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REVIEW

Transgelin-2 in immunity: Its implication in cell therapy

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Abstract

Transgelin-2 is a small 22-kDa actin-binding protein implicated in actin dynamics, which stabilizes actin structures and participates in actin-associated signaling pathways. Much curiosity regarding transgelin-2 has centered around its dysregulation in tumor development and associated diseases. However, recent studies have shed new light on the functions of transgelin-2, the only transgelin family member present in leukocytes, in the context of various immune responses. In this review, we outlined the biochemical properties of transgelin-2 and its physiological functions in T cells, B cells, and macrophages. Transgelin-2 regulates T cell activation by stabilizing the actin cytoskeleton at the immunological synapse. Transgelin-2 in B cells also participates in the stabilization of T cell–B cell conjugates. While transgelin-2 is expressed at trace levels in macrophages, its expression is highly upregulated upon lipopolysaccharide stimulation and plays an essential role in macrophage phagocytosis. Since transgelin-2 increases T cell adhesion to target cells via boosting the "inside-out" costimulatory activation of leukocyte function-associated antigen 1, transgelin-2 could be a suitable candidate to potentiate the antitumor response of cytotoxic T cells by compensating for the lack of costimulation in tumor microenvironment. We discussed the feasibility of using native or engineered transgelin-2 as a synergistic molecule in cell-based immunotherapies, without inducing off-target disturbance in actin dynamics in other cells.

KEYWORDS

actin-binding protein, B lymphocytes, immunological synapse, immunotherapy, macrophages, T lymphocytes, transgelin-2

1 | INTRODUCTION

The actin cytoskeleton plays a crucial role for immune functions, orchestrating numerous cellular processes including cell proliferation and differentiation, apoptosis, migration, and cellular signaling.[1–8] To accomplish these outcomes, the actin filaments are spatially and temporally regulated by actin-binding proteins (ABPs), which account for approximately 25% of the total cellular protein.[9] Transgelin-2, a 22-kDa ABP, is encoded by the gene *TAGLN2* and belongs to the transgelin superfamily of actin cross-linking/gelling proteins[10] consisting of transgelin-1 (also known as smooth muscle protein 22α, SM22α), transgelin-2 (SM22β),[11] and transgelin-3 (NP25).[12] Because the first member of the transgelin family, transgelin-1, was first identified in 1987[13] and has been considered as a tumor suppressor,[14] previous studies on transgelin-2 have centered around its relevance with tumor development and allied diseases. However, its fundamental mechanisms and physiological significance are largely unknown. Notably, recent findings regarding transgelin-2, the only transgelin family member present in leukocytes,[15] shed light on its biochemical properties and physiological roles in the immune system. In this review, we build a holistic picture of how transgelin-2 functions in cells of both innate and adaptive immune systems. We first provide the biochemical characteristics of transgelin-2 and its regulation in immune tissues and cells. We then review recently uncovered physiological functions of transgelin-2 in the immune system; this small ABP regulates cytoskeletal actin dynamics and stabilizes immune synapses that form when antigen-recognizing T cells meet antigen-presenting cells (APCs) or macrophages phagocytose infected bacteria.[16–19] Several studies have suggested the feasibility of transgelin-2 as an endogenous factor to enhance T cell function, thereby boosting the antitumor response of

Abbreviations: ABM, actin-binding motif; ABPs, actin-binding proteins; ACT, adoptive cellular therapy; APC, antigen-presenting cells; CAR, chimeric antigen receptor; CCR6, chemokine receptor 6; CH, calponin homology; CR, calponin-like repeat; DCs, dendritic cells; d-SMAC, distal-supramolecular activation cluster; GC, germinal center; IS, immunological synapse; miRNAs, MicroRNAs; PD1, programmed cell death protein 1; SD1, subdomain1; SMCs, smooth muscle cells; TILs, tumor-infiltrated lymphocytes

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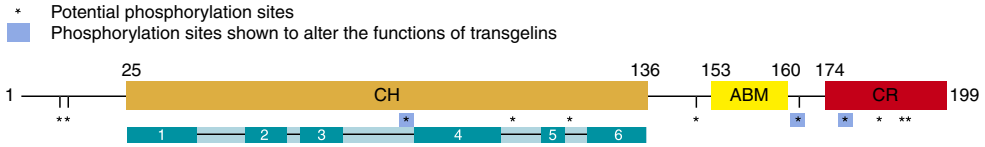

FIGURE 1 General structure of transgelin family (transgelin-1, -2, and -3). They contain single N-terminal CH domain, ABM, and C-terminal CR region in common, all being well conserved throughout family members. Six helices consisting of CH domain are marked in turquoise below the CH domain (orange). Potential phosphorylation sites by in silico prediction are marked (asterisk, amino acids number 8, 11, 83, 107, 121, 145, 163, 180, 186, 190, and 192 in transgelin-2). The known functions of each domain and several phosphorylation sites reported to alter the protein function (blue boxes) in vitro and in vivo are covered in main text

cytotoxic T cells for immune cell therapy. Its oncogenic aspects are not addressed in detail in this paper but have been reviewed recently.[20]

2 | STRUCTURE

The human transgelin-2 is transcribed from the 7.4-kb *TAGLN2* gene, which is located on chromosome 1q23.2 with 7 exons. Other isoforms, human transgelin-1 and transgelin-3, are encoded by distinct genes at a locus separate from transgelin-2; *TAGLN1* and *TAGLN3* are located on chromosome 11q23.3 and chromosome 3q13.2, respectively, each contains 5 exons. Therefore, the transcription of each gene is regulated by distinct noncoding promoter sequences. Each isoform performs unique biological roles and is expressed in different biological conditions. For example, transgelin-2, the only transgelin protein with an upstream promoter region containing a NF-κB consensus motif, is largely induced by the NF-κB pathway in macrophages, while the other two isoforms are not significantly influenced.[17]

Structurally, all three transgelins contain a N-terminal single calponin homology (CH) domain, actin-binding motif (ABM), and C-terminal calponin-like repeat (CR, also named as C-terminal calponin-like module repeats, CLIK repeats) region (Fig. 1).[14] The structure of the CH domain (residues 16–157) of human transgelin-2 has been determined to have a high similarity in tertiary structures to transgelin-1, although the N- and C-terminal structures remain inconclusive. The CH domain structures of all isoforms are globular and formed by 6 helices, which are conserved to some extent throughout the CH domains in other ABPs[21] (reference was also obtained from RCSB Protein Data Bank).

