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Degradation by Cullin 3 and effect on WNK kinases suggest a role of KLHL2 in the pathogenesis of Familial Hyperkalemic Hypertension

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A B S T R A C T

Mutations in WNK1 and WNK4, and in components of the Cullin-Ring Ligase system, kelch-like 3 (KLHL3) and Cullin 3 (CUL3), can cause the rare hereditary disease, Familial Hyperkalemic Hypertension (FHHt). The disease is characterized by overactivity of the renal sodium chloride cotransporter (NCC), which is phosphorylated and activated by the WNK-stimulated Ste20-type kinases, SPAK and OSR1. WNK kinases themselves can be targeted for ubiquitination and degradation by the CUL3-KLHL3 E3 ubiquitin ligase complex. It is unclear, however, why there are significant differences in phenotypic severity among FHHt patients with mutations in different genes. It was reported that kelch-like 2 (KLHL2), a homolog of KLHL3, can also target WNK kinases for ubiquitination and degradation, and may play a special role in the systemic vasculature. Our recent study revealed the disease mutant CUL3 exhibits enhanced degradation of its adaptor protein KLHL3, potentially resulting in accumulation of WNK kinases secondarily. To investigate if KLHL2 plays a role in FHHt, we studied the effect of wild type and FHHt mutant CUL3 on degradation of KLHL2 and WNK kinase proteins in HEK293 cells. Although CUL3 facilitates KLHL2 degradation, the disease mutant CUL3 is more active in this regard. KLHL2 facilitated the degradation of wild type but not disease mutant WNK4 protein. These results suggest that KLHL2 likely plays a role in the pathogenesis of FHHt, and aggravates the phenotype caused by mutations in CUL3 and WNK4.

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Introduction

Familial Hyperkalemic Hypertension [FHHt, also known as pseudohypoaldosteronism (PHA2) or Gordon syndrome; OMIM: 145260] is a rare Mendelian disorder, featuring hypertension, hyperkalemia, and metabolic acidosis [1]. Members of With No lysine(K) kinases, WNK4 and WNK1, and components of Cullin-Ring Ligases (CRL), kelch-like 3 (KLHL3) and Cullin 3 (CUL3) were identified as FHHt-causing genes [2,3]. CUL3 acts as a scaffold for ubiquitination by binding to an adaptor protein, KLHL3, via its N-terminal. WNK kinases can be recognized by KLHL3 as substrates and finally be ubiquitinated by the CUL3-KLHL3 E3 ubiquitin ligase complex [4–7]. There is a consensus that constitutive activation of NCC in distal convoluted tubule (DCT) is a major driving force behind the FHHt phenotype [8]. Since WNK kinases activate NCC through Ste20-related Proline/Alanine-rich Kinase (SPAK)/Odd-Skipped-Related 1 (OSR1) pathway [9], and both CUL3 and KLHL3 are responsible for degrading WNK kinases, it is reasonable to presume there is increased WNK activity in all 4 known FHHt-causing syndromes. Indeed, WNK1 and/or WNK4 are elevated in animal models of WNK1, WNK4 and KLHL3 disease mutations [2,4,6], and recently in CUL3-FHHt mice [10]. To date, all CUL3-FHHt mutations are heterozygous, resulting in the deletion of 57 amino acids encoded for exon 9 of the CUL3 mRNA (hereafter referred to as CUL3 Δ9) [3,11]. The phenotype of FHHt with different gene
mutations varies from mild to severe, with CUL3-FHHt displaying the most severe phenotype (earliest onset age and most severe hypertension and electrolyte disturbance [3,12,13]). It has been reported that KLHL2, a homolog of KLHL3, is also expressed in the kidney and could mediate degradation of WNK kinases [14,15]. We recently reported a dominant effect of CUL3 ΔΩ on KLHL3 causing WNK kinase accumulation [16]. In this study we investigated the degradation effect of CUL3 on KLHL2, and the degradation effect of CUL3-KLHL2 on WNK kinases, to explore a potential role of KLHL2 in pathogenesis of FHHt.

