

RhoH in TCR Signalling

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As an atypical member of the Rho family small GTPases, RhoH shares less than 50% sequence similarity with other members, and its expression is commonly observed in the haematopoietic lineage. To date, RhoH function was observed in regulating T cell receptor signalling, and less is known in other haematopoietic cells. Its activation may not rely on the standard GDP/GTP cycling of small G proteins and is thought to be constitutively active because critical amino acids involved in GTP hydrolysis are absent. Alternatively, its activation can be regulated by other types of regulation, including lysosomal degradation, somatic mutation and transcriptional repressor, which also results in an altered protein expression. Aberrant protein expression of RhoH has been implicated not only in B cell malignancies but also in immune-related diseases, such as primary immunodeficiencies, systemic lupus erythematosus and psoriasis, wherein its involvement may provide the link between immune-related diseases and cancer.

Keywords: small GTPase ; RhoH ; malignant B cell ; immunodeficiency ; autoimmune

1. Introduction

The Rho (Ras homologous) family of small GTPases is one of the members of the Ras superfamily. In humans, 20 Rho-family GTPase members have been identified and categorised into eight major subfamilies Rho-, Rac-, Cdc42-, RhoU/RhoV-(also known as Wrch/Wrch2), Rnd-, RhoD/RhoF-, RhoBTB- and RhoH subfamilies. The subfamilies are categorised based on the similarities in their primary amino acid sequence ([Table 1](#)), structural motifs and biological functions [1]. Initially, Miro and RhoBTB3 were included as members of the Rho family small GTPases, but they have been excluded due to the lack of similarity between these proteins and other members of the Rho-family. For instance, Miro subfamily proteins lack the Rho insert region and are assumed to be non-catalytic as the sequence in the highly conserved G2–G5 loops responsible for nucleotide binding and hydrolysis is different compared with that in canonical GTPase domains [2][3]. RhoBTB3 shares 25% sequence similarity with and contains the same BTB domains as RhoBTB1 and RhoBTB2. However, this protein is not considered as a Rho GTPase by some studies due to its lack of similarity with Rho and Ras [3][4].

Table 1. The percentage sequence similarity shared between Rho-family GTPases.

	Rho BTB1	Rho BTB2	RhoH	Rnd1	Rnd2	Rnd3	RhoD	RhoF	RhoA	RhoC	RhoB	Wrch2	Wrch1	TC10	TCL	Cdc42	RhoG	Rac2	Rac1	Rac3
RhoBTB1		70	34	33	31	30	34	28	38	37	38	34	32	38	35	40	40	41	42	41
RhoBTB2	70		32	32	31	29	34	28	39	37	38	33	32	39	37	40	40	42	42	41
RhoH	34	32		29	32	36	38	33	40	40	41	41	38	40	39	42	40	40	41	40
Rnd1	32	32	29		53	61	37	39	41	42	41	31	32	36	34	37	37	39	39	38
Rnd2	31	31	32	53		63	39	41	46	47	43	28	31	36	35	37	41	40	41	39
Rnd3	29	29	36	61	63		37	40	48	48	47	31	32	39	35	38	41	39	42	40

	Rho BTB1	Rho BTB2	RhoH	Rnd1	Rnd2	Rnd3	RhoD	RhoF	RhoA	RhoC	RhoB	Wrch2	Wrch1	TC10	TCL	Cdc42	RhoG	Rac2	Rac1	Rac3
RhoD	34	35	38	37	39	37		49	49	49	49	39	36	42	38	43	44	46	49	49
RhoF	28	28	33	39	41	40	49		47	48	47	36	37	46	43	43	46	50	59	47
RhoA	38	39	40	41	46	48	49	47		92	85	40	44	51	48	53	55	53	57	55
RhoC	37	37	40	42	47	48	49	48	92		85	40	44	50	49	51	55	53	57	54
RhoB	38	38	41	41	43	47	49	47	85	85		42	45	51	48	50	53	54	55	54
Wrch2	34	33	41	31	28	31	39	36	40	40	42		59	51	48	53	46	51	52	53
Wrch1	32	32	37	32	31	32	36	37	44	44	45	59		50	46	56	48	54	54	54
TC10	38	39	40	36	36	39	42	46	51	50	51	51	50		76	66	54	60	62	61
TCL	35	37	39	34	35	35	38	44	48	49	48	48	46	76		63	53	58	60	59

Compared with other Ras superfamily proteins, the Rho-family small G-proteins have a Rho insert region, which is a unique α -helical sequence located between the fifth β strand and the fourth α helix in the G domain [5]. Many of the typical

Rho-family GTPases only have a Rho-type G domain with short N₁ and C-terminal extensions [6][7]. Similar to other Ras superfamily members, they also have a hypervariable region encoding a prenylation site at their C-termini and sometimes a polybasic region. These signals allow them to associate with specific membrane compartments [8].