3 | BIOCHEMICAL CHARACTERISTICS OF TRANSGELIN-2: ACTIN BINDING, BUNDLING, AND STABILIZATION

Transgelin-2, like other transgelins, binds to both F-actin and G-actin through ABM, as determined by in vitro and in vivo observations with an ABM deletion mutant (ΔABM) in different contexts.[15] In particular, the binding to G-actin is interesting as it implies that transgelin-2 has diverse roles in controlling actin structures and dynamics. For example, it may hinder or transform the binding sites for other accessory proteins, which results in the impediment of other ABP actions. For example, Na et al. reported that transgelin-2 competes with cofilin, an actin-severing and sequestering protein,[15] due to the presence of an overlapping binding site at the actin subdomain1 (SD1), thereby, obstructing cofilin-mediated disassembly of actin filaments. In addition, actin side-binding proteins, such as EPLIN, have been known to inhibit the secondary activation of nucleation mediated by the Arp2/3 complex.[19,22] As transgelin-2 also acts as a side-binding protein, it is plausible that transgelin-2 can compete with the Arp2/3 complex if the location of the transgelin-2 binding site in actin overlapped with the Arp2/3 actin-binding site.[23]

The transgelin family has been assumed to consist of actin-bundling and gelling proteins.[24] However, the bundling activity was observed only at exceptionally high concentrations (16–24 μM), which corresponds to a ratio of transgelin-2 to actin of over 2:1. Additionally, since the working ratio of actin-bundling proteins, such as α-actinin, filamin, and fimbrin, to actin ranges from 1:2 to 1:20,[25–28] transgelin-2 is not likely a direct actin-bundling protein. However, the strong localization in the cellular bundled actin structures, such as stress fibers or podosomes, similar to transgelin-1[14,15] suggests that transgelin-2 has an actin-bundling activity in vivo. However, how it promotes actin bundling in living cells remains unknown. One possibility is that transgelin-2 may not simply connect two actin filaments to form bundles as easily as observed for other actin-bundling proteins, but instead, it can be intercalated between two G-actin molecules since it is a G-actin-binding protein, thus, aiding in the formation of multimeric transgelin-2/actin structures. Because the affinity of transgelin-2 for F-actin is lower than that of other bundling proteins,[15] this multimeric feature may suggest that it acts as a "molecular zipper or staple" for joining actin filaments into the bundles. The association of the N-terminus near the CH domain and the C-terminus CR region has been predicted as the mechanism of multimeric interactions of transgelin-2 at the site of actin polymerization.[15] The property of transgelin-2 allowing it to be intercalated into the each G-actin can also influence the stability of F-actins.[15] In cells, this property may result in the augmentation of F-actin contents at the distal-supramolecular activation cluster (d-SMAC) of the immunological synapse (IS) in T cells, localization at the filopodia of B cells during B–T conjugation, and ruffles and phagocytic cups in macrophages.[2,15,17,19]

4 | EXPRESSION AND LOCALIZATION OF TRANSGELIN-2 IN IMMUNE CELLS

4.1 | Expression and localization in various cell types

Transgelin-2 has been reported to be widely expressed in various cell types, from smooth muscle cells (SMCs) to non-SMCs, whereas

the expressions of transgelin-1 and transgelin-3 are rather restricted to SMC and the brain, respectively.[29,30] However, of interest is that transgelin-2 is the only transgelin member expressed in immune tissues and cells, such as the thymus, spleen, lymph nodes, and primary immune cells and their cell lines.[15] In T cells, transgelin-2 expression is constitutive, although its expression is slightly altered by external stimulation.[15] In both bone marrow-derived and peritoneal macrophages, transgelin-2 is basally expressed in the resting state, but its expression is highly upregulated upon TLR-mediated macrophage activation.[17] In B cells, it is likely that the basal expression level is initially high and further elevated upon the activation of B cells,[31] although it remains contentious,[19,31,32] particularly across the subpopulation. Peritoneal B-1 cells were reported to express 60-fold more transgelin-2 at the protein level than splenic B-1 and splenic B-2 (conventional B cells),[32] which exhibit virtually no expression of transgelin-2. On the contrary, two other studies demonstrated that the primary B cells and B cell lines express considerable levels of transgelin-2.[19,31]

Together with its two isoforms,[10,13,30] transgelin-2 binds to actin cytoskeletons, showing a high correlation coefficient in the F-actin-rich regions, including the lamellipodial leading edge, membrane ruffles, d-SMAC area of IS, and podosomes.[16,17,19] In addition, it moves along together with F-actin flow upon BCR, TCR, and TLR stimulations in B cells, T cells, and APCs, respectively.[17,19,31] Transgelin-2 has been shown to be expressed in the nucleus as well,[15] whereas its functions within the nucleus have yet to be studied.

