed from the bottom chamber and counted. The normalized chemotactic index was calculated by dividing the number of cells migrating in samples containing anti-TLT2 or isotype control mAbs by the number migrating in response to the chemotactic agent alone.

Ear model of inflammation

To induce inflammation in the ear, 20 μl 2% croton oil (Sigma-Aldrich) in acetone was applied to both sides of the pinna of one ear, whereas acetone alone was applied to the control ear. Either 100 μg anti-TLT2 mAb or 1× PBS alone was injected i.v. into mice 30 min prior to the application of croton oil. Four hours following the application of croton oil, 4-mm biopsies were obtained from the proximal portion of the ear, mechanically homogenized with a Tissue Tearor homogenizer (Biospec Products, Bartlesville, OK), and assayed for MPO activity. MPO levels were determined by the addition of the chromogenic substrate 3,3’,5,5’-tetramethylbenzidine (TMB; Sigma-Aldrich) to 100 μl of ear lysate. The absorbance at 450 nm was then measured using a Vmax plate reader ( Molecular Devices, Sunnyvale, CA). These samples were assayed with a standard curve of known concentrations of the enzyme HRP. Comparing the MPO activity present in specific numbers of purified neutrophils to this standard curve allowed for the estimation of the number of neutrophils present in the biopsy samples. To examine the effect of administration of anti-TLT2 mAb or PBS alone on treatment of cells and architecture of the ear, mice were sacrificed and the ears were removed, fixed overnight in 10% neutral buffer formalin, and paraffin embedded, and 8-μm-thick sections were prepared. The sections were treated to remove the paraffin and rehydrated, after which they were stained with H&E (Harris H&E, Sigma-Aldrich). The stained sections were subsequently dehydrated, cleared, and mounted with Permount (Fisher SP15). The slides were examined with a Zeiss AX10 microscope using a ×20 objective, and pictures were taken using a Zeiss AxiosCam MRC.

Lung model of inflammation and adoptive transfer of neutrophils

To induce inflammation in the lung, 5 μg LPS was introduced intracheally. Bone marrow neutrophils were isolated from CD45.1 donor mice, as previously described. Once isolated, the neutrophils were divided...
equally into three groups of $3 \times 10^7$ neutrophils and subsequently incu-
bated for 10 min in 500 $\mu$L of PBS containing either 5 $\mu$L isotype 
mAb or 5 $\mu$L Cell Tracker CMTPX Red, or without fluorescent additives, 
CMTPX cell-permeable tracking dyes were obtained from Invitrogen. 
Each group of neutrophils was then subjected to the indicated treatment 
for 15 min at 37°C, followed by three washes in prewarmed PBS, and 
resuspended in 100 $\mu$L. After loading, the cells were mixed in a 1:1:1 ratio, 
and $3 \times 10^9$ total neutrophils in 100 $\mu$L were injected i.v. into 
CD45.2 mice 2 h after the initiation of lung inflammation. After an additional 4 h, 
mice were sacrificed and cells were isolated from lungs by bronchoalve-
olar lavage. The isolated cell suspensions were stained with anti-CD45.1 
allophycocyanin (eBioscience). Flow cytometry was performed to identify 
CD45.1-expressing cells, and neutrophils subjected to the indicated treat-
ment conditions were then resolved based on CSFE or CMTPX fluores-
cence, or the absence of fluorescent labeling.

*Flow cytometry*

Cells were washed three times with FACS buffer (1× PBS, 0.01% NaN₃, 
0.5% FBS) and then incubated with the appropriate fluorescent Ab mixture 
in 96-well microtiter plates for 15 min on ice. After this incubation, the 
cells were again washed three times with FACS buffer. When necessary, 
samples were incubated with secondary Abs for an additional 15 min on 
ice. Samples were analyzed immediately following labeling on either a 
FACScan, FACSCalibur, or LSR II flow cytometer (BD Biosciences), and 
the resultant data were analyzed using FlowJo (Tree Star, Ashland, OR).

*Statistical analysis*

Statistical analyses were computed via the Student two-tailed t test. 
The CD45.1 adoptive transfer experiment was analyzed with the one-way 
ANOVA. The $p$ value of significant differences is reported, with a $p$ 
value $<0.05$ considered statistically significant.

