Preligand assembly domain-mediated ligand-independent association between TRAIL receptor 4 (TR4) and TR2 regulates TRAIL-induced apoptosis

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The regulation of cell death by members of the TNF family plays a critical role in immune function and homeostasis (1). TRAIL is a TNF-like cytokine that selectively induces apoptosis in many tumor cells, but not in normal cells. Administration of recombinant TRAIL or antibodies against TR2 in several experimental tumor models exhibited potent antitumor activity (2–6). Moreover, recombinant TRAIL or antibodies against TR2 in several experimental tumor models exhibited potent antitumor activity (2–6). These reagents often synergize with chemotherapy or radiation to induce tumor-cell apoptosis (7–10). This unique property of TRAIL has prompted many to consider it as a potential therapeutic agent against malignant diseases. Despite its potency against tumor cells, the physiological function of TRAIL is largely unknown, although some reports have implicated TRAIL to be involved in tumor surveillance (11), target cell killing by various immune effector cells (12–13), and the regulation of innate immune responses (14).

TRAIL binds to distinct TNF receptor (TNFR)-like receptors, TR1 (TRAIL-R1/DR4), TR2 (TRAIL-R2/DR5/Killer/Trick), TR3 (TRAIL-R3/DcR1/LIT/TRID), TR4 (TRAIL-R4/DcR2/TRUNDD), and the soluble receptor osteoprotegerin (OPG). OPG is a soluble receptor that also binds another TNF-like cytokine called TRANCE/RANK-L and may have a more prominent role in bone and myeloid cell development than in regulating TRAIL-induced apoptosis. The four membrane-anchored TRAIL receptors contain two complete cysteine-rich domains (CRDs) for ligand binding that are pre-
ceded at the NH2 termini by a highly conserved partial CRD with unknown function (15, 16). TR1 and TR2 signal for apoptosis through their cytoplasmic death domains (DDs). Similar to Fas/CD95/APO-1, stimulation of TR1 or TR2 results in the recruitment of FADD and subsequently the initiator caspases caspase-8 and caspase-10 (17). The recruited caspase-8 and caspase-10 undergo autocatalytic cleavage and activation to trigger the caspase cascade that ultimately leads to the apoptotic death of the cell.

Unlike TR1 and TR2, neither TR3 nor TR4 contain intact cytoplasmic DDs that signal for apoptosis. TR4 possesses a partially truncated DD, whereas TR3 is anchored on the membrane via glycosyl-phosphatidylinositol (GPI) linkage. Because they can bind TRAIL but do not signal for apoptosis, TR3 and TR4 have been proposed to serve as “decoys” that inhibit apoptosis by sequestering TRAIL from the death-inducing TRAIL receptors. Alternatively, the decoy receptors may inhibit apoptosis by complexing with TR1 and/or TR2 upon binding to the trimeric ligand (18). Both of these ligand-dependent models of inhibition of apoptosis by the decoy receptors require the decoy receptors to bind TRAIL with relatively high affinities. Moreover, they predict that high expression of the decoy receptors will correlate with resistance to TRAIL-induced apoptosis.

Here, we report that inhibition of apoptosis by the decoy receptor TR4 does not depend on ligand binding of the receptor. Rather, inhibition of apoptosis critically depends on the formation of ligand-independent complexes between TR2 and TR4. We found that the NH2 termini overlapping the first partial CRD of TR2 and TR4, termed the preligand assembly domains (PLADs), are essential for the formation of this ligand-independent, death-inhibitory complex. The formation of this death-inhibitory complex regulates sensitivity of primary human CD8+ T cells to TRAIL-induced apoptosis. Thus, PLAD-mediated preligand receptor assembly is a previously uncharacterized ligand-independent mechanism by which TR4 regulates cellular sensitivity to TRAIL-induced apoptosis.

Materials and Methods

Reagents. CD8+ T cells, Jurkat cells, and BW5147 thymoma were cultured in RPMI medium 1640. 293T cells were cultured in cultured in RPMI medium 1640. 293T cells were cultured in RPMI medium 1640. 293T cells were cultured in RPMI medium 1640. 293T cells were cultured in RPMI medium 1640. 293T cells were cultured in RPMI medium 1640. 293T cells were cultured in
DMEM. All media were supplemented with 10% FCS, 100 units/ml penicillin, 100 μg/ml streptomycin, 30 μg/ml l-glutamine, and 60 μM 2-mercaptoethanol. Recombinant TRAIL, antibodies against TRAIL receptors, and TRAIL receptor fusion proteins were obtained from R & D Systems and Axxora Biochemicals.