4.2 | Regulation of transgelin-2 in immune cells

The regulation of transgelin-2 expression has not been sufficiently studied. However, some studies have suggested that transgelin-2 expression is controlled at the transcriptional, translational, and post-translational levels in response to the various intercellular events. For instance, transgelin-2 expression is linked to the NF-κB pathway in macrophages.[17] Kim et al. reported that transgelin-2 is selectively induced in LPS-activated macrophages via the NF-κB pathway, whereas other transgelin family members are not likely controlled by external signals, such as LPS.[17] NFAT, a down-stream transcription factor of calcium signaling, seems to insignificantly contribute to its induction.[17] In primary B cells, at the germinal center (GC), the *TAGLN2* mRNA level increased approximately 3-fold after BCR stimulation.[31] Consistent with this, in conventional B-2 cells, which histologically correspond to primary B cells,[32] *TAGLN2* mRNA level was upregulated by 3-fold in response to either anti-Ig or LPS.[32] Moreover, as mentioned above, Francés et al. reported that transgelin-2 levels differ at the transcriptional and translational (3-fold and 60-fold difference, respectively) level even in the same samples.[32] Thus, a more accurate proteomic analysis would be needed to understand whether or how transgelin-2 expression is further controlled after transcription. Moreover, peritoneal B-1 cells, which also express *TAGLN2* mRNA 3-fold higher than that in B-2 cells, showed upregulated levels of NF-κB, PKCα, and phosphorylated p-ERK, the main players in the PI3K/Akt and Ras-ERK signaling pathways.[32] Furthermore, TGF-β stimulation resulted in a 1.47-fold upregulation of transgelin-2 expression in a Smad4-dependent manner.[33] This observation correlated with those in previous reports indicating that TGF-β regulated transgelin-1 expression.[34,35]

MicroRNAs (miRNAs) are endogenous, noncoding, short RNAs that regulate gene expression in a sequence-specific manner via translational repression or degradation of target mRNA.[36] Several reports have demonstrated that *TAGLN2* is a target gene of miR-1, miR-133a, miR-133a-2, and miR133b, which are known to work as tumor-suppressors targeting oncogenes.[36–45] These miRNAs are downregulated in various tumors and directly bind to the 3′-UTR of *TAGLN2* mRNA to downregulate *TAGLN2* at both the transcriptional and translational levels.[45] This inverse correlation between these miRNAs, and transgelin-2 has been revealed in many cell carcinomas and normal cells,[44,45] but little is known in lymphocytes or other immune cells.

Besides the *TAGLN2* gene expression regulation, the phosphorylation of transgelins might be regulated at the post-translational levels, which can alter its capability to bind and stabilize F-actin. Potential phosphorylation sites in transgelin family are marked in Fig. 1. Our unpublished results demonstrated that the substitution of putative phosphorylation sites in transgelin-2 affects its actin-stabilizing function. In addition, a serine phosphorylation mimic via a S181D substitution at a PKC phosphorylation site in transgelin-1 attenuates its actin-binding capacity in vitro,[46–48] thereby suggesting that phosphorylation at S181 represented the active state and was related with the actin depolymerization.[49] Several studies in vivo further corroborated the influence of transgelin-2 phosphorylation. For example, in hepatocellular carcinoma, cdc2-related serine/threonine protein kinase 1 (PFTK1), has been shown to induce phosphorylation at S84 and S163, and mediates actin depolymerization, thus promoting cell invasion.[50] Furthermore, phosphorylation at S163 may be related to glucose-stimulated insulin secretion.[51]

5 | FUNCTIONS IN VARIOUS IMMUNE CELLS

5.1 | T Lymphocytes

In adaptive immunity, activated T lymphocytes play crucial roles by secreting cytokines or directly killing pathogen-infected cells or cancerous cells. For the full activation, spatial and temporal regulation of actin dynamics is crucial at the IS between T cells and APC.[6,52] Transgelin-2 is essential for T cell effector functions; it stabilizes cortical F-actin cytoskeleton, regulates interactions between actin and other signaling proteins, and enhances LFA-1 integrin affinity and avidity, thereby maintaining the IS.[15,18] Upon TCR stimulation, it localizes at the d-SMAC along with the F-actin in the IS. It controls the F-actin content, presumably attenuating the spontaneous or cofilin-mediated dissociation of F-actin at the IS.[15,18] Interestingly, both transgelin-2 and cofilin share the same actin subunit, the SD1 site[53] (also our unpublished results). However, it is striking to note that cofilin and transgelin-2 can potentially function together by occupying distinct locations in the IS rather than competing with each other.[6,15] Cofilin mainly localizes to the upper region of d-SMAC and generates a large pool of actin monomers by severing and sequestering F-actin at the end of the actin flow,[54] whereas transgelin-2 is rather enriched at the

bottom region of d-SMAC and stabilizes the actin flow at the place.[15] Taken together, both cofilin and transgelin-2 favor the centripetal, retrograde actin flow at the IS[6,15] in their distinct ways. Interestingly, PLC-γ phosphorylation necessitates correct actin flow,[52] which requires transgelin-2 expression, and phosphorylated PLC-γ leads to dephosphorylation (activation) of cofilin through its downstream PI3K/ERK cascades in T cells.[6] Consistent with this, *TAGLN2* knockout in T cells resulted in diminished cofilin activation.[15]