Additionally, some of them also possess a CAAX (C: Cys, A: aliphatic residue, X: any amino acid) tetrapeptide sequence at their C-termini, which is important for lipid modification. This process involves three main steps, which are

isoprenylation, proteolysis and carboxyl methylation [9]. An isoprenoid lipid is attached to the CAAX box by a prenyltransferase, such as geranylgeranyltransferase (GGTase) or farnesyltransferase (FTase). Both of these enzymes recognise the CAAX sequence before adding a 20-carbon geranylgeranyl or 15-carbon farnesyl to the cysteine residue of the CAAX sequence via a thioether linkage. Prenylation is followed by the proteolysis of the three C-terminal residues (AAX) by a prenyl protein peptidase (from the Rce1 family as an example) to release AAX. The prenylated cysteine is then methylated by isoprenyl-cysteine carboxyl methyl-transferase. Compared with the atypical small RhoGTPases, many of the typical Rho-family GTPases are geranyl-geranylated or farnesylated, and only a few, such as RhoB, TC10 and Rac1, are palmitoylated (Table 2) [8][10]. However, some of the atypical small Rho GTPases also have a functional CAAX box that allows them to undergo prenylation (Table 2). For instance, both RhoU and RhoV only undergo palmitoylation, while Rnd proteins undergo farnesylation. Conversely, the RhoBTB subfamily does not possess any canonical CAAX motifs, suggesting that they may not undergo any lipid modification at the C-terminal.

Table 2. C-terminal sequences of the Rho-family small GTPases and their lipid modification.

Group	Rho Protein	C-Terminal Sequence	Lipid Modification	Ref
Typical	RhoA	KDGVREVFEMATRAALQARRGKKKSGCLVL	GG	
	RhoB	VREVFETATRAALQKRYGSQNGCINCKVL	GG, F, P	
	RhoC	KEGVREVFEMATRAGLQVRKNKRRRGCPIL	GG	
	Rac1	RGLKTVFDEAIRAVLCPPPVKKRKRKCLLL	GG, P	
	Rac2	RGLKTVFDEAIRAVLCQPTRQQKRACSL	GG	[11]
	Rac3	RGLKTVFDEAIRAVLCPPPVKKPGKKCTVF	GG	
	RhoG	QDGVKEVFAEAVRAVLNPTPIKRGRSCILL	GG	
	Cdc42	QKGLKNVFDEAILAALPEPEPKSRRCVLL	GG	
	TCL	AVFDEAILTIFHPKKKKKRCSEGHSCCSII	F	
	TC10	DEAIIAILTPKKHTVKKRIGSRCINCLIT	F, P	
Atypical	RhoU	QQQPKKSKSRTPDKMKNLSKSWWKYCCFV	P	[11]
	RhoV	EHKARLEKKNLAKGVRTLSRCRWKFFCFV	P	
	RhoD	AVFQEAAEVALSSRGRNFWRRITQGFCVVT	F, GG	[12]
	RhoF	EDVFREAAKVALSALKKAQRQKKRRRLCLLL	F, GG	
	Rnd1/ RhoS	LSKRLHLPSRSELISSTFKKEKAKSCSIM	F	
	Rnd2/ RhoN	MQRSAQLSGRPDRGNEGEIHKDRAKSCNLM	F	[11]
	Rnd3/ RhoE	KRISHMPSPPELSAVATDLRKDKAKSCTVM	F	
	RhoH/ TTF	VFECVRTAVNQARRRNRRLFSINECKIF	GG, F	[11][12]
	RhoBTB1	KREREKEDIALNKHRSRRKWCFWNSSPAVA	Unknown	N/A
	RhoBTB2	KRRWLFWNSSPSSSAASSSSPSSSSAVV	Unknown	

Putative palmitoylated cysteines are in boldface type and coloured red and CAAX prenylation motifs are underlined. N/A: not applicable.

Among the Rho-family GTPases, the most extensively studied members are RhoA, Rac1 and Cdc42. These proteins and their subfamilies are known as classical or typical Rho-family GTPases. The other Rho-family proteins are known as the non-classical or atypical Rho GTPases and include the RhoBTB and Rnd subfamilies. This classification is made based

on the ability of the Rho-family GTPases to undergo the standard GTPase cycle [6][13]. The atypical Rho GTPases often contain extra domains and are therefore longer than classical Rho GTPases.