*Results*

**TLT2 ligation potentiates the functional response of neutrophils to FMLF**

Previous studies have demonstrated that TLT2 is constitutively 
expressed by both macrophages and neutrophils (5). Under experi-
mental inflammatory conditions, including administration of 
thioglycolate, LPS, or staphylococcal enterotoxin B in vivo, 
responding macrophages and neutrophils exhibit significant up-
regulation of TLT2 on their surface (5). This rapid upregulation 
of TLT2 by neutrophils suggests that TLT2 may play a role in reg-
ulation of neutrophil function at sites of inflammation. A princi-
pal function of neutrophils is to respond to bacterial pathogens; 
therefore, experiments were performed to determine whether li-
gation of TLT2 with mAb enhances the antimicrobial activity of 
neutrophils by inducing ROS generation. To determine the effect 
that engagement of TLT2 has on ROS production, neutrophils 
were isolated from murine bone marrow and were analyzed using a 
chemiluminescence assay to measure the generation of ROS. 
As seen in Fig. 1A and Supplemental Fig. 1, ligation of TLT2 with 
either of the mAbs 1H4 or 1C5 alone does not induce a respiratory 
burst response.

Neutrophils generate ROS in response to a variety of extracel-
lular stimuli, including inflammatory cytokines and growth factors, 
as well as bacterial products such as LPS and formylated peptides 
derived from prokaryotic pathogens. FMLF is a short, formylated 
bacterial peptide that is released during degradation of the bacterial 
membrane, and is a strong chemoattractant for phagocytic cells 
such as neutrophils (11). The response of innate immune cells to 
formylated peptides is mediated by binding to the FMLF receptor, 
a GPCR, resulting in activation of phospholipase C, protein kinase 
C, and calcium mobilization (12). Experiments were performed to 
determine whether preincubation of neutrophils with anti-TLT2 
mAb exerts a priming effect resulting in a change in the kinetics 
or magnitude of the respiratory burst elicited in response to 
FMLF. Preincubation with anti-TLT2 mAb prior to stimulation 
with FMLF resulted in a substantial increase in ROS production

compared with neutrophils incubated with FMLF alone (Fig. 1, 
Supplemental Fig. 1). In contrast, preincubation of neutrophils 
with isotype control mAb had no effect on ROS production 
(Supplemental Fig. 1) or on the subsequent response following 
addition of FMLF, regardless of the concentration of isotype 
control Ab used (Fig. 1). The potentiation of ROS production 
occurs over a broad range of anti-TLT2 mAb concentrations (Fig. 1A). 
When the potentiation of FMLF-induced ROS generation 
based on anti-TLT2 mAb pretreatment is compared with that 
induced by pretreatment with LPS, a prototypic priming agent, 
the effects, although similar in magnitude, differ in their kinetics 
(i.e., initiation and duration). The priming effect of LPS is very 
rapid, as seen in Fig. 1B (upper panel). After a 15-min pre-
incubation with LPS, the kinetics of the response to FMLF are 
shifted, and the overall magnitude of the response is substantially 
increased, compared with treatment of cells with FMLF alone. In 
contrast, preincubation with anti-TLT2 mAb for 15 min fails to 
significantly alter ROS production induced by FMLF. However, 
after a 45-min preincubation with anti-TLT2 mAb, ROS 
production in response to FMLF is similar to that observed with 
LPS pretreatment in terms of magnitude. Whereas cells pretreated 
with LPS exhibited an accelerated, transient potentiation of ROS 
production, TLT2 ligation did not accelerate the kinetics of the re-
response, but was observed to potentiate ROS production for a 
prolonged period of time. Finally, pretreatment of neutrophils 
for 2 h with anti-TLT2 mAb resulted in a slight shift in the kinetics 
of the response similar to that observed with LPS treatment, as 
well as a prolongation of the potentiated response (Fig. 1B). 
Potentiation of ROS production can be further enhanced by sec-
ondary cross-linking, as demonstrated by treatment of neutrophils 
with biotinylated 1C5 in the presence of streptavidin, which 
results in a further enhancement of ROS production in response 
to FMLF at all time points assayed (Fig. 1B). This observation 
suggests that cross-linking of TLT2 may be important for eliciting 
an enhanced response to FMLF. In summary, whereas ligation 
of TLT2 alone does not induce the generation of ROS by neutrophils, 
cross-linking of this receptor serves to potentiate ROS production 
response to FMLF. Although ROS generation was similar for 
neutrophils primed either with anti-TLT2 mAb or LPS in terms of 
magnitude, significant differences were observed in the kinetics 
of ROS production. TLT2 ligation primarily acts to enhance the 
magnitude of ROS production over an extended period of time, 
but does not alter the kinetics of the response. In contrast, LPS 
accelerates the kinetics and increases the magnitude of the re-
sponse in a transient manner. These data suggest that the mech-
anism by which TLT2 ligation potentiates ROS production is 
different from that associated with the priming effect of LPS.