The activation of LFA-1, a leukocyte β2 integrin, and LFA-1/ICAM-1 interaction is the essential "outside-in" costimulatory signal for prolonged adhesion of T cells to APCs and thus T-cell activation.[15] LFA-1 activation also requires signals transduced by chemokines or TCR signaling,[55] referred to as "inside-out" signaling. While further studies are necessary, transgelin-2 is involved in LFA-1 activation in TCR-activated T cells. Several mechanisms can be postulated as to how transgelin-2 augments LFA-1 function. First, it can control LFA-1 activity through the activation of Rap1, a small GTPase that regulates both LFA-1 affinity (conformational change) and avidity (clustering).[55–57] Second, TCR-activated actin rearrangement also corresponds to the spatial regulation of LFA-1 (clustering).[58] Large-scale actin rearrangement by transgelin-2 may indirectly influence the avidity change of LFA-1. Lastly, it may directly associate with LFA-1 in T cells. In this regard, actin might be an adapter molecule that interacts with both transgelin-2 and LFA-1.[15] Unlike to its role in T-cell effector functions, transgelin-2 is not involved in the development of lymphocytes. Mice with trnasgelin-2 deficiency or overexpression show normal development of T cells and B cells without any changes of primary and secondary lymphoid organs.[15,19]

5.2 | B Lymphocytes

In B lymphocytes, transgelin-2 appears to be less crucial with respect to B-cell activation compared to its essential role in T-cell activation. In response to an antigen bound to BCR, the timing of the actin cytoskeletal reorganization corresponds to both the initiation and maintenance of B-cell stimulation.[59–61] Initially, the induction of transgelin-2 as well as its colocalization with the F-actin ring to the periphery of BCR clusters after BCR stimulation implied a positive role for B-cell activation.[31] Consistent with this, after antigen-driven B-cell stimulation, upregulation of the expression of some proteins, including the chemokine receptor 6 (CCR6) and Abl-interactor 2 (ABI2), was retarded in transgelin-2-deficient B cells compare to that in wild-type cells,[31] and phosphorylation of PLCγ2, an early player in the BCR-signaling cascade, was diminished,[31] indicating that transgelin-2 might affect B-cell activation. However, the influence of transgelin-2 in B-cell activation might not be as essential as that in T cells, since PI3K, ERK, and Akt, downstream proteins of phosphorylated PLCγ2, were not affected, and neither of surface molecules such as CXCR5 and BCR was affected.[31] Consistent with these results, Na et al. demonstrated that knockout of *TAGLN2* had little effect on B-cell functions, as determined by a lack of significant changes in the expression of CD69, MHC class II, CD80, and CD86, all of which are markers of B-cell activation.[19] Interestingly, although transgelin-2 shows little influence on B-cell activation, it may be an important regulator for controlling B-cell-mediated T-cell activation. During IS formation, transgelin-2 accumulated at the F-actin-rich filopodia of B cells. It stabilizes T–B conjugates partly by enhancing its adhesion to T cells, which consequently induces T-cell activation.[19] In a reverse manner, even though transgelin-2 in B cells has a minor function in B-cell activation, it is still important for B cells as transgelin-2 in T cells facilitates T-cell activation that subsequently activates B cells.[15]

5.3 | Macrophages

Macrophages serve several essential roles at the initial host defense; they produce inflammatory cytokines and destroy pathogens by phagocytosis, which blocks early dissemination of pathogens.[62] Upon TLR-mediated activation, highly induced levels of transgelin-2 in macrophages contribute to the receptor-mediated (FcγR- or CR-mediated) phagocytosis as well as the release of inflammatory cytokines.[17] Transgelin-2 enriched in the actin-rich membrane apical region facilitates fMLP-induced actin polymerization and subsequent ruffles and phagocytic cup formation, which are important structures for the phagocytosis of bacteria. In conjunction with the actin remodeling, transgelin-2 is linked to the PI3K/AKT- and ERK-signaling pathways, a well-known actin-linked signaling axis in receptor-mediated activation.[63,64] Interestingly, transgelin-2 deficiency significantly retarded the fMLP-induced activation of PI3K, AKT, and ERK, demonstrating an involvement for fMLP-mediated actin reorganization[65] in activated macrophages. As a consequence, large-scale transgelin-2 induction can explain the elevated phagocytic activity of activated macrophage. Furthermore, *TAGLN2* knockout mice showed higher plasma levels of inflammatory cytokines secreted by macrophages: TNF-α, IL-6, IL-1β, and IL-12, as well as defective bacterial clearance due to damaged phagocytic function, therefore demonstrating the comprehensive influence of transgelin-2 in macrophages.[17] As a consequence, *TAGLN2* knockout mice showed highly increased susceptibility to bacterial infection.[17]

6 | TRANSGELIN-2 AS A T CELL BOOSTER FOR IMMUNOTHERAPY

For the management of cancer, cancer immunotherapy exploits the patients' tumor-specific immunity by several strategies originating from studies on endogenous immune surveillance. Along with immune checkpoint blockades such as anticytotoxic T lymphocyte-associated protein 4-B7-1, B7-2, and antiprogrammed cell death protein 1 (PD1)-PD-L1 axis, one emerging immunotherapeutic regime is an adoptive cellular therapy (ACT) with reactivated tumor-infiltrated lymphocytes (TILs) and chimeric antigen receptor (CAR)-transformed T or NK cells.[66,67] However, even though genetic engineering has been broadening the application of ACT, the immunosuppressive tumor microenvironment extensively limits the efficacy of regimes; a lack of costimulatory signals and the presence of inhibitory signals such as PD-L1 in tumor microenvironments inhibit the activation of immune cells.[66] One possible strategy to overcome this insufficient costimulation at TILs or CAR-engineered T and NK cells could be the

