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Prohibitin is a prognostic marker of relapse and therapeutic target to block chemotherapy resistance in Wilms tumor

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33

34 **Abstract**

35

36 Wilms tumor (WT) is the most common childhood kidney cancer. To improve risk stratification
37 and identify novel therapeutic targets for patients with WT, we used high-resolution mass spectrometry
38 proteomics to identify urine tumor markers associated with WT relapse. We determined urine proteomes
39 at diagnosis of 49 patients with WT, non-WT renal tumors, and age-matched controls, leading to the
40 quantitation of 6,520 urine proteins. Supervised analysis revealed specific urine markers of renal rhabdoid
41 tumors, kidney clear cell sarcomas, renal cell carcinomas, as well as those detected in cured and relapsed
42 WT. In particular, urine prohibitin was significantly elevated at diagnosis in patients with relapsed as
43 compared to cured WT. In a validation cohort of 139 patients, a specific urine prohibitin enzyme-linked
44 immunosorbent assay demonstrated that prohibitin concentrations greater than 998 ng/mL at diagnosis
45 were significantly associated with ultimate WT relapse. Immunohistochemical analysis revealed that
46 prohibitin was highly expressed in primary WT specimens and associated with disease stage. Using
47 functional genetic experiments, we found that prohibitin was required for the growth and survival of WT
48 cells. Overexpression of prohibitin was sufficient to block intrinsic mitochondrial apoptosis and to cause
49 resistance to diverse chemotherapy drugs, at least in part by dysregulating factors that control apoptotic
50 cytochrome c release from mitochondrial cristae. Thus, urine prohibitin may improve therapy
51 stratification, non-invasive monitoring of treatment response and early disease detection. In addition,
52 therapeutic targeting of chemotherapy resistance induced by prohibitin dysregulation may offer
53 improved therapies for patients with Wilms and other relapsed or refractory tumors.

54

55 **Introduction**

56 Wilms tumor (WT) is the most common kidney tumor in children. With current stratification and
57 a combination of surgery, chemotherapy and radiotherapy, more than 90% of patients with low risk
58 disease can now be cured. ¹ However, treatment of patients with advanced, anaplastic, or relapsed
59 disease remains challenging, with inadequate curative therapies and substantial long-term effects. ^{1,2}

60 While anaplastic histology WT, most frequently due to inactivating mutations of *TP53*, is
61 associated with unacceptably poor survival, distinct subsets of patients with favorable histology WT also
62 suffer disease relapse. ^{1,3,4} Loss of heterozygosity (LOH) at 1p and 16q was found to be associated with
63 inferior prognosis of favorable histology WT. ^{4,5} This led to new clinical trials to investigate whether
64 intensification of therapy for patients with tumor LOH of 1p and 16q could be used to improve survival.
65 However, additional biomarkers of adverse prognosis, therapy resistance and disease relapse will be
66 needed for improved stratification of existing therapies and development of new therapies that are
67 precise, curative, and safe. For renal tumors in particular, urine biomarkers offer the ability to monitor
68 disease and therapy response non-invasively.

69 Neuron-specific enolase, basic fibroblast growth factor (bFGF), and hyaluronidase have been
70 reported to be enriched in the urine of patients with WT. ⁶⁻⁹ In particular, elevation of urinary bFGF was
71 correlated with WT disease stage. ⁷ Though its specificity and sensitivity were not sufficient to permit
72 clinical use, continued elevation of urinary bFGF in a subset of WT patients who developed persistent or
73 relapsed disease suggests that urine profiling may reveal prognostic biomarkers and improved therapeutic
74 targets for WT and other kidney tumors.

75 We and others used high-resolution mass spectrometry proteomics to profile urine in order to
76 identify improved disease biomarkers. ¹⁰⁻¹³ Here, we profiled urine proteomes of patients with diverse
77 childhood kidney tumors as compared to age-matched controls. By comparing initial urine proteomes of

78 patients who relapsed to those who were cured, we identified elevated urinary prohibitin (PHB) at
79 diagnosis as a prognostic biomarker of relapse in favorable histology WT. Urinary PHB elevation was
80 significantly associated with WT relapse in an independent patient cohort, with tumor PHB overexpression
81 associated with WT disease stage. Using a battery of functional studies, we found that PHB
82 overexpression regulates mitochondrial apoptosis and induces resistance to diverse chemotherapy drugs.
83 These findings should enable improved WT therapy stratification and future strategies to overcome
84 chemotherapy resistance to increase the cure rates of patients.