In addition to FMLF, other stimuli, including growth factors, 
induce a respiratory burst response in neutrophils. Therefore, 
experiments were performed to determine whether the significant 
enhancement in ROS generation induced by TLT2 ligation in 
response to FMLF would be observed in response to other agonists. 
The GM-CSF receptor (also known as CD116) is expressed on 
several cell types, including mature neutrophils. GM-CSF, like 
FMLF, has been shown to elicit ROS production by neutrophils; 
however, the GM-CSF receptor mediates a phosphotyrosine-based 
signal leading to ROS production (13). As seen in Fig. 1C, unlike 
the response to FMLF, ROS generation by neutrophils in response 
to GM-CSF was not potentiated by ligation of TLT2.

In addition to promoting the generation of ROS, FMLF is a 
potent chemoattractive agent for neutrophils (11). Because ligation 
of TLT2 was observed to potentiate ROS production in response to 
FMLF, experiments were performed to determine whether the 
chemotactic response of neutrophils to FMLF is also potentiated.
Medium containing varied concentrations of FMLF receptor agonist was placed in the bottom chamber of a 3-μm transwell device, and neutrophils were placed in the upper chamber. Anti-TLT2 or isotype control mAb, or medium alone was added to the neutrophils just prior to their addition to the upper chamber, and after a 1-h incubation at 37˚C, cells that migrated to the lower chamber were collected and counted. As shown in Fig. 2A, inclusion of anti-TLT2 mAb in these assays resulted in a substantial increase in the number of cells migrating through the transwell in response to FMLF. Of note, the concentration of anti-TLT2 mAb that maximally potentiates the chemotactic response of neutrophils is the same as that which provides maximal potentiation of ROS production. To rule out the possibility that Fc receptor-mediated signaling generated by the binding of intact Abs to neutrophils was responsible for these observed effects, F(ab')2 fragments of the 1H4 mAb were generated and used in these assays (Fig. 2B). The observed potentiation of cell migration in response to FMLF was identical whether cells were treated with F(ab')2 fragments or intact 1H4, suggesting that signals delivered via TLT2 were responsible for the observed effects on ROS production and cell migration.

Additional experiments were performed to determine whether secondary cross-linking would further enhance this effect using biotinylated 1C5, either alone or in the presence of streptavidin. As seen in Fig. 2C, the inclusion of streptavidin alone has no effect on cell migration in response to FMLF, whereas the inclusion of biotinylated 1C5 mAb alone results in a nearly 2-fold increase in the number of migrating cells. As seen in ROS assays, the inclusion of streptavidin and biotinylated 1C5 mAb results in a further enhancement, suggesting again that secondary cross-linking of TLT2 is responsible for this effect.

A possible mechanism by which TLT2 ligation potentiates the response to FMLF is by decreasing the neutrophil threshold of sensitivity for agonist binding to the FMLF receptor. If this were true, then one would expect to see a shift in the dose response to FMLF in neutrophils on which TLT2 has been ligated. To determine whether this is the case, neutrophil migration was assayed over a wide range of FMLF concentrations in the presence or absence of anti-TLT2 mAb.
absence of anti-TLT2 mAb. As seen in Fig. 2D, the inclusion of an optimal concentration of anti-TLT2 mAb potentiates neutrophil migration over a wide range of FMLF concentrations. However, TLT2 ligation does not result in a shift in the dose response to FMLF. Indeed, the observed potentiation in the number of migrating neutrophils treated with anti-TLT2 mAb is proportional regardless of the FMLF concentration as the ligation of TLT2 resulted in a chemotactic index (\(\sim 1.7\)) that is nearly identical for all concentrations of FMLF tested (Fig. 2E). In contrast, inclusion of LPS shifts the chemotactic response curve to FMLF, suggesting that it lowers the threshold of sensitivity to this chemoattractant (Fig. 2D). Collectively, these results suggest a potential role for TLT2 in amplifying the cellular response to FMLF, as opposed to altering the threshold of sensitivity to this FMLF receptor. This suggests that TLT2 ligation could amplify the magnitude of the signal delivered via the FMLF receptor and/or prolong the duration of that signal, thereby enhancing the cellular functional response. Alternatively, TLT2 ligation could in theory activate a parallel signaling pathway that amplifies the functional response of the neutrophil. Although, if this were true, one would expect that ligation of TLT2 alone would drive ROS production and chemotaxis in the absence of FMLF triggering, which was not observed. These data further support the conclusion that the mechanism by which TLT2 modifies the response to GPCR-mediated signaling is distinct from that of LPS.