Compared with the atypical small GTPases are further divided into fast-cycling and GTPase-defective G proteins (Table 3). In resting cells, the typical Rho-family GTPases are generally assumed to be in their inactive GDP-bound form either alone or in complex with RhoGDIs [14]. However, in contrast to the typical Rho-family GTPases, RhoD, RhoF, RhoU and RhoV have a rapid nucleotide exchange compared with standard GTP hydrolysis, which classifies them as fast-cycling small G proteins [15][16][17]. The Phe28 mutations of Ras, Rac1, Cdc42 and RhoA have rapid nucleotide exchange and can induce oncogenic transformation [18][19]. RhoU and RhoV also have mutated phenylalanine at position 28 (Table 3), and this factor might be one of the reasons for considering both of these proteins as fast-cycling small G proteins.

Table 3. Selected amino acid sequences of the typical and atypical small Rho GTPases.

Amino Acids 12, 59 and 61			
Group	Subfamily	Member	Sequence
			12 59 61
Classic	Cdc42	Cdc42	
			GDGAV---AGQED
Fast-cycling	RhoU/RhoV	RhoU	GDGAV---AGQED
		RhoV	GDGAV---AGQDE
	RhoD/RhoF	RhoD	GDGGC---AGQDD
		RhoF	GDGGC---AGQED
GTPase defective	RhoBTB	RhoBTB-1	GDNVAV---FGDHH
		RhoBTB-2	GDNVAV---FGDHH
	Rnd	Rnd1	GDVQC---SGSPY
		Rnd2	GDAEC---SGSSY
		Rnd3	GDVQC---SGSPY
		RhoH	GDSAV---AGNDA
Amino acids 28			

Amino Acids 12, 59 and 61			
Group	Subfamily	Member	Sequence
Classic	Rac	Rac1	<u>28</u> SYTTNAFPGEYIP
		RhoU	SYTTNGYPTEYIP
Fast-cycling	RhoU/RhoV	RhoV	SYTCNGYPARYRP
		RhoD	VFADGAFPESYTP
	RhoD/RhoF	RhoF	VYSQGSFPEHYAP

Amino acid residues 12, 28, 59 and 61 are in boldface type and underlined [13].

The fast-cycling Rho GTPases have GTPase activity and are identical to Cdc42 at amino acids Gly12, Ala59 and Gln61 (Ras numbering) (Table 3) [13]. Gly12 and Ala59 are important for GTP hydrolysis, while Gln61 is necessary to stabilise the transition state of hydrolysis [20]. These amino acid residues are reported to be mutated in GTPase-deficient Ras [21]. By contrast, the GTPase defective atypical Rho-family members, including Rnd1, Rnd2, Rnd3, RhoBTB1, RhoBTB2 and RhoH, do not possess the conserved Gly12, Ala59 and Gln61 compared with Cdc42 (Table 3) [4][13].

Most studies have focused on the role of the typical small Rho GTPases in diseases, but information on the atypical small Rho GTPases is limited. Among the rare small Rho GTPases that receive much attention is RhoH as it is associated with several diseases, such as B cell malignancies, immunodeficiency and autoimmune diseases. This small GTPase has a unique role compared with others because it acts as a tumour-suppressor protein. Hence, a thorough understanding of the function of RhoH in both normal and disease conditions may help to identify and design an efficacious target.

2. RhoH, An Atypical Rho Family Small GTPase

Within the family, RhoH and Cdc42 share 42% sequence similarity, with the major differences in the C-terminal region (Figure 1). It also contains a shorter Rho insert region that is more similar to classical Rho-family proteins but is GTPase defective because conserved residues corresponding to Gly12, Ala59 and Gln61 (Ras numbering) are absent (Table 3). However, RhoH has a CAAX box, a CKIF motif at its C-terminus, which allows farnesylation and geranyl-geranylation [22] and facilitates membrane targeting. RhoH myristoylation at the N-terminal may also assist RhoH attachment to the plasma membrane and promote its interacting partners, Lck, ZAP-70 and Syk recruitment to the membrane to facilitate T cell receptor (TCR) signalling [23][24][25]. Among the Rho family members, RhoH is the only member with an ITAM-like motif, which is characterised by two tyrosines, spaced by six amino acids: Y73xxA76₆Y83xxA86 (Figure 1). This consensus motif is crucial for the recruitment of ZAP-70 to CD3ζ in the immunological synapse [23].