85

86 **Results**

87 ***Comparative urine proteomics of Wilms tumor, kidney rhabdoid tumor, kidney clear cell sarcoma, and***
88 ***renal cell carcinoma reveals new biomarkers.***

89 In previous studies, we optimized methods for the analysis of clinical urine proteomes, including
90 protein isolation, fractionation, and high-resolution mass spectrometry.¹⁰⁻¹³ For this study of childhood
91 kidney tumors, we assembled a cohort of specimens collected at diagnosis from 49 patients, including 16
92 with favorable histology WT, 6 with rhabdoid tumor of the kidney (RTK), 9 with clear cell sarcoma of the
93 kidney (CCSK), and 2 with renal cell carcinoma (RCC). For comparison, we included 16 age-matched
94 control specimens collected from 10 healthy children and 6 children with acute abdominal pain who were
95 evaluated as part of our prior study of acute appendicitis, and whose symptoms resolved spontaneously.
96 ¹¹ Mass spectrometric proteomic analysis of all specimens led to the identification of 6,520 urine proteins,
97 detected with at least 2 unique peptides at the false discovery rate threshold of 1% (Figure 1A). As
98 expected, supervised analysis of all kidney tumor specimens versus the age-matched controls revealed
99 that urine tumor proteomes are dominated by markers of tissue injury and hematuria, consistent with
100 kidney and blood vessel invasion (Supplemental Figure 1A).

101 Importantly, supervised analysis of distinct tumor specimens revealed new tumor markers, such
102 as PGBD5 (Supplemental Figure 1B), which we recently validated as an oncogenic DNA transposase and
103 therapeutic target in rhabdoid tumors.¹⁴⁻¹⁷ In the case of favorable histology WT, we identified the most
104 abundant proteins specifically detected in WT as compared to other non-WT kidney tumor urine
105 specimens (Supplemental Figures 1B-E). Finally, we stratified WT patients based on clinical outcome and
106 identified urine proteins detected specifically in cases of relapsed favorable histology WT as compared to
107 favorable histology WT (Figure 1B). These included β -catenin antagonist DACT2, mitochondrial regulators
108 DAD1 and PHB, among others. Thus, comparative urine proteomics can be used to identify urine

109 biomarkers, including new tumor markers that may represent improved biomarkers and therapeutic
110 targets.

111 ***Urine prohibitin is a prognostic marker of Wilms tumor relapse.***

112 To validate their prognostic significance and identify improved therapeutic targets of relapsed
113 WT, we assembled an independent cohort of 139 specimens, including 99 favorable histology WT
114 specimens, and 40 age-matched controls ([Supplemental Table 1](#)). First, we used enzyme-linked
115 immunosorbent assay (ELISA) to measure protein concentration of candidate WT markers in clinical urine
116 specimens. We used commercially available antibodies measure the top 3 urine markers enriched in
117 patients with relapsed WT. While we could not develop specific ELISAs for DACT2 and DAD1 due to the
118 limitations of commercially available antibodies, we confirmed that ELISA for PHB provided accurate
119 measurements of urine PHB, with a linear signal response in the ng/mL range, as determined using
120 purified recombinant PHB ([Figure 2A](#)). Thus, we measured the urine concentration of PHB, as compared
121 to urine creatinine as a control for overall urine concentration ([Supplemental Figure 2](#)). We found that
122 urine PHB was significantly enriched in diagnostic urine specimens from patients who ultimately relapsed
123 (median 1672 ng/mL), as compared to those from patients who were ultimately cured (median 131
124 ng/mL) or age-matched controls (median 218 ng/mL). Using logistic regression, we determined that the
125 PHB urine concentration of 998 ng/mL was significantly associated with WT relapse (odds ratio = 153.3,
126 [Figure 2B](#)). Both urine PHB concentration and urine PHB concentration normalized to urine creatinine (Cr)
127 were statistically significant predictors of relapse, independent of stage and therapy ([Figure 2](#),
128 [Supplemental Figure 2](#)). Similarly, receiver operating characteristic (ROC) curve analysis showed that
129 urine PHB in patients with WT relapse had the prognostic area under the curve (AUC) of 0.78 (95%
130 confidence interval 0.68-1.0; [Figure 2C](#)). Almost all patients with elevated urine PHB at diagnosis
131 developed WT relapse within 2 years after therapy ([Figure 2D](#)). We confirmed that urine PHB elevation