Ligation of TLT2 specifically potentiates the neutrophil response to GPCR-mediated signaling

Besides triggering both ROS production and neutrophil migration, FMLF and GM-CSF induce degranulation of murine neutrophils. The release of specific granules in response to these stimuli has been shown to mediate the rapid expression of the integrin CD11b, resulting in an increase in cell adhesion, and is thought to be a mechanism to promote transmigration of neutrophils into inflamed tissues (14). Because the rapid upregulation of CD11b is associated with cellular activation, experiments were performed to determine whether TLT2 ligation alone is sufficient to induce the upregulation of CD11b, or whether ligation of the TLT2 receptor potentiates upregulation of CD11b induced by FMLF or the complement component C5a, which bind to GPCRs, versus GM-CSF or TLR agonists, which activate distinct signaling pathways that do not use heterotrimeric G proteins.

As seen in Fig. 3A, ligation of TLT2 alone has no effect on CD11b expression on purified neutrophils, regardless of the
mAb concentration used, compared with the FMLF receptor agonist WKYMVm, which induced CD11b expression in a dose-dependent manner (Fig. 3B). However, when neutrophils were preincubated with 100 ng/ml 1H4 mAb and were subsequently stimulated with 1 nM WKYMVm, a concentration that does not significantly alter CD11b expression, a synergistic upregulation of CD11b was observed (Fig. 3C). As was seen in the ROS assay, the potentiation of CD11b expression in response to FMLF following TLT2 ligation was further enhanced when neutrophils were preincubated in the presence of biotinylated 1C5 mAb plus streptavidin as a secondary cross-linking agent (Fig. 3D–F). Exposure to C5a also results in neutrophil degranulation, and like FMLF, activation of cells by C5a is the result of signal transduction mediated by the C5a receptor, a GPCR. Therefore, experiments were performed to determine whether TLT2 ligation would potentiate the cellular response to C5a. As seen in Fig. 3G, preincubation of neutrophils with anti-TLT2 mAb potentiates degranulation in response to C5a, resulting in the upregulation of CD11b. In contrast, ligation of TLT2 does not affect CD11b upregulation when used in conjunction with GM-CSF (Fig. 3H, 3I). Pretreatment of neutrophils with isotype control mAb alone or in conjunction with any of the agonists tested did not alter CD11b expression (data not shown).

To determine whether ligation of TLT2 potentiates the ability of TLR agonists to induce degranulation of neutrophils, experiments were performed in which neutrophils were preincubated in the presence of anti-TLT2 or isotype control mAb, followed by addition of TLR agonists, including LPS, poly(I:C), monophosphoryl lipid A, flagellin, imiquimod, and CpG-oligodeoxynucleotide, which bind to TLR2, 3, 4, 5, 7/8, and 9, respectively. Neutrophil degranulation in response to these TLR agonists was not affected by preincubation of neutrophils with anti-TLT2 or isotype control mAb (data not shown). A second assay was performed to monitor the effect that TLT2 ligation has on the ability of TLR agonists to prime neutrophil degranulation in response to low concentrations of GM-CSF. TLT2 ligation had no effect on the priming activity of any of the TLR agonists examined (data not shown).

The fact that TLT2 ligation specifically potentiates the response of neutrophils to FMLF, a bacterial component, and is upregulated on neutrophils at sites of inflammation suggests that it may play an important role in the innate immune response to bacterial infection. Phagocytosis of bacteria by neutrophils is mediated by multiple