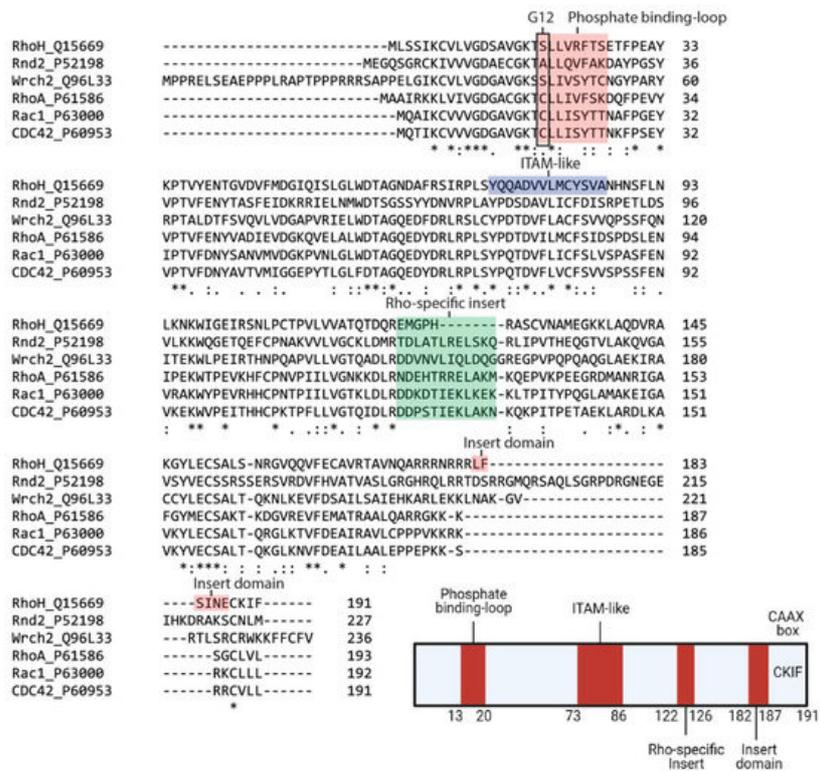


Figure 1. Sequence alignment and architecture of RhoH. Sequence alignment of RhoH, Rnd2, Wrch2, RhoA, Rac1 and Cdc42. Rnd2 and Wrch2 are representatives of the fast-cycling and GTPase-defective small GTPases, while RhoA, Rac1 and Cdc42 are typical small Rho GTPases (**Top**). RhoH shares a phosphate-binding loop with other small Rho GTPases but is assumed as GTPase defective due to the absence of Gly12. The Rho-specific insert in RhoH is shorter than that in other small Rho GTPases. RhoH also has an ITAM-like motif at position Tyr73 to Ala86 and a carboxyl-terminal insert domain (L₁₈₂FSINE₁₈₇) that function to regulate RhoH stability. RhoH also undergoes prenylation at the C-terminal due to the presence of the CAAX box (CKIF), similar to other typical small Rho GTPases (**Bottom**). (Created with Biorender).

Given that RhoH may be GTPase defective, other mechanisms have been described to regulate RhoH activity, including the regulation of mRNA level and tyrosine phosphorylation of the unique ITAM-like motif [22]. Additionally, RhoH activity can be regulated by lysosomal degradation through its unique C-terminal region, L₁₈₂FSINE₁₈₇ domain, located in between its polybasic region and CAAX box. This insert domain has been shown to regulate RhoH stability via chaperone-mediated autophagy (CMA) [26].

In contrast to the typical Rho-family members, which are best studied for their role in promoting actin cytoskeleton reorganisation, especially during cell division and migration [2], RhoH does not regulate actin reorganisation in NIH3T3 or MDCK cells [27]. However, Mino et al., (2018) showed that RhoH is involved in modulating the structure of actin-cytoskeleton and transcriptional activity during T cell migration and adhesion by forming a multi-protein complex with p120 catenin and the transcriptional regulator, Kaiso, to attenuate Rac1 signalling. Aside from regulating Rac1 signalling, RhoH interaction with Kaiso is necessary to facilitate Kaiso nuclear localisation to repress *BCL6* gene, a transcriptional repressor expression, resulting in an increase in tumour suppressor p53 protein [28]. Collectively, the inhibitory function of RhoH would help to reduce the events of cell survival, migration and invasion [29][30]. By contrast, although RhoH is assumed to be expressed only in haematopoietic cells, it was shown to promote cell migratory polarity in prostate cancer cell line by directing Rac1 and PAK2 to membrane protrusions [31]. These contrary functions of RhoH might be dependent on the type and origin of the cells. For instance, RhoH is dispensable for the development of myeloid, erythroid, and B cells but is crucial for T cell production, survival and migration [32][33]. This function is consistent with the study of Chae et al., (2010) that showed a lack of RhoH-impaired thymocyte development and stimulation of peripheral T cell unresponsiveness [23][34].