132 was not due to urine concentration, as evident by the lack of statistically significant differences in urine
133 creatinine concentration ([Supplemental Figure 2A-C](#)). We found that urine PHB was significantly elevated
134 in patients with abdominal as compared to lung WT relapse ([Figure 2E](#)). Indeed, urine PHB exhibited a
135 near perfect prognostic performance for abdominal WT relapse, with the ROC AUC of 0.96 (95%
136 confidence interval 0.91-1.0; [Figure 2F](#)). In all, these results indicate that urine PHB is a significant
137 prognostic marker of WT relapse.

138 ***Prohibitin is overexpressed in Wilms tumor cells and correlates with tumor stage.***

139 To determine whether elevated PHB in WT patient urine samples was due to increased expression
140 of PHB in WT cells, we used immunohistochemistry (IHC) using formalin-fixed paraffin embedded primary
141 patient WT specimens, as compared to adjacent normal kidney tissue. We found that PHB was highly
142 expressed in both favorable histology WT ([Figure 3B and 3E](#)), as well as diffusely anaplastic WT ([Figure 3C](#)
143 [and 3F](#)). In agreement with prior studies, we also observed PHB expression in normal kidney tubules
144 ([Figure 3A and 3D](#)).¹⁸ We assembled a cohort of 59 primary favorable histology WT specimens and 10
145 control non-WT benign and malignant renal samples, uniformly stained for PHB ([Supplemental Table 2](#)).
146 We scored IHC PHB expression in a blinded manner on the 0 to 3+ scale. Representative images of score
147 levels are shown in [Supplemental Figure 3](#). Notably, all Wilms tumors expressed PHB from 1+ to 3+
148 ([Supplemental Figures 3D-F](#)). Consistent with the specific detection of PHB in WT but not other kidney
149 tumors ([Figure 1B](#)), we found no detectable PHB expression in pre-malignant nephrogenic rests
150 ([Supplemental Figure 3A](#)), embryonal rhabdomyosarcoma ([Supplemental Figure 3B](#)), and clear cell
151 sarcoma of the kidney ([Supplemental Figure 3C](#)). We found that PHB expression in WT correlated with
152 higher tumor stage and increased percentage of tumors with higher PHB expression ([Figure 3G](#)).

153 We further validated PHB expression using quantitative image densitometry in a second cohort
154 of 38 primary WT patients, including both favorable histology and anaplastic WT ([Supplemental Table 4](#)).

155 We observed increased PHB expression in favorable histology WT cells of specimens that ultimately
156 relapsed, as compared with those that were cured with surgery and chemotherapy (Figure 3H). On a per-
157 cell-basis, PHB expression was increased in favorable histology WT as compared to anaplastic histology
158 WT (Figure 3I). We did not observe a statistically significant correlation between *PHB* mRNA expression
159 and *TP53* mutations in diffusely anaplastic WT samples (Supplemental Figure 4). Likewise, we did not find
160 recurrent mutations or amplification of *PHB* in a recently analyzed cohort of 117 patient WT specimens.
161 ¹⁹ Though we found that cellular PHB expression was similar between WT and some normal kidney cells
162 (Supplemental Figure 5A), we found that WT cells were 12% smaller, with 27% smaller cytoplasm and 11%
163 larger nuclei, as compared to normal kidney cells (Supplemental Figure 5B). These findings suggest that
164 WT cells overexpress PHB in specific subcellular compartments, presumably through post-transcriptional
165 mechanisms.