**FIGURE 3.** TLT2 ligation potentiates neutrophil degranulation and upregulation of the activation marker CD11b in response to GPCR-mediated signaling. Purified neutrophils (1 × 10⁶) were incubated either with the anti-TLT2 mAb 1H4 (at the concentrations indicated) or biotinylated 1C5 (1 μg/ml). Where indicated, streptavidin (2–40 μg) was included to mediate secondary cross-linking of TLT2. Neutrophils were stimulated with the FMLF agonist WKYMVm (W) at the indicated concentrations (A–F), the activated complement component C5a (2 ng/ml) (G), or GM-CSF (1 ng/ml) (H, I). At the indicated time points, the cells were harvested and stained to detect surface expression of CD11b and analyzed by flow cytometry. Filled histograms represent CD11b expression on neutrophils incubated in medium alone. Representative histograms of CD11b expression are shown. All data are representative of at least three independent experiments.
receptors, including integrins, lectins, and scavenger receptors (15). However, the phagocytosis of bacteria by neutrophils is greatly enhanced in the presence of opsonizing Abs, which promote engulfment of particles via FcR. Thus, experiments were performed to determine whether the FcR-dependent phagocytic activity of neutrophils is enhanced by ligation of TLT2. To experimentally determine the effect of TLT2 ligation on the engulfment of opsonized particles, 2-μm polystyrene beads were conjugated to FITC to facilitate visualization, and then incubated with purified neutrophils either alone or following opsonization with polyclonal anti-FITC Ab. After 15 min, trypan blue was added to quench extracellular FITC fluorescence, and phagocytosis was assayed by flow cytometry. As seen in Supplemental Fig. 2, ligation of TLT2 had no measurable effect on the percentage of neutrophils that phagocytosed beads via a FcR-dependent mechanism, as anti-TLT2 mAb-pretreated samples were identical to nonpretreated controls, regardless of whether intact mAb, F(ab′)2 fragments, or secondary cross-linking was used.

TLT2 ligation potentiates the functional response of neutrophils to FMLF and C5a, including cell migration, ROS production, and upregulation of CD11b, but exhibits no effect on neutrophil functional responses to TLR agonists, GM-CSF, or FcR-mediated activation. Given the important role that GPCRs play in regulating neutrophil migration in vivo, it was of interest to determine whether TLT2 ligation potentiates the migration of these cells in response to other chemokines. Chemotaxis of purified neutrophils was assayed in response to a variety of chemotactants, including the murine chemokines, KC and MIP-2, their human homolog IL-8, as well as the activated complement component C5a. In this assay, TLT2 ligation in the absence of chemotactant has no measurable effect. However, in the presence of chemokine, anti-TLT2 mAb resulted in a 1.7- to 2.0-fold increase in the number of cells that migrate in response to these chemokines (Fig. 4). Importantly, this effect is not observed in response to GM-CSF, which is the only member of this panel of chemotactants that does not signal via a GPCR. Treatment with isotype control mAb had no effect on neutrophil chemotaxis nor did it potentiate migration in response to any of the chemotactants tested (Fig. 2 and data not shown). Instead, neutrophils were transferred to a transwell chamber (Fig. 3) using the colorimetric substrate TMB (16). The percentage of migration for neutrophils incubated with each chemoattractant in the presence or absence of anti-TLT2 mAb was assayed in response to a variety of chemoattractants in vitro. Purified neutrophils were subjected to migration assays using 3-μm transwell filters. Neutrophils (1 × 10⁶) were placed in the upper chamber in medium alone (control) or in the presence of the indicated concentration of anti-TLT2 mAb. Medium alone (control) or containing chemotactants (FMLF, 1 μM; MIP-2, 5 ng/ml; KC, 5 ng/ml; IL-8, 50–100 ng/ml; or GM-CSF, 0.5–10 ng/ml) was placed in the lower chamber, as indicated. After a 1-h incubation at 37°C, the neutrophils present in the lower chamber were harvested and counted. The percentage of cells present in the lower chamber (A) and the chemotactic index (B) are shown. The chemotactic index was calculated by dividing the percentage of migration for neutrophils incubated with each chemotactant in the presence or absence of anti-TLT2 mAb by the percentage of migration for neutrophils incubated with medium alone. Data represent the average of triplicate samples with the mean ± SD shown. Asterisks denote significance of values for anti-TLT2 mAb-treated samples compared with the respective control sample.

FIGURE 4. TLT2 ligation results in enhanced migration of neutrophils in response to a variety of chemoattractants in vitro. Purified neutrophils were subjected to migration assays using 3-μm transwell filters. Neutrophils (1 × 10⁶) were placed in the upper chamber in medium alone (control) or in the presence of the indicated concentration of anti-TLT2 mAb. Middle alone (control) or containing chemotactants (FMLF, 1 μM; MIP-2, 5 ng/ml; KC, 5 ng/ml; IL-8, 50–100 ng/ml; or GM-CSF, 0.5–10 ng/ml) was placed in the lower chamber, as indicated. After a 1-h incubation at 37°C, the neutrophils present in the lower chamber were harvested and counted. The percentage of cells present in the lower chamber (A) and the chemotactic index (B) are shown. The chemotactic index was calculated by dividing the percentage of migration for neutrophils incubated with each chemotactant in the presence or absence of anti-TLT2 mAb by the percentage of migration for neutrophils incubated with medium alone. Data represent the average of triplicate samples with the mean ± SD shown. Asterisks denote significance of values for anti-TLT2 mAb-treated samples compared with the respective control sample.