**TRAIL-Induced Cell Death in CD8+ T Cells.** CD8+ T cells were purified from peripheral blood mononuclear cells by using the CD8 T cell purification system (R & D Systems). FACS staining of TRAIL receptor expression was performed by using specific antibodies from Axxora Biochemicals. Cell death was induced with recombinant TRAIL upon treatment with 20 ng/ml phorbol myristate acetate (PMA) for 30–240 min. Immunoprecipitation (IP) in CD8+ T cells were performed by using an antibody specific for TR2 (R & D Systems). Western blots were performed by using TR2 and TR4 antibodies. Small interference RNA was introduced into primary CD8+ T cells by using the Amaxa nucleofection method. RNA interference (RNAi) sequences against TR4 were: si506, r(GGAAGCUUCCAGGAUAAAA)dTdT; and si1142, r(GGAUCGCAAAGAAACA)dTdT. Transfection efficiency was typically >90% as determined by transfection with a FITC-conjugated oligonucleotide duplex. Maximal silencing of TRAIL-R4 expression was normally achieved 4 days posttransfection.

**293T Coimmunoprecipitation.** 293T cells were transfected by using FuGENE 6 (Roche). Twenty-four to 48 hr posttransfection, cells were harvested and lysed in IP buffer (150 mM NaCl/20 mM Tris-Cl, pH 7.5/1% Nonidet P-40) supplemented with Complete protease inhibitors (Roche). After the lysates were cleared by centrifugation, IP was performed by using monoclonal antibodies against GFP (Roche), which also reacts with yellow fluorescent protein (YFP), for 2 h at 4°C with protein G coupled to agarose beads. The beads were washed twice with IP buffer, twice with IP buffer supplemented with 500 mM NaCl, and once with IP buffer. Immunoprecipitates and whole-cell lysates were resolved on 10% Bis/Tris NuPAGE gels (Invitrogen).

**TRAIL-Binding Assay.** Murine BW5147 thymoma was transfected with the respective TRAIL receptor expression plasmids encoding TRAIL receptor fusions to the YFP by electroporation. Twenty-four hours later, cells were stained with recombinant FLAG-tagged TRAIL, followed by anti-FLAG tag antibody (M2, Sigma) and goat anti-mouse IgG antibody conjugated to phycoerythrin.

**Functional Dominant Interference Assay.** Jurkat cells were transfected by electroporation with the BTX Electro Cell Manipulator 600 (Genetronics). Transfected cells were treated with TRAIL for 6 h at 37°C. In some experiments, TR fusion proteins were added to the cells 15 min before stimulation with TRAIL. Apoptosis of the transfected cells was analyzed by using phycoerythrin-conjugated Annexin V (BD Pharmingen) and YFP fluorescence. The percentage of apoptotic cells in the transfected population was determined by the percentage of YFP-positive cells that also exhibited positive Annexin V staining. Percentage of cell loss was determined as described in ref. 19.

**Results**

Successful expansion of memory CD8+ T cells during recall responses requires CD4+ T cell help and priming when the CD8+ T cells are challenged during the primary response. The lack of CD4+ T cell help during primary antigenic challenge led to abortive memory CD8+ T cell expansion during recall response due to TRAIL-induced apoptosis (20). This sensitization to TRAIL-induced cell death could be attributed to the partial activation signals the cells received during the initial antigen priming stage in the absence of CD4+ T cell help. We sought to understand the mechanism that underlies the sensitization of human primary CD8+ T cells to TRAIL-induced apoptosis by using PMA to mimic partial activation of CD8+ T cells. We found that human peripheral CD8+ T cells or human CD8+ T cell clones that recognize the influenza M1 peptide were normally resistant to TRAIL-induced apoptosis. However, pretreatment with PMA for as little as 30 min sensitized the cells to TRAIL-induced apoptosis (Fig. 1A). Because CD8+ T cells express predominantly TR2 and TR4 on the cell surface (Fig. 1B), we speculated that the PMA-induced sensitization to TRAIL-induced apoptosis might be caused by changes in cell-surface expression of the inhibitory receptor TR4. Such a scenario would be consistent with the previously reported sequestration of decoy TRAIL receptors in an intracellular compartment as a means to modulate TRAIL responses (21). Indeed, PMA stimulation did modestly reduce TR4 expression on CD8+ T cells (Fig. 1C, mean fluorescence intensity from 146 to 110). The expression of TR2 was also reduced slightly in response to PMA (Fig. 1C, mean fluorescence intensity from 5.99 to 3.82). Hence, changes in cell-surface expression of TR2 and TR4 may account for the sensitization of CD8+ T cells to TRAIL-induced apoptosis.
Although PMA treatment sensitized cells to TRAIL-induced apoptosis with a concomitant reduction in TR4 surface expression, it is possible that PMA might trigger other molecular events that contribute to the enhanced sensitivity to TRAIL. However, we found no change in the expression of FADD, caspase-8, and cFliP1 in the PMA-treated cells (data not shown). To determine whether TR4 expression alone was sufficient to confer protection against TRAIL in CD8+ T cells, we transiently knocked down TR4 expression using RNAi. We found that RNAi against TR4 specifically reduced expression of TR4, but not TR2 expression, in CD8+ T cells (Fig. 1D). Moreover, RNAi-mediated silencing of TR4 resulted in an enhanced sensitivity of CD8+ T cells to TRAIL-induced apoptosis (Fig. 1E). The effect of the TR4 RNAi was specific to TRAIL because CD8+ T cells were not sensitized to TNF-induced apoptosis (Fig. 1E). Moreover, RNAi against TR4 did not affect Fas ligand-induced apoptosis in CD8+ T cells (Fig. 1E). Hence, TR4 plays a critical role in the protection of CD8+ T cells against TRAIL-induced apoptosis.