Materials and methods

**Antibodies and reagents:** The polyclonal CUL3 antibody has previously been published [17]. Anti-myc (catalog no. M5546) and anti-flag (catalog no. F3165) antibodies used for WB were sigma mouse monoclonal. Actin polyclonal antibody (rabbit) used was from sigma. Human CUL3 WT and ΔΩ, and WNK kinase constructs have been reported [16]. CUL3 siRNA (catalog no. 4392420) was purchased from ThermoFisher Scientific. KLHL2 was amplified from mouse kidney cDNA, and human KLHL3 cDNA was purchased from GeneCopeia, INC (catalog no. EX-A1395-M11). Both cDNA were subcloned into the pmo-myc vector using PCR.

**Western blotting:** Transfected HEK293 cells were harvested in 1 mM EDTA in phosphate-buffered saline and sonicated for 10 s in radioimmunoprecipitation assay (RIPA) buffer (1% NP-40, 1% sodium deoxycholate, 0.1% SDS, 150 mM NaCl, 0.01 M sodium phosphate buffer pH 7.2 and 2 mM EDTA). Protein samples were separated by electrophoresis on 10% polyacrylamide gels, transferred to PVDF membranes (Bio-Rad, Hercules, CA), and incubated overnight in primary antibodies. Proteins were visualized using horseradish peroxidase-conjugated secondary antibodies and enhanced chemiluminescence followed by digital acquisition using an Alpha Innotech (San Leandro, CA) Fluorochem SP system.

**Cell culture and transfections:** HEK293 cells were maintained in DMEM supplemented with 10% FBS. Cells were transiently transfected using Lipofectamine™ 2000 (Ambion, Invitrogen) as previously described.

**Nephron segment PCR:** Mouse renal tubule segments were isolated by microdissection as described previously [18]. RNA was extracted from segments using RNA extraction kit (Invitrek) according to the manufacturer’s protocol and CDNA was synthesized by reverse transcription (Tetro Reverse Transcriptase, Promega). qPCR was performed using HOT FIREPol EvaGreen qPCR Mix Plus (Solis BioDyne) and primers specific for Klhl2 (fwd: 5'-ccgccaacctgctcggcagatt-3', rev: 5'-ccacccctttatgatcactctttgccggcgcgtc-3'). Gene expression analysis was performed applying the ΔΔCt method and normalized against β-Actin.

**Statistical analysis:** Unpaired t tests were used to compare 2 groups. Differences between a single control group and multiple experimental groups were first analyzed by one way ANOVA, followed by Dunnett’s Multiple Comparison Test. Time course differences were by ANOVA with repeated measures. P < 0.05 was considered significant.

Results

1) KLHL2 mRNA is expressed along the kidney tubules

We first examined KLHL2 expression in mouse kidney. Quantitative PCR confirmed that Klhl2 is expressed almost evenly along the tubule including thick ascending limb (TAL), DCT, and collecting duct (CD) (Fig. 1) at the mRNA level. We previously reported, using the same technique, that the pattern of Klhl3 expression was quite different, with abundant expression along the DCT and modest expression along TAL and CD [16].

2) Both KLHL2 and KLHL3 can mediate L-WNK1-Δ11, WNK3, and WNK4 degradation

Previous studies showed KLHL3 can degrade WNK4 and L-WNK1, and that FHHt mutant KLHL3 lost the ability to degrade WNK4 and L-WNK1; this is presumed to increase NCC activity leading to FHHt [4,6]. We found that when KLHL3 and WNK3 are co-expressed in HEK293 cells, KLHL3 WT can also degrade WNK3; disease mutant KLHL3 R528H lacks this effect (Fig. 2A). As Hadchouel and colleagues reported that a form of L-WNK1 lacking exon 11 is the kidney enriched form [19], we also tested the effect of KLHL3 on L-WNK1-Δ11. Similar to L-WNK1, L-WNK1-Δ11 can also be degraded by KLHL3 WT: FHHt mutant R528H lacks this effect, as well (Fig. 2B). We also found that KLHL2 can mediate degradation of all 3 WNKs (data not shown), similar to a previous report [14].