TLT2 ligation promotes neutrophil recruitment to sites of inflammation in vivo

Because ligation of TLT2 potentiates the chemotactic response of neutrophils to agonists that bind GPCRs, and given the importance of these receptors in controlling the migration and recruitment of neutrophils, it was of interest to determine whether TLT2 ligation potentiates neutrophil recruitment to sites of experimentally induced inflammation in vivo. Croton oil (2% in acetone) was used to induce a nonspecific inflammatory response in the ear. Thirty minutes following i.v. administration of either 1H4 mAb in the experimental group or saline in control mice, croton oil was applied to the pinna of one ear, whereas acetone alone was applied to the other. After 4 h, the mice were sacrificed and a 4-mm biopsy was removed from both ears. These biopsies were mechanically dissociated, and the resulting lysate was analyzed for the presence of MPO (Fig. 5A) using the colorimetric substrate TMB (16). Assaying the MPO activity present in these samples against standard curves of HRP facilitates the estimation of the number of neutrophils present in these samples. As seen in Fig. 5B, administration of 1H4 mAb resulted in a 2-fold increase in the number of neutrophils present in the inflamed ears, whereas there was no significant difference in the number of neutrophils present in samples derived from noninflamed ears. To further examine the effect that administration of anti-TLT2 mAb in vivo has on neutrophil recruitment and the inflammatory process in control and croton oil-treated ears, H&E staining of sections taken from the ear was performed to assess the cellular infiltrate as well as to examine the architecture of the ear. As seen in Fig. 5C, administration of anti-TLT2 mAb was observed to increase the recruitment of neutrophils to croton oil-treated ears in comparison with mice that received a sham injection of saline. The cellular influx consisted of primarily neutrophils in both treated and control animals based on examination of the sections at high magnification (data not shown). Administration of anti-TLT2 mAb had no effect on the recruitment of neutrophils to the control ear (Fig. 5C) and as demonstrated by an analysis of MPO activity (Fig. 5A). Finally, examination of the architecture of the ear did not reveal any significant differences at 3 h between the control and anti-TLT2–treated animals for either the control or croton oil-treated ear. These data support the conclusion that TLT2 engagement in vivo results in an enhanced chemotactic response to signals generated during inflammation, thereby increasing the number of neutrophils accumulating in the inflamed tissue.
Because TLT2 is broadly expressed by immune cells, including macrophages, neutrophils, and B lymphocytes, it is difficult to determine whether enhanced recruitment of neutrophils following administration of anti-TLT2 mAb is the result of a direct effect of TLT2 ligation on neutrophils or due to an indirect effect resulting from TLT2 ligation on other cell types. In an effort to determine whether the observed enhancement of neutrophil accumulation at sites of inflammation is a direct effect of TLT2 ligation on responding neutrophils in vivo, a series of adoptive transfer experiments were performed in which neutrophils were isolated from the bone marrow of CD45.1 C57BL/6 mice and labeled with either CFSE or CMTPX, or left unlabeled. These cells were then treated either with isotype control Abs, F(ab\')2 fragments of 1H4 anti-TLT2 mAb, or intact 1H4. An equal mixture of treated cells was then adoptively transferred into CD45.2 C57BL/6 recipient mice, which had been challenged intratracheally with 5 μg LPS to induce inflammation in the lung 2 h prior to adoptive transfer. Four hours after adoptive transfer of treated neutrophils, the recipient mice were sacrificed, and cells present in the lung were isolated by lavage, stained with the appropriate Abs, and analyzed by flow cytometry. Adoptively transferred neutrophils were discriminated by the expression of CD45.1, and these cells were then analyzed based on the dye they were loaded with: green, red, or unlabeled, allowing for the identification of these populations present in the lungs of recipient mice (Fig. 6A). As seen in Fig. 6B, neither pretreatment with isotype control Ab nor dye loading affected the recruitment of adoptively transferred neutrophils into the inflamed lung. Pretreatment with anti-TLT2 mAb, however, increased the frequency of treated neutrophils recovered in comparison with untreated or isotype control cells, regardless of the labeling conditions (Fig. 6B). The difference in frequencies between controls and anti-TLT2 mAb-treated neutrophils results in a ~2-fold increase in the absolute number of anti-TLT2–treated cells isolated from the lungs of the recipient mice (Fig. 6C). The observed increase in the number of neutrophils that migrated occurs whether neutrophils were treated with intact 1H4 mAb or F(ab\')2 fragments of this mAb. As these experiments used pooled neutrophils isolated from the same group of donor animals and represent a specific enhancement in the recruitment of anti-TLT2 mAb-treated neutrophils compared with control cells within the same recipient animal, these data strongly support the conclusion that ligation of TLT2 potentiates the chemotactic response of neutrophils to chemokines in vivo via a direct effect on the neutrophil itself.