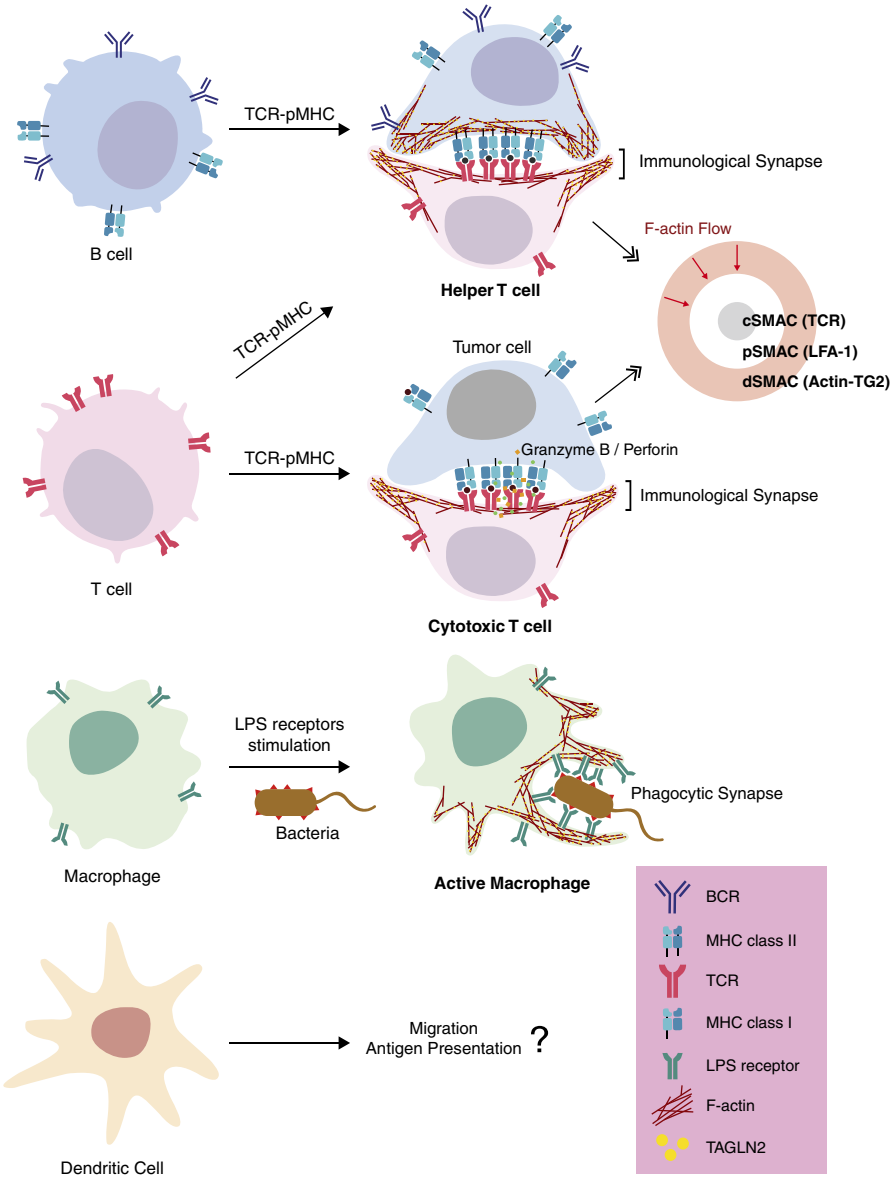

FIGURE 2 Functions of transgelin-2 in various immune cells. Transgelin-2 expression is controlled at the transcriptional, translational, and post-translational levels in B cells and macrophages. However, its expression is relatively constitutive in T cells. Transgelin-2 stabilizes the immunological synapses that are formed during $CD4^+$ T cell interaction with APCs and $CD8^+$ T cell conjugation with tumor target cells. In macrophages, transgelin-2 is involved in the formation of phagocytic synapses that facilitates the clearance of infectious bacteria in the body. More studies are needed to elucidate the function of transgelin-2 in DCs and for its application in adoptive cell therapy

stabilization of the cytotoxic IS between killer T cells and tumor target cells. Transgelin-2 is a good candidate for this approach, particularly via actin engineering at the T-cell side; upon TCR activation, it potentiates cytotoxic T cell functions through "inside-out" costimulatory LFA-1 activation via Rap1 and F-actin stabilization at the IS.[15] Its significance is further supported by the fact that $CD8^+$ T-cell costimulation requires only high affinity (transgelin-2-Rap1-activated) LFA-1, whereas $CD4^+$ T-cell costimulation depends on both high and low affinity LFA-1.[56] Recently, our group has observed that retroviral transduction of transgelin-2 in adoptively transferred CTLs largely enhanced its antitumor activity in an LFA-1/ICAM-1-dependent manner, targeting ICAM-1-expressed tumor tissues, both in vitro and in vivo (unpublished results). Moreover, the internalization of recombinant transgelin-2 fused with a protein transduction domain showed similar efficacy to viral transduction of transgelin-2 in the same study, thereby indicating the feasibility of recombinant transgelin-2 peptide as an active adjuvant in cell-based immunotherapies, including tumor-specific TILs or CAR-engineered killer cells.

7 | CONCLUDING REMARKS

The mechanisms underlying actin dynamics in a variety of immunological processes are quite sophisticated, involving the ABPs and interlaced signaling pathways. Transgelin-2 is actively involved in the actin cytoskeletal rearrangements and its expression seems to be up- or downregulated in different conditions, including BCR/TCR/TLR stimulation. Although transgelin-2 has been mainly studied within T cells,

B cells, and macrophages, there have been other immune cell types that have been reported to express transgelin-2, such as dendritic cells (DCs). A proteomic analysis of differentially matured DCs demonstrated that transgelin-2 expression was highly upregulated in some DC subpopulations.[68] Moreover, it may be also worth mentioning that the DC cytoskeleton promotes T-cell adhesion and activation via ICAM-1 avidity alteration.[69] In this regard, the function of transgelin-2 in controlling the actin cytoskeleton in B cells, another APC, implies an important role of transgelin-2 in DCs as well.[19] Currently, our group is in the process of investigating how transgelin-2 functions in DCs. Figure 2 summarizes the known and potential functions of transgelin-2 in various immune cells.