The current knowledge of RhoH function is only limited in T cells (Figure 2), whereupon during response to TCR activation, RhoH is phosphorylated by kinases, such as DRAK2 [35]. This phosphorylation event promotes its interaction with ZAP-70 via the ITAM-like motif. ZAP-70 and Lck will then be recruited to the TCR, where ZAP-70 is activated and colocalised with its substrates. As a result, activated ZAP-70 will promote linker of activated T cells (LAT) and SLP76 signalling in T cell, crucial for T cell activation and development [23][24][25][36]. Additionally, RhoH was also found to act as an adaptor protein that retains Lck in an inactive state, thereby suggesting that RhoH can regulate both pre-TCR and TCR signalling during T cell development. However, in response to ligand-mediated TCR activation, Lck is recruited to the

membrane by RhoH and dephosphorylated by CD45, resulting in Lck auto-activation and its release from RhoH [37]. Active Lck will then stimulate PI3K signalling and the activity of RhoGEF, Vav1. Nonetheless, despite the obvious role of RhoH in T cell development, RhoH involvement in T cell-specific malignancies, such as in T cell lymphomas, is not well understood. Conversely, RhoH is known to be associated with B-cell neoplasm, but its function in regulating B cell signalling should be further studied.

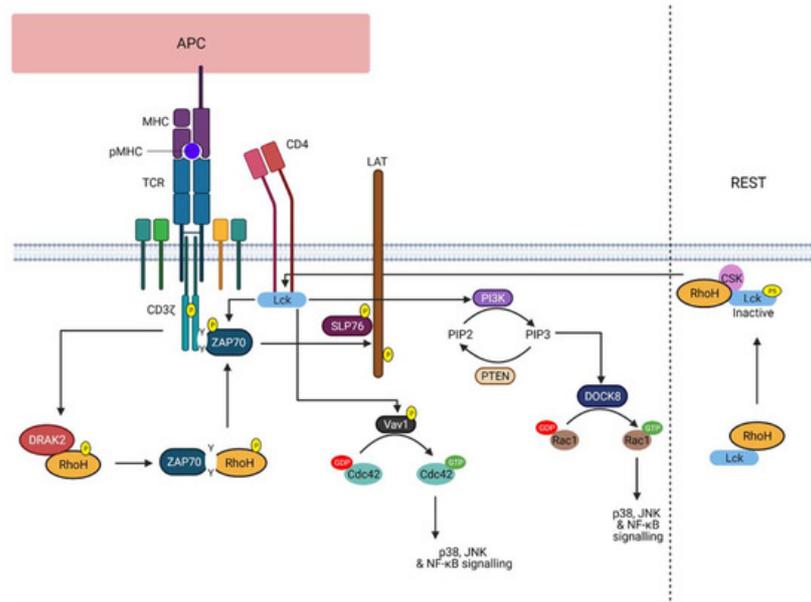


Figure 2. RhoH function upon TCR activation. The illustration shows the role of RhoH in regulating TCR signalling. Upon TCR stimulation, RhoH is phosphorylated by DRAK2 that promotes the interaction between RhoH and ZAP-70 via the ITAM-like motif of RhoH. ZAP-70 is recruited to the TCR CD3 ζ chain, thereby activating LAT and SLP76 signalling. As for Lck, RhoH functions to assist Lck recruitment to the membrane to facilitate TCR signalling. Active Lck promotes PI3K signalling and PIP3-induced DOCK8 activation. As a result, Rac1-related signalling is activated. Vav1-induced Cdc42 activation can also be regulated by Lck. However, at rest, RhoH recruits Lck to the plasma membrane, where RhoH accelerates and supports the inhibitory phosphorylation of Lck at Y505 (labelled with P5) by CSK (Created with Biorender).

3. RhoH as a Therapeutic Target

Considering the importance of RhoH in regulating TCR and BCR signalling pathways, much effort has been exerted on targeting RhoH to control diseases derived from abnormal T and B cell activation, such as cancer, immunodeficiency disorders and autoimmune diseases. RhoH protein levels are frequently reduced in the aforementioned diseases, suggesting the need to rectify the aberrant RhoH expression in the haematopoietic cells. The current drugs known to modulate RhoH activities are lenalidomide and ibrutinib [38]. However, the use of these drugs is critically dependent on the types of disease as these drug treatments were shown to regulate RhoH protein expression. For instance, the use of lenalidomide in the CLL murine model results in a decreased RhoH protein expression that promotes Rac1 and RhoA activation [39]. Additionally, deregulated RhoH protein expression can be corrected by using the current approach that relies on the potential therapeutic opportunity to target CMA [40]. This factor is based on the understanding that cellular protein levels are significantly influenced by protein stability. Hence, regulating their modes of degradation may promote protein stability. For instance, all-*trans* retinoic acid can be used to block the inhibitory effect of retinoic acid receptor alpha (RAR α) on the CMA process, especially on LAMP2A expression and its trafficking to lysosomes [41]. This approach can be applied to RhoH as the presence of the inserted domain, LFSINE, at the C-terminal was shown to act as a recognition signal for lysosomal uptake and CMA-mediated degradation, while not affecting its function on both T cells and B cells [26].