Discussion

The Trem locus encodes several receptors expressed on myeloid lineage cells that function to modulate the response of cells to ligands for PRRs. In the case of TREM-1, ligation potentiates the systemic inflammatory response following stimulation of cells via TLRs, and in some instances can exert a direct effect on macrophages leading to the production of inflammatory cytokines (7, 8, 10, 17). In contrast, TREM-2, which is expressed on a range of cell types, including macrophages, has been shown to exert an inhibitory effect on TLR-mediated signaling, resulting in attenuation of activation and cytokine production (9, 18). TLT2 is expressed on cells of the myeloid lineage, including neutrophils and macrophages, and is upregulated in response to inflammatory conditions in vivo (5). Based on these observations, it was of interest to determine whether TLT2, like other members of the
FIGURE 6. TLT2 ligation enhances neutrophil recruitment into sites of inflammation in vivo. A. Purified neutrophils from CD45.1 mice were labeled with either CFSE or CMTPX, or left unlabeled. These cells were then incubated in the presence of the anti-TLT2 mAb as indicated, or an isotype control Ab, or medium alone. After treatment, the purified, labeled neutrophils were mixed at equivalent ratios, and 3 x 10^6 total cells were adoptively transferred into CD45.2 recipient mice, which had received an intratracheal challenge with 5 μg LPS to induce inflammation in the lung 30 min prior to adoptive transfer. After 4 h, the recipient mice were sacrificed, and the neutrophils present in the lung were isolated by lavage. Donor-derived neutrophils were identified based on the expression of CD45.1, and these cells were analyzed for the presence of the fluorescent dyes, which discriminated the pretreatment conditions. B. Ligation of TLT2 increases the relative frequency of neutrophils recruited into the lungs of recipient mice. A total of eight mice is depicted, and for each mouse the percentage of polymorphonuclear cells recruited to the lung for each of three pretreatment conditions is shown. The pretreatment condition was coted on the color of the symbol. C. TLT2 ligation causes an absolute increase in the number of neutrophils that migrate into inflamed lungs. The absolute number of neutrophils for each treatment condition was calculated based on flow cytometric analysis. The mean ± SD for a minimum of five mice is shown for each treatment condition. Asterisks denote significance of values for anti-TLT2 mAb-treated samples compared with the respective control sample.

TREM family, modulates the functional response of myeloid lineage cells to signals derived from PRRs. This study demonstrates that TLT2 ligation potentiates ROS production, degranulation, and chemotaxis in response to numerous GPCR agonists, including FMLF, C5a, MIP-2, KC, and IL-8. Importantly, TLT2 ligation was not observed to potentiate the cellular response to GM-CSF receptor or FcR-mediated signaling, which involves reversible protein tyrosine phosphorylation. Moreover, TLT2 ligation did not potentiate neutrophil degranulation in response to TLR. Thus, TLT2 appears to mediate signaling processes that selectively potentiate the response to GPCRs. Importantly, ligation of TLT2 was not observed to decrease the threshold of sensitivity to GPCR agonists, supporting the conclusion that it may act by amplifying or prolonging the GPCR signal, which in turn potentiates the functional response of the cell. Alternatively, because studies have yet to be performed demonstrating that TLT2 ligation affects the qualitative or quantitative nature of the biochemical signals associated with GPCRs, it is formally possible that TLT2 ligation potentiates the functional response to GPCRs without directly intersecting those pathways. Regardless, the role of TLT2 as a receptor that potentiates the cellular response to signals delivered via the GM-CSF receptor, which is a receptor protein tyrosine kinase, or Fc receptors, which also engage protein tyrosine kinases. Moreover, studies do not support the conclusion that TLT2 ligation modulates the response to TLR signaling, as is the case for TREM-1 and TREM-2. Therefore, it appears that TLT2 selectively modulates the cellular response to GPCR-mediated signaling. However, studies have yet to determine whether this is true for receptors coupled to a wide range of heterotrimeric G proteins as the receptors examined to date engage G proteins of the Gα subclass. Whether TLT2 can modulate the response to signaling via receptors coupled to other subclasses of heterotrimeric G proteins, such as Gαq, or Gαq, remains to be determined.