The regulation of the actin cytoskeleton is critical both in cancer and CTL functions in immune surveillance, as it controls fundamental tumor-related processes including cell migration (cancer metastasis)[70] and regulates IS formation, respectively. While microtubule, another essential cytoskeletal component, has been largely studied and established as a target for antitumor drugs and chemotherapeutic agents,[71] actin-targeting approaches have yet to gain approval for clinical use, presumably due to the lack of knowledge in targeting tumor-specific pathways and concomitant off-target effects.[72] However, transgelin-2 overexpression in ACT does not affect the actin cytoskeleton and cellular processes in other tissues or cells, as transgelin-2 or its engineered constructs can be transduced or treated ex vivo. The deleterious impact of transgelin-2-overexpressing cytotoxic T cells is not expected because of its endogenous nature in T cells, which has not been reported thus far. Notably, transgelin-2 has been suggested as a promising antasthmatic drug target in a recent study; its agonist, TSG12, relaxes both human and mice airway smooth muscle cells and reduces pulmonary resistance without detectable toxicity or desensitization.[73] Taken together, transgelin-2-mediated actin and LFA-1-ICAM-1 axis concurrent enhancement may be a safe and potential supplementary regime for conventional cell-mediated cancer immunotherapies. In conclusion, recent studies have shown that transgelin-2 is an important immune regulator in the context of immune cell–cell interaction. Based on its role in CTL activation, an immunotherapeutic regime using transgelin-2 as a synergist of ACT is currently under investigation, and further engineering of transgelin-2 would facilitate translation of this approach from bench to bedside.

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AUTHORSHIP

S.J. and H.R.K. wrote the review. Y.M. created the figures. C.D.J. wrote and finalized the review.

DISCLOSURE

The authors declare no competing financial interests.

REFERENCES

1. Goley ED, Welch MD. The ARP2/3 complex: an actin nucleator comes of age. *Nat Rev Mol Cell Biol*. 2006;7:713–726.
2. Fritzsche M, Fernandes RA, Chang VT, et al. Cytoskeletal actin dynamics shape a ramifying actin network underpinning immunological synapse formation. *Sci Adv*. 2017;3:e1603032.
3. Chhabra ES, Higgs HN. The many faces of actin: matching assembly factors with cellular structures. *Nat Cell Biol*. 2007;9:1110–1121.
4. Comrie WA, Burkhardt JK. Action and traction: cytoskeletal control of receptor triggering at the immunological synapse. *Front Immunol*. 2016;7:1–25.
5. Beemiller P, Jacobelli J, Krummel MF. Integration of the movement of signaling microclusters with cellular motility in immunological synapses. *Nat. Immunol*. 2012;13:787–795.
6. Samstag Y, Eibert SM, Klemke M, Wabnitz GH. Actin cytoskeletal dynamics in T lymphocyte activation and migration. *J Leukoc Biol*. 2003;73:30–48.
7. Ritter AT, Angus KL, Griffiths GM. The role of the cytoskeleton at the immunological synapse. *Immunol Rev*. 2013;256:107–117.
8. Dustin ML, Cooper JA. The immunological synapse and the actin cytoskeleton: molecular hardware for T cell signaling. *Nat. Immunol*. 2000;1:23–29.
9. Hartwig JH, Kwiatkowski DJ. Actin-binding proteins. *Curr Opin Cell Biol*. 1991;3:87–97.
10. Shapland C, Hsuan JJ, Totty NF, Lawson D. Purification and properties of transgelin: a transformation and shape change sensitive actin-gelling protein. *J Cell Biol*. 1993;121:1065–1073.
11. Stanier P, Abu-Hayyeh S, Murdoch JN, Eddleston J, Copp AJ. Paralogous sm22alpha (Tagln) genes map to mouse chromosomes 1 and 9: further evidence for a paralogous relationship. *Genomics*. 1998;51:144–147.
12. Ren W, Ng GYK, Wang R, et al. The identification of NP25: a novel protein that is differentially expressed by neuronal subpopulations. *Mol Brain Res*. 1994;22:173–185.
13. Lees-Miller JP, Heeley DH, Smillie LB, Kay CM. Isolation and characterization of an abundant and novel 22-kDa protein (SM22) from chicken gizzard smooth muscle. *J Biol Chem*. 1987;262:2988–2993.
14. Assinder SJ, Stanton JAL, Prasad PD. Transgelin: an actin-binding protein and tumour suppressor. *Int J Biochem Cell Biol*. 2009;41:482–486.
15. Na BR, Kim HR, Piragyte I, et al. TAGLN2 regulates T cell activation by stabilizing the actin cytoskeleton at the immunological synapse. *J Cell Biol*. 2015;209:143–162.
16. Akber U, Na BR, Ko YS, et al. Phytocomponent 4-hydroxy-3-methoxycinnamaldehyde ablates T-cell activation by targeting protein kinase C-θ and its downstream pathways. *Int J Immunopharmacol*. 2015;25:130–140.
17. Kim HR, Lee HS, Lee KS, et al. An essential role for TAGLN2 in phagocytosis of lipopolysaccharide-activated macrophages. *Sci Rep*. 2017;7:8731.
18. Na BR, Jun CD. TAGLN2-mediated actin stabilization at the immunological synapse: implication for cytotoxic T cell control of target cells. *BMB Rep*. 2015;48:369.
19. Na BR, Kwon MS, Chae MW, et al. Transgelin-2 in B cells controls T-cell activation by stabilizing T cell-B cell conjugates. *PLoS One*. 2016;11:e0156429.