166 ***PHB is required for the growth and survival of Wilms tumor cells by regulating mitochondrial functions.***

167 Relative overexpression of PHB in WT cells suggests that PHB may contribute to their growth and
168 survival. To assess this, we examined PHB expression and subcellular localization in WT cell lines WIT49,
169 WTCLS1, and CCG9911, as compared to immortalized human BJ fibroblasts. Using quantitative
170 fluorescent Western blot immunoassays, we found that PHB is more highly expressed in WT cell lines, as
171 compared to BJ fibroblasts (Figure 4A). Normalized to cellular actin, PHB expression was an average 2.9,
172 2.7, and 3.3-fold higher in the WIT49, WTCLS1, and CCG9911 cells, respectively, as compared to normal
173 BJ fibroblasts (Figure 4B).

174 Relative overexpression of PHB in WT cells and their relatively smaller size as compared to normal
175 cells suggest that tumor PHB overexpression may be due to its increased expression in specific subcellular
176 compartments, such as mitochondria. ²⁰ Compelled by the finding of PHB staining in the cytoplasm of
177 WT cells (Figure 3), we used confocal immunofluorescence microscopy to define the subcellular

178 localization of PHB in WT cell lines. We observed that most of cellular PHB co-localized with the specific
179 mitochondrial inner membrane marker CoxIV (Figure 4C). These findings are consistent with prior studies
180 that identified PHB heterodimerization with PHB2 in association with the inner mitochondrial membrane
181 to regulate mitochondrial morphogenesis.²¹⁻²⁶ Thus, we reasoned that PHB overexpression may
182 contribute to the growth or survival of WT cells. To test this hypothesis, we used three independent short
183 hairpin RNA (shRNA) interference lentiviral constructs to deplete PHB in WT cell lines, as compared to the
184 control shRNA targeting the green fluorescent protein (GFP) which is not expressed (Figure 5 A, B, and C).
185 We confirmed PHB depletion using Western immunoblotting (Figure 5 A, B, and C). Consistently, cells
186 depleted of PHB exhibited significantly decreased proliferation, as compared to wild-type cells or those
187 expressing the control GFP-targeting shRNA (Figure 5 D, E, and F).

188 PHB has been reported to regulate mitochondrial morphology by interacting with the OPA1
189 GTPase, and the YME1L and OMA1 proteases that proteolytically process OPA1 that can control the
190 release of cytochrome c from mitochondrial cristae during apoptosis.^{27 28,29} We found that WT cells have
191 elevated levels of OMA1 and variable levels of YME1L relative to BJ fibroblasts (Figure 6A). Consistent
192 with the putative interaction of PHB with OPA1, depletion of PHB was associated with apparent reduction
193 of OMA1 in all WT cell lines tested, but not in control cells transduced with GFP-targeting controls (Figure
194 6B-D). Since YME1L can proteolytically cleave OPA1^{30,31}, we analyzed apparent OPA1 isoforms by Western
195 immunoblotting. We found that cells with elevated endogenous YME1L, such as WTCLS1, depletion of
196 PHB was associated with a reduction of YME1L and the S4 isoform of OPA1 (Figure 6D). Conversely, in
197 cells with relatively low endogenous YME1L, such as WiT49 and CCG9911, depletion of PHB increased
198 YME1L and the S4 OPA1 isoform (Figures 6B and C). In all, these findings indicate that PHB directly or
199 indirectly interacts with the mitochondrial intermembrane proteases OMA1 and YME1L that
200 cooperatively process OPA1.

201

202 ***PHB overexpression causes resistance to mitochondrial apoptosis and diverse chemotherapy drugs.***

203 PHB-mediated control of OPA1 processing that can regulate apoptotic cytochrome c release raises
204 the possibility that PHB overexpression in WT may impair mitochondrial apoptosis and cause
205 chemotherapy resistance. To test this hypothesis, we ectopically overexpressed PHB in WT cell lines
206 WTCLS1 and WiT49 as well as BJ fibroblasts using lentiviral transduction and confirmed transgene
207 expression by Western immunoblotting of PHB and its V5 epitope tag in two independent clones ([Figure](#)
208 [7](#)). Even though we found relatively modest overexpression of PHB as compared to its endogenous levels,
209 all PHB-overexpressing cells exhibited significantly increased resistance to vincristine, doxorubicin and
210 dactinomycin, as compared to wild-type cells or control cells transduced with empty vectors ([Figure 8](#)).
211 This effect was more pronounced in BJ fibroblasts and WTCLS1 WT cells, as compared to WiT49 WT cells,
212 consistent with the relatively higher levels of endogenous PHB in WiT49 cells ([Figure 4](#)).