3) WNK4 FHHt mutants are not sensitive to degradation by either KLHL3 or KLHL2

It was reported that KLHL3 does not degrade the disease mutant WNK4 normally, leading to an increase of WNK4 and therefore to NCC activation; this is considered to be the mechanism of WNK4-FHHt [4]. In the current study, we found that KLHL2 also exhibited a partial loss of degradating capacity, with regard to WNK4 disease mutants (Fig. 2C), suggesting that KLHL2 may also play a role in WNK4 accumulation in WNK4-FHHt.

4) Endogenous cullin 3 regulates WNK kinase abundance

Exogenous CUL3 was usually used to test effects in cells, yet HEK293 cells express CUL3 endogenously. Here, we tested the effects of knockdown endogenous CUL3 on KLHL2-or KLHL3-mediated WNK degradation. The results showed that CUL3 knockdown increases the abundance of all 3 WNK kinases (Fig. 3A–C, similar results of KLHL3 not shown), indicating that endogenous CUL3 in cells, together with its adaptors KLHL2 and KLHL3, regulates WNK kinase abundance.

5) CUL3 ΔΩ is a gain of function mutation capable of degrading both KLHL3 and KLHL2 to promote WNK signaling

CUL3 can degrade its own adaptor protein KLHL3 [7], and our recently published data showed that CUL3 ΔΩ is a gain of function, instead of loss-of-function in regards to degrading KLHL3 [16].

![Fig. 1. The expression of KLHL2 and KLHL3 along the renal tubule in mRNA level. Klhl2 and Klhl3 expression along the nephron, analyzed by quantitative PCR. Proximal tubule (PT), TAL, DCT, CD, and glomerulus (Glon) are compared with total kidney. Values are mean ± SD from 3 independent experiments.](image)
Since KLHL2 is highly homologous to KLHL3, and KLHL2 can also serve as adaptor protein for CUL3 [14], we investigated the effect of WT and disease mutant CUL3 on KLHL2. The results show that CUL3 Δ9 degraded not only KLHL3 more than WT CUL3, but also KLHL2 (Fig. 4A).

As shown in Fig. 4B, C and D, when co-transfected with WNK kinase, the increased degradation of KLHL2 by CUL3 Δ9 was associated with a substantial increase in WNK4 and WNK3 (P < 0.05); the effect on L-WNK1-D11 was not significant, similar to the finding regarding KLHL3 in our previous report [16].

**Discussion**

It has been reported that WNK1, WNK3 and WNK4 are expressed in the distal nephron and are believed to be key regulators of NCC function through activation of SPAK and OSR1 [20].

The deletion in intron 1 of WNK1 and missense mutations of WNK4 were the first identified as causing FHHt [2]. Later, components of the Cullin-Ring-ligase complex, the scaffold protein CUL3 and the adaptor protein KLHL3, were reported to cause FHHt more commonly than WNK kinases [3]. CUL3 and KLHL3 are involved in ubiquitylation reactions and protein degradation; they ubiquitylate WNK kinases, affecting their abundance and thereby their activity. This suggests that WNKs, KLHL3, and CUL3 comprise a single regulatory network in the distal nephron.

It is widely recognized that NCC overactivation is a common feature of FHHt [8]. NCC activation in WNK1-FHHt is a result of increased expression of WNK1 due to a large deletion of intron 1, then via phosphorylation and activation of SPAK/OSR1 [2,21].