Ligand-independent formation of receptor complexes plays a crucial role in the function and signaling of TNF and Fas receptors (22, 23). Although TNF and Fas receptors appear to form only homotypic receptor complexes via the extracellular PLAD, we hypothesized that the TRAIL receptors might form mixed receptor complexes because of the high degree of homology in their extracellular CRDs. Indeed, we found that TR2 and TR4 associated with each other in CD8+ T cells (Fig. 1F). Interestingly, treatment with PMA abolished this interaction (Fig. 1F). Because these interactions occurred in the absence of exogenously added TRAIL, our results strongly suggest that TR4 may inhibit apoptosis by complexing with TR2 before binding exogenous TRAIL.

The inhibitory receptors TR3 and TR4 were thought to protect cells against TRAIL-induced apoptosis by competing with the death-inducing receptors for ligand binding. Alternatively, the trimeric ligand TRAIL may drive the formation of an abortive receptor complex containing TR1 or TR2 and the decoy receptors (18). However, our data in CD8+ T cells implied that sensitivity to TRAIL might be regulated through ligand-independent TR2–TR4 interaction. We therefore sought to determine the precise role of ligand binding by TR4 in the protection against TRAIL-induced cell death. We reasoned that any ligand-dependent mechanisms of inhibition by TR3 or TR4 would require them to bind TRAIL with relatively high affinities. Thus, we first evaluated the ligand-binding affinities of the different TRAIL receptors using a cellular assay. Jurkat cells expressed only TR2 and are highly sensitive to TRAIL-induced apoptosis (24). We therefore compared the efficacy of soluble TR-Fc fusion proteins [extracellular domain (ECD) of TR fused to the constant region of Ig] to inhibit TRAIL-induced apoptosis in Jurkat T cells as an indirect measurement of the ligand-binding affinity of TRAIL receptors. We found that the half maximal inhibitory dose (ID50) for TR3-Fc and TR4-Fc were 10- to 100-fold greater than that of TR1-Fc and TR2-Fc (Fig. 2A), indicating that TR3 and TR4 bind TRAIL with lower affinities than TR1 and TR2. The weak inhibition by TR3-Fc and TR4-Fc was not due to differences in protein stability or misfolding (Fig. 2B). Collectively, these data indicate that TR4 could inhibit apoptosis by forming abortive receptor complexes containing TR1 or TR2 and the decoy receptors.

Although soluble TR4-Fc did not bind TRAIL with high affinity, transfection of full-length TR4 or TR4 with a cytoplasmic domain (CD) substitution with the YFP conferred strong protection against TRAIL-induced apoptosis in Jurkat cells (Fig. 2B and data not shown). The inhibition conferred by TR4 was as strong as that conferred by a similarly built dominant negative TR2 and stronger than that of a dominant negative TR1 mutant (Fig. 2B). By contrast, a dominant negative version of Fas did not interfere with TRAIL-induced apoptosis, although it potently suppressed Fas-induced apoptosis. None of the dominant negative TRAIL receptors had any effects on Fas-induced apoptosis, indicating that the inhibitory effect was specific against TRAIL (Fig. 2B). Flow cytometric measurement of YFP fluorescence also revealed comparable expression between the different transfected samples (Fig. 8, which is published as supporting information on the PNAS website). Surprisingly, transient or stable transfection of TR3 did not protect against TRAIL-induced death in Jurkat cells (Fig. 2C and data not shown). Collectively, these data indicate that TR4 could potentiate interference with TR2-mediated apoptosis, but ligand-dependent mechanisms are unlikely to account for its inhibitory effect.