20. Meng T, Liu L, Hao R, Chen S, Dong Y. Transgelin-2: a potential oncogenic factor. *Tumor Biol*. 2017;39:101042831770265.
21. Li M, Li S, Lou Z, et al. Crystal structure of human transgelin. J. *Struct Biol*. 2008;162:229–236.
22. Maul RS, Song Y, Amann KJ, Gerbin SC, Pollard TD, Chang DD. EPLIN regulates actin dynamics by cross-linking and stabilizing filaments. *J Cell Biol*. 2003;160:399–407.
23. Ge P, Durer ZAO, Kudryashov D, Zhou ZH, Reisler E. Cryo-EM reveals different coronin binding modes for ADP- and ADP-BeFx actin filaments. *Nat Struct Mol Biol*. 2014;21:1075–1081.
24. Han M, Dong LHH, Zheng B, Shi JHH, Wen JKK, Cheng Y. Smooth muscle 22 alpha maintains the differentiated phenotype of vascular smooth muscle cells by inducing filamentous actin bundling. *Life Sci*. 2009;84:394–401.
25. Gordón-Alonso M, Sala-Valdés M, Rocha-Perugini V, et al. EWI-2 association with α-actinin regulates T cell immune synapses and HIV viral infection. *J Immunol*. 2012;189:689–700.
26. Van der Flier A, Sonnenberg A. Structural and functional aspects of filamins. *Biochim Biophys Acta*. 2001;1538:99–117.
27. Stokes DL, DeRosier DJ. Growth conditions control the size and order of actin bundles in vitro. *Biophys J*. 1991;59:456–465.
28. Glenney JR, Kaulfus P, Matsudaira P, Weber K. F-actin binding and bundling properties of fimbrin, a major cytoskeletal protein of microvillus core filaments. *J Biol Chem*. 1981;256:9283–9288.
29. Camoretti-Mercado B, Forsythe SM, LeBeau MM, et al. Expression and cytogenetic localization of the human SM22 gene (TAGLN). *Genomics*. 1998;49:452–457.
30. Mori K, Muto Y, Kokuzawa J, et al. Neuronal protein NP25 interacts with F-actin. *Neurosci Res*. 2004;48:439–446.
31. Kiso K, Yoshifuji H, Oku T, et al. Transgelin-2 is upregulated on activated B cells and expressed in hyperplastic follicles in lupus erythematosus patients. *PLoS One*. 2017;12:1–16.
32. Francés R, Tumang JR, Kaku H, Gurdak SM, Rothstein TL. B-1 cells express transgelin 2: unexpected lymphocyte expression of a smooth muscle protein identified by proteomic analysis of peritoneal B-1 cells. *Mol Immunol*. 2006;43:2124–2129.
33. Ali NA, McKay MJ, Molloy MP. Proteomics of Smad4 regulated transforming growth factor-beta signalling in colon cancer cells. *Mol BioSyst*. 2010;6:2332–2338.
34. Adam PJ, Regan CP, Hautmann MB, Owens GK. Positive- and negative-acting Kruppel-like transcription factors bind a transforming growth factor β control element required for expression of the smooth muscle cell differentiation marker SM22α in vivo. *J Biol Chem*. 2000;275:37798–37806.
35. Sinha S, Hoofnagle MH, Kingston PA, Mccanna ME, Owens GK, Mary E. Transforming growth factor- beta 1 signaling contributes to development of smooth muscle cells from embryonic stem cells. *Am J Physiol Cell Physiol*. 2004;22908:1560–1568.
36. Yakabe K, Murakami A, Kajimura T, et al. Functional significance of transgelin-2 in uterine cervical squamous cell carcinoma. *J Obstet Gynaecol Res*. 2016;42:566–572.
37. Moriya Y, Nohata N, Kinoshita T, et al. Tumor suppressive microRNA-133a regulates novel molecular networks in lung squamous cell carcinoma. *J Hum Genet*. 2012;57:38–45.
38. Yoshino H, Enokida H, Itesako T, et al. Tumor-suppressive microRNA-143/145 cluster targets hexokinase-2 in renal cell carcinoma. *Cancer Sci*. 2013;104:1567–1574.
39. Nohata N, Sone Y, Hanazawa T, et al. miR-1 as a tumor suppressive microRNA targeting TAGLN2 in head and neck squamous cell carcinoma. *Oncotarget*. 2011;2:29–42.
40. Kawakami K, Enokida H, Chiyomaru T, et al. The functional significance of miR-1 and miR-133a in renal cell carcinoma. *Eur J Cancer*. 2012;48:827–836.
41. Yoshino H, Chiyomaru T, Enokida H, et al. The tumour-suppressive function of miR-1 and miR-133a targeting TAGLN2 in bladder cancer. *Br J Cancer*. 2011;104:808–818.
42. Nohata N, Hanazawa T, Kikkawa N, et al. Identification of novel molecular targets regulated by tumor suppressive miR-1/miR-133a in maxillary sinus squamous cell carcinoma. *Int J Oncol*. 2011;39:1099–1107.
43. Du YY, Zhao LM, Chen L, et al. The tumor-suppressive function of miR-1 by targeting LASP1 and TAGLN2 in esophageal squamous cell carcinoma. *J Gastroenterol Hepatol*. 2016;31:384–393.
44. Liu N, Bezprozvannaya S, Williams AH, et al. microRNA-133a regulates cardiomyocyte proliferation and suppresses smooth muscle gene expression in the heart. *Genes Dev*. 2008;22:3242–3254.
45. Xiao G, Xia C, Yang J, et al. MiR-133b regulates the expression of the actin protein TAGLN2 during oocyte growth and maturation: a potential target for infertility therapy. *PLoS One*. 2014;9:1–9.
46. Fu Y, Liu HW, Forsythe SM, et al. Mutagenesis analysis of human SM22 : characterization of actin binding. *J Appl Physiol*. 2000;89:1985–1990.
47. Fan L, Jaquet V, Dodd PR, Chen W, Wilce PA. Molecular cloning and characterization of hNP22: a gene up-regulated in human alcoholic brain. *J Neurochem*. 2001;76:1275–1281.
48. Mischak H, Dammeier S, Lovric J, et al. Identification of the smooth muscle-specific protein, sm22, as a novel protein kinase C substrate using two-dimensional gel electrophoresis and mass spectrometry. *Electrophoresis*. 2000;21:2443–2453.
49. Lv P, Miao SB, Shu YN, et al. Phosphorylation of smooth muscle 22α facilitates angiotensin II-induced ROS production via activation of the PKCδ-P47phox axis through release of PKCδ and actin dynamics and is associated with hypertrophy and hyperplasia of vascular smooth muscle cells. *Circ Res*. 2012;111:697–707.
50. Leung W, Ching A, Chan A, et al. A novel interplay between oncogenic PFTK1 protein kinase and tumor suppressor TAGLN2 in the control of liver cancer cell motility. *Oncogene*. 2011;30:4464–4475.
51. Li J, Li Q, Tang J, Xia F, Wu J, Zeng R. Quantitative phosphoproteomics revealed glucose-stimulated responses of islet associated with insulin secretion. *J Proteome Res*. 2015;14:4635–4646.
52. Babich A, Li S, O'Connor RS, Milone MC, Freedman BD, Burkhardt JK. F-actin polymerization and retrograde flow drive sustained PLCγ1 signaling during T cell activation. *J Cell Biol*. 2012;197:775–787.
53. Sun HQ, Kwiatkowska K, Yin HL. Actin monomer binding proteins. *Curr Opin Cell Biol*. 1995;7:102–110.
54. Huang Y, Burkhardt JK. T-cell-receptor-dependent actin regulatory mechanisms. *J Cell Sci*. 2007;120:723–730.
55. Katagiri K, Maeda A, Shimonaka M, Kinashi T. RAPL, a Rap1-binding molecule that mediates Rap1-induced adhesion through spatial regulation of LFA-1. *Nat Immunol*. 2003;4:741–748.
56. Wang Y, Li D, Nurieva R, et al. LFA-1 affinity regulation is necessary for the activation and proliferation of naive T cells. *J Biol Chem*. 2009;284:12645–12653.
57. Katagiri K, Hattori M, Minato N, Kinashi T. Rap1 functions as a key regulator of T-cell and antigen-presenting cell interactions and modulates T-cell responses. *Mol Cell Biol*. 2002;22:1001–1015.
58. Lub M, van Kooyk Y, van Vliet SJ, Figdor CG. Dual role of the actin cytoskeleton in regulating cell adhesion mediated by the integrin lymphocyte function-associated molecule-1. *Mol Biol Cell*. 1997;8:341–351.