Numerous molecular and biochemistry studies, as well as animal models, confirmed that SPAK/OSR1 can phosphorylate and activate NCC. Most of the WNK4 disease mutations are located in its acidic domain, which is responsible for binding to KLHL3. The disease mutant WNK4 is unable to bind to KLHL3, and be degraded by the CUL3-KLHL3 E3 ubiquitin ligase complex; this results in elevated WNK4 and NCC activation [4]. In terms of KLHL3-FHHt, KLHL3 mutants lose their ability to bind to either CUL3, or WNK kinases, thereby causing WNK kinase accumulation and NCC activation.
We hypothesized there might be some other adaptor protein of CUL3 that can bind to CUL3, among which KLHL2 has the closest homology of KLHL3 [14]. KLHL2 was expressed in the kidney, aorta and vascular smooth muscle cells, and KLHL2 can also regulate the degradation of WNK kinases. In CUL3-FHHt, we speculate that not only KLHL3, but also KLHL2 cannot form CRL with CUL3, so the degradation of WNK4 in CUL3-FHHt is partly due to increased vascular tone [10]. However, since all clinical presentations including metabolic acidosis, hyperkalemia, and hyperchloremia were also more severe in CUL3-FHHt, a principal role of the kidney may also explain the different severity between CUL3-FHHt and non-CUL3-FHHt.

We hypothesized there might be some other adaptor protein of CUL3 which serves as “secondary” adaptor of CUL3 for ubiquitinating WNK kinases in the distal nephron. There might be dozens of adaptors that can bind to CUL3, among which KLHL2 has the closest homology of KLHL3 [14]. KLHL2 was expressed in the kidney, aorta and vascular smooth muscle cells, and KLHL2 can also degrade WNK kinases, similar to KLHL3 [14,15]. Here we report the segmental expression of KLHL2 mRNA in the renal tubule, and find KLHL2 mRNA is expressed almost evenly along the tubule, which is in contrast to the high expression of KLHL3 in the DCT.

In addition to KLHL3, KLHL2 can also regulate the degradation of WNK kinases, and it can be degraded by CUL3, which helps to explain the different phenotype severity of FHHt–causing mutations. The phenotypic severity of FHHt is as follows CUL3 > KLHL3 > WNK4 > WNK3, with CUL3 being the most severe and WNK1 being the least severe [3]. In WNK1–FHHt, only WNK1 level increases, which causes a modest NCC activation. We propose that, in WNK4–FHHt, the degradation of mutant WNK4 is hampered by decreased binding to not only KLHL3, but also KLHL2; thus, the accumulated WNK4 causes NCC activation. In KLHL3–FHHt, the degradation of both WNK1 and WNK4 are decreased because of KLHL3 mutation, and therefore NCC is activated by two WNK kinases. In CUL3–FHHt, we speculate that not only KLHL3, but also KLHL2 cannot form CRL with CUL3, so the degradation of WNK1 and WNK4 mediated by both KLHL3 and the alternative adaptor, KLHL2 is weakened; this causes the strongest NCC activation. As mentioned above, increased vascular tone is likely to be part of the reason for severe hypertension in CUL3–FHHt. Interestingly, since KLHL2 can mediate WNK3–NKCC1 signaling pathway to regulate vascular tone induced by angiotensin II [15], we also predict that the disruption of CUL3–KLHL2 complex might be the reason for increased vascular tone in CUL3–FHHt.

WNK3 has been reported to be a strong activator of NCC [23,24], so the degradation effect of KLHL3 on WNK3 probably suggests a potential role of WNK3 in the pathogenesis of KLHL3–FHHt and CUL3–FHHt. WNK3 can also activate NKCC2 [24,25], another member of Cation Chloride Cotransporter, as NCC. We cannot exclude the possibility that NKCC2, which is specifically expressed in TAL, is also activated because of WNK3 mutation accumulation caused by disruption of CUL3–KLHL3 and/or CUL3–KLHL2 complexes in TAL. Obviously NKCC2 activation, if it exists, could cause increased renal absorption of sodium, chloride, and potassium, which would aggravate the FHHt phenotype. In vivo work with the CUL3–FHHt animal is important for answering this question.
although till now there is no good KLHL2 antibody available for detecting immunofluorescence and western blot signal in kidney. In summary, we found that KLHL2 was strikingly degraded by CUL3 Δ9, which in turn caused increased WNK kinase abundance. KLHL2, like KLHL3, is unable to bind and degrade mutant WNK4. Our results suggest that KLHL2 likely plays a role in the pathogenesis of FHHt and aggravates the phenotype caused by mutation in CUL3 and WNK4.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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