An equally important question that remains to be determined concerns the identity of the ligand for TLT2. Previous studies have suggested that TLT2 binds to B7-H3 and that TLT2 plays a role in modulating the function of CD8+ T cells in response to engaging its ligand (20). However, it is unlikely that this is the case. First, studies by our group have consistently failed to detect expression of TLT2 on cells of the T lineage (5). Regardless of whether CD4+ proteins to mediate signal transduction (4, 19). Indeed, the cytoplasmic tail of human and mouse TLT2 is not highly conserved, and there are no apparent signaling motifs that would, a priori, be predicted to be important for potentiating GPCR-mediated signaling. The TLT2 cytoplasmic domains from human and mouse are proline rich, and it is possible that this could confer the ability to interact with WW or Src homology 3 domain-containing proteins. Alternatively, the proline residues may play a role in providing tertiary structure to the cytoplasmic domain that is important for mediating interactions with key effector proteins. Regardless, it is clear that ligation of TLT2 does not potentiate the cellular response to signals delivered via the GM-CSF receptor, which is a receptor protein tyrosine kinase, or Fc receptors, which also engage protein tyrosine kinases. Moreover, studies do not support the conclusion that TLT2 ligation modulates the response to TLR signaling, as is the case for TREM-1 and TREM-2. Therefore, it appears that TLT2 selectively modulates the cellular response to GPCR-mediated signaling. However, studies have yet to determine whether this is true for receptors coupled to a wide range of heterotrimeric G proteins as the receptors examined to date engage G proteins of the Gα subclass. Whether TLT2 can modulate the response to signaling via receptors coupled to other subclasses of heterotrimeric G proteins, such as Gαq, or Gαq, remains to be determined.

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or CD8+ T cells are examined in their resting or activated state, TLT2 expression is not observed using two anti-TLT2 mAbs that bind to distinct epitopes. Secondly, it has been reported by an independent group that TLT2 does not bind B7-H3 (21). In conclusion, the identity of the physiological ligand for TLT2 remains to be determined. Currently, little is known regarding the ligands for other TREM family receptors. Studies using recombinant TREM-1 fusion proteins have detected putative ligands on the surface of neutrophils and platelets as well as on necrotic cells and in the serum of patients with sepsis, but their identity has not been determined (22–24). Similarly, TREM-2 fusion proteins have detected putative ligands on the surface of peritoneal and bone marrow-derived macrophages (18). More recently, TREM-2 has been shown to exist in a complex with Plexin-A1, which binds to Sema6D (25). Thus, DAP12-mediated signaling can be initiated by virtue of the TREM-2-Plexin-A1 interaction via binding of Plexin-A1 to Sema6D. This observation explains the phenotypic consequences of a genetic loss of the TREM-2 receptor and DAP12 and demonstrates that at least one member of the Trem locus is responsible for mediating signals in response to a ligand that binds to a distinct, associated receptor (25). Because TLT2 is expressed on both neutrophils and macrophages, which are critical effectors of the innate immune response against bacteria, and its expression is increased on these cells in response to inflammation, one might predict that the ligand for TLT2 could be derived from infectious organisms, or be generated as a byproduct of the innate immune response against pathogens (e.g., an acute-phase protein). This concept is also supported by the fact that TLT2 is most highly expressed on marginal zone and B1 B cell subpopulations, which are involved in mounting the natural/innate humoral immune response against bacterial pathogens (5).

In summary, this study demonstrates that TLT2 plays an important role in potentiating the neutrophil response to GPCR agonists, leading to enhanced ROS production, degranulation, and chemotaxis. Importantly, TLT2 does not appear to potentiate the cellular response to other types of receptors. Because TLT2 is upregulated on myeloid lineage cells in response to inflammatory conditions in vivo, and plays a role in potentiating the cellular response against agonists derived from pathogens or generated during the innate immune response, it is clear that this member of the TREM locus is important in potentiating the antibacterial innate immune response via a novel mechanism that involves the potentiation of the response to GPCR signaling.

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