Another alternative is by targeting the RhoH interacting partner, ZAP-70. RhoH mediates TCR-induced ZAP-70 activation by recruiting it to CD3 ζ in the immunological synapse [23][32][34]. Additionally, RhoH was also found to promote ZAP-70-induced BCR signalling, which has been implicated in CLL [33][42][43][44]. Hence, preventing ZAP-70 recruitment to the plasma membrane may help to block excessive signalling. Several studies have identified potential ZAP-70 inhibitors that can modulate the interaction with TCR [45]. However, despite its therapeutic potential in autoimmune diseases and organ transplant rejection in vitro and in vivo, these inhibitors have never been tested in clinical trials, indicating the need for further investigation.

Alternatively, a peptide that can block or stimulate RhoH-related signalling may be used as a potential therapeutic target. The use of therapeutic peptides is an emerging targeted therapy that is often associated with rapid production and capacity for modification. However, this strategy has several drawbacks that usually arise due to their limited bioavailability and specificity [46][47]. Thus, far, no specific RhoH-therapeutic peptide is available or has been reported that may be due to the limited knowledge of RhoH functional activities.

References

1. Hodge, R.G.; Ridley, A.J. Regulating Rho GTPases and their regulators. *Nat. Rev. Mol. Cell Biol.* 2016, 17, 496–510.
2. Fransson, Å.; Ruusala, A.; Aspenström, P. Atypical Rho GTPases Have Roles in Mitochondrial Homeostasis and Apoptosis. *J. Biol. Chem.* 2003, 278, 6495–6502.
3. Boureux, A.; Vignal, E.; Faure, S.; Fort, P. Evolution of the Rho Family of Ras-Like GTPases in Eukaryotes. *Mol. Biol. Evol.* 2006, 24, 203–216.
4. Aspenström, P.; Ruusala, A.; Pacholsky, D. Taking Rho GTPases to the next level: The cellular functions of atypical Rho GTPases. *Exp. Cell Res.* 2007, 313, 3673–3679.
5. Valencia, A.; Chardin, P.; Wittinghofer, A.; Sander, C. The ras protein family: Evolutionary tree and role of conserved amino acids. *Biochemistry* 1991, 30, 4637–4648.
6. Wennerberg, K.; Der, C.J. Rho-family GTPases: It's not only Rac and Rho (and I like it). *J. Cell Sci.* 2004, 117, 1301–1312.
7. Citalán-Madrid, A.F.; García-Ponce, A.; Vargas-Robles, H.; Betanzos, A.; Schnoor, M. Small GTPases of the Ras superfamily regulate intestinal epithelial homeostasis and barrier function via common and unique mechanisms. *Tissue Barriers* 2013, 1, e26938.
8. Michaelson, D.; Silletti, J.; Murphy, G.; D'Eustachio, P.; Rush, M.; Philips, M.R. Differential localization of Rho GTPases in live cells: Regulation by hypervariable regions and RhoGDI binding. *J. Cell Biol.* 2001, 152, 111–126.
9. Choy, E.; Chiu, V.K.; Silletti, J.; Feoktistov, M.; Morimoto, T.; Michaelson, D.; Philips, M.R. Endomembrane Trafficking of Ras: The CAAX Motif Targets Proteins to the ER and Golgi. *Cell* 1999, 98, 69–80.
10. Adamson, P.; Paterson, H.F.; Hall, A. Intracellular localization of the P21rho proteins. *J. Cell Biol.* 1992, 119, 617–627.
11. Ridley, A.J. Rho GTPases and actin dynamics in membrane protrusions and vesicle trafficking. *Trends Cell Biol.* 2006, 16, 522–529.
12. Roberts, P.J.; Mitin, N.; Keller, P.J.; Chenette, E.J.; Madigan, J.P.; Currin, R.O.; Der, C.J. Rho Family GTPase modification and dependence on CAAX motif-signaled posttranslational modification. *J. Biol. Chem.* 2008, 283, 25150–25163.
13. Aspenström, P. Fast-cycling Rho GTPases. *Small Gtpases* 2020, 11, 248–255.
14. Dovas, A.; Couchman, J.R. RhoGDI: Multiple functions in the regulation of Rho family GTPase activities. *Biochem. J.* 2005, 390, 1–9.
15. Jaiswal, M.; Fansa, E.K.; Dvorský, R.; Ahmadian, M.R.; Communication, S.; Jaiswal, M.; Fansa, E.K.; Dvorsky, R.; Ahmadian, M.R. New insight into the molecular switch mechanism of human Rho family proteins: Shifting a paradigm. *Biol. Chem.* 2012, 394, 89–95.
16. Shutes, A.; Berzat, A.C.; Cox, A.D.; Der, C.J. Atypical Mechanism of Regulation of the Wrch-1 Rho Family Small GTPase. *Curr. Biol.* 2004, 14, 2052–2056.
17. Shutes, A.; Berzat, A.C.; Chenette, E.J.; Cox, A.D.; Der, C.J.B.T.-M. Biochemical Analyses of the Wrch Atypical Rho Family GTPases. *Regul. Eff. Small Gtpases Rho Fam.* 2006, 406, 11–26.
18. Lin, R.; Bagrodia, S.; Cerione, R.; Manor, D. A novel Cdc42Hs mutant induces cellular transformation. *Curr. Biol.* 1997, 7, 794–797.
19. Aspenström, P. Activated Rho GTPases in Cancer-The Beginning of a New Paradigm. *Int. J. Mol. Sci.* 2018, 19, 3949.
20. Prive, G.G.; Milburn, M.V.; Tong, L.; de Vos, A.M.; Yamaizumi, Z.; Nishimura, S.; Kim, S.H. X-ray crystal structures of transforming p21 ras mutants suggest a transition-state stabilization mechanism for GTP hydrolysis. *Proc. Natl. Acad. Sci. USA* 1992, 89, 3649–3653.
21. Muñoz-Maldonado, C.; Zimmer, Y.; Medová, M. A Comparative Analysis of Individual RAS Mutations in Cancer Biology. *Front. Oncol.* 2019, 9, 1088.