59. Song W, Liu C, Upadhyaya A. The pivotal position of the actin cytoskeleton in the initiation and regulation of B cell receptor activation. *Biochim Biophys Acta*. 2014;1838:569–578.

60. Seeley-fallen MK. Actin-mediated feedback loops in B-cell receptor signaling. *Immunol. Rev*. 2013:177–189.

61. Harwood NE, Batista FD. Early events in B cell activation. *Annu Rev Immunol*. 2010;28:185–210.

62. Andrews T, Sullivan KE. Infections in patients with inherited defects in phagocytic function. *Clin Microbiol Rev*. 2003;16:597–621.

63. Yeo JC, Wall AA, Luo L, Stow JL. Rab31 and APPL2 enhance FcγR-mediated phagocytosis through PI3K/Akt signaling in macrophages. *Mol Biol Cell*. 2015;26:952–965.

64. Monick MM, Powers LS, Barrett CW, et al. Constitutive ERK MAPK activity regulates macrophage ATP production and mitochondrial integrity. *J Immunol*. 2008;180:7485–7496.

65. Belisle B, Abo A. N-Formyl peptide receptor ligation induces rac-dependent actin reorganization through Gbeta gamma subunits and class Ia phosphoinositide 3-kinases. *J Biol Chem*. 2000;275:26225–26232.

66. Intlekofer AM, Thompson CB. At the Bench: preclinical rationale for CTLA-4 and PD-1 blockade as cancer immunotherapy. *J Leukoc Biol*. 2013;94:25–39.

67. Farkona S, Diamandis EP, Blasutig IM. Cancer immunotherapy: the beginning of the end of cancer. *BMC Med*. 2016;14:73.

68. Ferret-Bernard S, Castro-Borges W, Dowle AA, et al. Plasma membrane proteomes of differentially matured dendritic cells identified by LC-MS/MS combined with iTRAQ labelling. *J Proteomics*. 2012;75:938–948.

69. Comrie WA, Li S, Boyle S, Burkhardt JK. The dendritic cell cytoskeleton promotes T cell adhesion and activation by constraining ICAM-1 mobility. *J Cell Biol*. 2015;208:457–473.

70. Olson MF, Sahai E. The actin cytoskeleton in cancer cell motility. *Clin Exp Metastasis*. 2009;26:273–287.

71. Zhou J, Giannakakou P. Targeting microtubules for cancer chemotherapy. *Curr Med Chem Anticancer Agents*. 2005;5:65–71.

72. Foerster F, Braig S, Moser C, et al. Targeting the actin cytoskeleton: selective antitumor action via trapping PKCε. *Cell Death Dis*. 2014;5:e1398–e1413.

73. Yin LM, Xu YD, Peng LL, et al. Transgelin-2 as a therapeutic target for asthmatic pulmonary resistance. *Sci Transl Med*. 2018. 10:eaam8604.

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