Because ligand-independent receptor complex formation is crucial for the function and signaling of TNF and Fas receptors (22, 23, 24), we postulated that it might similarly control apoptosis induction of TRAIL. Specifically, we reasoned that the highly conserved extracellular CRDs between TR2 and TR4 might permit ligand-independent formation of mixed, abortive receptor complexes. Such an event would produce heterotrimERIC complexes between TR2 and TR4 that would lack three functional intracytoplasmic DDs and therefore would interfere with apoptosis induction (27). We tested this proposition by examining the interaction between different TRAIL receptors lacking the cytoplasmic DDs. Because previous work indicates that ligand-independent interactions occur in the ECD of
NH2-terminal partial CRD contributes little to ligand binding within the two complete CRDs of the receptor while the interaction. TR2 binds TRAIL through two patches of residues ECDs of TR2 and TR4 that mediate this ligand-independent data not shown). Hence, the ECDs of TR2 and TR4 interact with wild-type TR2-CFP and TR4-CFP (Fig. 4A).

The interaction between the ECD of TR2 and TR4 was confirmed by FRET analysis with cyan fluorescent protein (CFP)- and YFP-tagged receptors. An increase in FRET signal was observed in cells cotransfected with TR2-CFP/TR2-YFP, TR4-CFP/TR4-YFP, and TR2-CFP/TR4-YFP receptor pairs (Fig. 4A–C, bold lines) compared with the noninteracting receptor pairs TR2-CFP/Fas-YFP (Fig. 4A–C, thin lines). These interactions did not require an intact ligand-binding site, because the Fas receptor was not precipitated (Fig. 5C, compare lanes 2–4). Again, the interaction measured in this assay is specific, because the Fas receptor was not precipitated (Fig. 5B, lane 5). Thus, PLADs exist for TR2 and TR4 within the partial CRD at the NH2 termini of the receptors. This arrangement is similar to the PLADs in TNFR-1, TNFR-2, and Fas (22, 23).

Our results thus far strongly implicate that ligand-independent mechanisms are involved in the inhibition of apoptosis by TR4. However, it is possible that both ligand-dependent and -independent mechanisms contribute to the inhibition of apoptosis by TR4. To more definitively evaluate the contributions of ligand binding and PLAD-mediated association to the inhibitory effect of TR4 on TRAIL-induced apoptosis, we tested the PLAD-deleted and non-ligand-binding TR4 mutants for protection against TRAIL-induced apoptosis in Jurkat cells. Strikingly, deletion of the PLAD completely eliminated the protective
effect of TR4 [Fig. 6A, TR4(42–184)-YFP]. As expected, the DD-deleted TR2 and TR4 conferred strong protection (>95%) against TRAIL-induced death but not Fas-induced death (Fig. 6A). Moreover, the removal of the NH2-terminal non-CRD sequences that were not essential for PLAD-mediated association did not perturb the protective effect of TR4 [Fig. 6A, TR4(27–184)-YFP]. Similar deletion mutants of TR2 revealed that the NH2-terminal partial CRD was also required for dominant interference of apoptosis by a tailless TR2 (Fig. 9, which is published as supporting information on the PNAS web site). A tailless, dominant-interfering Fas receptor had no effect on TRAIL killing but strongly suppressed death induced by an anti-Fas agonistic antibody (Fig. 6A). Strikingly, we found that deletion of the PLAD, but not the NH2-terminal non-PLAD sequences, abolished TRAIL binding by TR4 (Fig. 6Bc and d). The loss of TRAIL binding is unlikely to be caused by misfolding of the receptor because the PLAD-deleted TR4 was expressed on the cell surface and could be recognized by antibody specific for TR4 (Fig. 10, which is published as supporting information on the PNAS web site). Hence, the PLAD in TR4 is crucial for receptor association and efficient ligand binding, similar to TNFR-1 and TNFR-2 (22).