22. Fueller, F.; Kubatzky, K.F. The small GTPase RhoH is an atypical regulator of haematopoietic cells. *Cell Commun. Signal.* 2008, 6, 6.
23. Chae, H.-D.; Siefiring, J.E.; Hildeman, D.A.; Gu, Y.; Williams, D.A. RhoH regulates subcellular localization of ZAP-70 and Lck in T cell receptor signaling. *PLoS ONE* 2010, 5, e13970.
24. Tamehiro, N.; Oda, H.; Shirai, M.; Suzuki, H. Overexpression of RhoH Permits to Bypass the Pre-TCR Checkpoint. *PLoS ONE* 2015, 10, e0131047.
25. Sunshine, H.; Iruela-Arispe, M.L. Membrane lipids and cell signaling. *Curr. Opin. Lipidol.* 2017, 28, 408–413.
26. Troeger, A.; Chae, H.-D.; Senturk, M.; Wood, J.; Williams, D.A. A Unique Carboxyl-terminal Insert Domain in the Hematopoietic-specific, GTPase-deficient Rho GTPase RhoH Regulates Post-translational Processing. *J. Biol. Chem.* 2013, 288, 36451–36462.
27. Li, X.; Bu, X.; Lu, B.; Avraham, H.; Flavell, R.A.; Lim, B. The Hematopoiesis-Specific GTP-Binding Protein RhoH Is GTPase Deficient and Modulates Activities of Other Rho GTPases by an Inhibitory Function. *Mol. Cell. Biol.* 2002, 22, 1158–1171.
28. Horiguchi, H.; Ciuculescu, M.F.; Troeger, A.; Xu, H.; Brendel, C.; Williams, D.A. Deletion of Murine RhoH induces More Aggressive Diffuse Large B Cell Lymphoma (DLBCL) Via Interaction with Kaiso and Regulation of BCL-6 Expression. *Blood* 2018, 132, 1574.
29. Gu, Y.; Chae, H.-D.; Siefiring, J.E.; Jasti, A.C.; Hildeman, D.A.; Williams, D.A. RhoH GTPase recruits and activates Zap70 required for T cell receptor signaling and thymocyte development. *Nat. Immunol.* 2006, 7, 1182.
30. Muller, P.A.J.; Vousden, K.H.; Norman, J.C. p53 and its mutants in tumor cell migration and invasion. *J. Cell Biol.* 2011, 192, 209–218.
31. Tajadura-Ortega, V.; Garg, R.; Allen, R.; Owczarek, C.; Bright, M.D.; Kean, S.; Mohd-Noor, A.; Grigoriadis, A.; Elston, T.C.; Hahn, K.M.; et al. An RNAi screen of Rho signalling networks identifies RhoH as a regulator of Rac1 in prostate cancer cell migration. *Bmc Biol.* 2018, 16, 1–20.
32. Dorn, T.; Kuhn, U.; Bungartz, G.; Stiller, S.; Bauer, M.; Ellwart, J.; Peters, T.; Scharffetter-Kochanek, K.; Semmrich, M.; Laschinger, M.; et al. RhoH is important for positive thymocyte selection and T-cell receptor signaling. *Blood* 2007, 109, 2346–2355.
33. Sanchez-Aguilera, A.; Rattmann, I.; Drew, D.Z.; Müller, L.U.W.; Summey, V.; Lucas, D.M.; Byrd, J.C.; Croce, C.M.; Gu, Y.; Cancelas, J.A.; et al. Involvement of RhoH GTPase in the development of B-cell chronic lymphocytic leukemia. *Leukemia* 2010, 24, 97–104.
34. Tybulewicz, V.L.J.; Henderson, R.B. Rho family GTPases and their regulators in lymphocytes. *Nat. Rev. Immunol.* 2009, 9, 630–644.
35. Kay, L. Characterisation of Atypical Human GTPases: Elucidation of Molecular Functions and Interactors. Ph.D. Thesis, Northumbria University, Newcastle, UK, 2016.
36. Yablonski, D. Bridging the Gap: Modulatory Roles of the Grb2-Family Adaptor, Gads, in Cellular and Allergic Immune Responses. *Front. Immunol.* 2019, 10, 1704.
37. Wang, H.; Zeng, X.; Fan, Z.; Lim, B. RhoH modulates pre-TCR and TCR signalling by regulating LCK. *Cell. Signal.* 2011, 23, 249–258.
38. Pollyea, D.; Gore, L.; Gutman, J.; Eckhardt, S.G.; Hagelstrom, N.; Coutre, S.; Thirman, M.; Byrd, J. A Dose Escalation Study of Ibrutinib with Lenalidomide for Relapsed and Refractory Chronic Lymphocytic Leukemia/Small Lymphocytic Lymphoma. *Ann. Oncol.* 2013, 24, i33.
39. Troeger, A.; Johnson, A.J.; Wood, J.; Blum, W.G.; Andritsos, L.A.; Byrd, J.C.; Williams, D.A. RhoH is critical for cell-microenvironment interactions in chronic lymphocytic leukemia in mice and humans. *Blood* 2012, 119, 4708–4718.
40. Robert, G.; Jacquelin, A.; Auberger, P. Chaperone-Mediated Autophagy and Its Emerging Role in Hematological Malignancies. *Cells* 2019, 8, 1260.
41. Anguiano, J.; Garner, T.P.; Mahalingam, M.; Das, B.C.; Gavathiotis, E.; Cuervo, A.M. Chemical modulation of chaperone-mediated autophagy by retinoic acid derivatives. *Nat. Chem. Biol.* 2013, 9, 374–382.
42. Wagner, M.; Oelsner, M.; Moore, A.; Götte, F.; Kuhn, P.-H.; Haferlach, T.; Fiegl, M.; Bogner, C.; Baxter, E.J.; Peschel, C.; et al. Integration of innate into adaptive immune responses in ZAP-70–positive chronic lymphocytic leukemia. *Blood* 2016, 127, 436–448.
43. Burger, J.A.; Chiorazzi, N. B cell receptor signaling in chronic lymphocytic leukemia. *Trends Immunol.* 2013, 34, 592–601.

44. Kohlhaas, V.; Blakemore, S.J.; Al-Maarri, M.; Nickel, N.; Pal, M.; Roth, A.; Hövelmeyer, N.; Schäfer, S.C.; Knittel, G.; Lohneis, P.; et al. Active Akt signaling triggers CLL toward Richter transformation via overactivation of Notch1. *Blood* 2021, 137, 646–660.
 45. Visperas, P.R.; Wilson, C.G.; Winger, J.A.; Yan, Q.; Lin, K.; Arkin, M.R.; Weiss, A.; Kuriyan, J. Identification of Inhibitors of the Association of ZAP-70 with the T Cell Receptor by High-Throughput Screen. *SLAS Discov. Adv. Life Sci. R D* 2017, 22, 324–331.
 46. Boohaker, R.J.; Lee, M.W.; Vishnubhotla, P.; Perez, J.M.; Khaled, A.R. The use of therapeutic peptides to target and to kill cancer cells. *Curr. Med. Chem.* 2012, 19, 3794–3804.
 47. Cooper, B.M.; Iegre, J.; O' Donovan, D.H.; Ölwegård Halvarsson, M.; Spring, D.R. Peptides as a platform for targeted therapeutics for cancer: Peptide–drug conjugates (PDCs). *Chem. Soc. Rev.* 2021, 50, 1480–1494.
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