Although our results indicate that PLAD-mediated, ligand-independent interaction between TR2 and TR4 impairs receptor signaling of cell death, it is possible that deletion of the PLAD resulted in severe disruption of the ligand-binding domain and rendered the truncated receptor nonfunctional. To conclusively show that ligand was not required for PLAD-mediated inhibition of TR2, we tested the non-ligand-binding TR4 mutant R101A for inhibition against TRAIL-induced apoptosis in Jurkat cells. The R101A mutation abolished ligand binding but did not interfere with PLAD-mediated receptor interaction [Figs. 4D and 6B (compare a and b)]. Significantly, the R101A mutant strongly protected Jurkat cells against TRAIL-induced apoptosis at a level comparable to that conferred by wild-type TR4 ECD (Fig. 6A). Similarly, an analogous mutation in TR2 (M97A) that abolished ligand binding had no effect on the ability of a tailless, dominant interfering TR2 to inhibit apoptosis (Fig. 9). Taken together, our data clearly demonstrate that TR4 associates with TR2 via the PLAD and that this ligand-independent association between the two receptors is critically important for the inhibitory effect of TR4 on TR2-induced apoptosis.

**Discussion**

TR3 and TR4 were originally proposed to regulate TRAIL-induced cytotoxicity through ligand competition or ligand-driven formation of mixed trimer complexes with TR1 or TR2 (18). We demonstrated here that TR4 inhibits TR2-mediated cytotoxicity through ligand-independent association with TR2 via the PLAD. Contrary to previous reports, we found no evidence that TR4 acts as a “decoy” that competes for ligand binding. In fact, our evidence rules out that possibility. Because our data conclusively overrule the “decoy” model for TR4 inhibition of TRAIL signaling, we propose the term “regulatory receptor” for TR4. Formation of TR2–TR4 heterotrimeric complexes explains how the low-affinity receptor TR4 could effectively inhibit apoptosis signaling by the high-affinity receptor TR2. In this case, as in the other dominant interfering TNFR superfamily receptors, a deficiency of the DD potently reduces the transmission of the death signal (23, 27). Evidently, three intact DDs must be present for signaling to occur normally. The PLADs in both receptors allow both homotypic as well as heterotypic associations, unlike the homo-specific PLADs found in TNFR-1, TNFR-2, and Fas. This property is likely attributable to the strong sequence conservation within the PLADs of the TRAIL receptors. It is noteworthy that the other decoy receptor TR3 did not protect against TRAIL-induced apoptosis in Jurkat cells or interact with other TRAIL receptor ECDs. It is possible that TR3 may only interact with other TRAIL receptors in a complex containing three distinct receptors. Further experiments will be...
needed to evaluate the mechanism by which TR3 regulates TRAIL-induced apoptosis.

Many cytokine receptors signal as multisubunit entities. The association of the α, β, and γ subunits of the IL-2 receptor increases the affinity of the receptor. Swapping the α subunit of the IL-2 receptor with that from the IL-15 receptor changes the ligand specificity of the receptor. By contrast, the TR2–TR4 hetero-complexes did not alter the ligand specificity of the receptor. Rather, TR2–TR4 hetero-complexes dramatically affect the biological outcome of TRAIL stimulation through inhibition of apoptosis. Although the TR2–TR4 complexes are deficient for apoptosis induction, it is unclear whether they are also defective in NF-κB or MAP kinase signaling. Nonetheless, the PLAD-mediated mixed complexes have a dramatic regulatory effect on the cellular response to TRAIL.

Ligand-independent association between TR2 and TR4 may explain the resistance of CD8$^+$ T cells and other untransformed cells to TRAIL. The lack of CD4$^+$ T cell help during priming of CD8$^+$ T cells causes TRAIL-induced apoptosis of these cells, which limits the expansion of the memory CD8$^+$ T cells during secondary recall responses (20). Using PMA as a mimic for partial activation without CD4$^+$ T cell help, we found that primary CD8$^+$ T cells were rendered sensitive to TRAIL-induced apoptosis. Strikingly, this change in cellular sensitivity to TRAIL accompanied the ablation of ligand-independent interaction between TR2 and TR4. The heightened response to TRAIL in PMA-treated CD8$^+$ T cells does not involve changes in expression of apoptosis inhibitors such as cFLIP (data not shown). Rather, RNAi-mediated knock down of TR4 expression was sufficient to sensitize cells to TRAIL. These data strongly implicate that ligand-independent interaction between TR2 and TR4 is a regulatory mechanism that controls cellular sensitivity to TRAIL. Similar regulation on the assembly of ligand-independent Fas complexes and sensitivity to Fas-induced apoptosis in CD4$^+$ T cells has recently been reported, suggesting that ligand-independent receptor assembly is a general mechanism that regulates cellular sensitivity to death receptor stimulation (29). Finally, mutations in the PLAD or ligand-binding domain of TRAIL receptors have been identified in certain lung cancers (30, 31). These mutations may affect ligand-independent receptor assembly and cellular responses to TRAIL-induced apoptosis. Modulation of ligand-independent interactions between TRAIL signaling and regulatory receptors may be a useful strategy in cancer therapies.

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