213 Overexpression of PHB in patient Wilms tumors and urine, its requirement for enhanced WT cell
214 growth, control of OPA1 and other factors that can regulate mitochondrial cytochrome c release, and
215 sufficiency to cause resistance to chemotherapy drugs with diverse mechanisms of action suggest that
216 PHB overexpression may contribute to WT therapy failure and relapse by blocking intrinsic mitochondrial
217 apoptosis. To test this prediction, we used BH3 profiling, a dynamic assay of mitochondrial apoptotic
218 function, of WiT49 WT and normal BJ cells ([Figure 9, Supplemental Figure 6](#)), as optimized to specifically
219 measure mitochondrial cytochrome c release using flow cytometry.³² Upon activation of mitochondrial
220 apoptosis, we observed that PHB overexpression caused increased resistance to multiple different
221 synthetic BH3 apoptotic activators, including PUMA, BAD, and BID ([Figure 9, Supplemental Figure 6](#)).

222 To further elucidate mitochondrial abnormalities in WT, we used transmission electron
223 microscopy to determine the mitochondrial structure of newly diagnosed favorable histology WT

224 immediately following nephrectomy. We observed that WT cells exhibited smaller mitochondria with
225 blunted cristae and reduced matrix density, as compared to normal kidney tissue ([Figure 10A-C](#)). This is
226 consistent with abnormal mitochondrial fission in WT, in agreement with aberrant mitochondrial
227 morphogenesis induced by PHB overexpression, and prior ultrastructural studies of WT.³³ Thus, PHB
228 overexpression causes intrinsic mitochondrial apoptosis resistance, thereby promoting chemotherapy
229 resistance and WT therapy failure.

230 **Discussion**

231 Pathogenesis of childhood solid tumors remains poorly understood. ¹⁵ In particular, distinct renal
232 tumors remain difficult to treat, with limited knowledge of prognostic biomarkers and therapeutic targets.
233 In the case of Wilms tumors, the most common childhood kidney tumor, subsets of patients remain
234 incurable, with no effective means to monitor therapy response, stratify existing therapies, and identify
235 improved therapeutic targets. In this context, our findings are significant for several reasons. First,
236 reported urine proteome profiles of diverse kidney tumors provide a rich source of tumor biomarkers and
237 therapeutic targets. Indeed, our recent study of PGBD5, identified in the proteomic profiles of renal
238 rhabdoid tumors, revealed an unanticipated mechanism of solid tumor pathogenesis and improved
239 therapeutic targets. ¹⁵⁻¹⁷

240 In the case of Wilms tumors, we found that overexpression of PHB at diagnosis is a prognostic
241 marker of WT relapse. Levels of urinary PHB above 998 ng/mL were found to be significantly associated
242 with relapse in independent cohorts of WT patients ([Figures 1 and 2](#)). PHB overexpression was found to
243 be elevated not only in urine but also in tumor tissue samples in both favorable and anaplastic histology
244 WT, and primarily localized to the mitochondria ([Figures 3 and 4](#)). We found that PHB was required for
245 the growth and survival of WT cells, at least in part by regulating mitochondrial function and apoptosis
246 ([Figures 5 and 6](#)). Importantly, ectopic overexpression of PHB was sufficient to cause resistance to diverse
247 chemotherapy agents used for clinical treatment of WT. PHB overexpression blocked cytochrome c
248 release from mitochondria, an essential step in the initiation of intrinsic mitochondrial apoptosis ([Figures](#)
249 [7-9](#)), at least in part by dysregulating mitochondrial cristae ([Figure 10](#)). Thus, we conclude that PHB
250 overexpression impairs mitochondrial morphogenesis and apoptotic priming, and causes chemotherapy
251 resistance, as schematized in [Figure 11](#), which can be monitored non-invasively by urine PHB
252 measurements.

253 Overexpression of PHB has been described in other tumors, such as breast carcinomas, where
254 somatic amplifications of the *PHB* gene have been reported in a subset of tumors.³⁴⁻³⁶ We did not observe
255 any cases of WT with *PHB* mutations or amplifications, suggesting that WT overexpression of PHB may
256 involve post-transcriptional mechanisms. *PHB* expression has been found to be regulated by miR-27a in
257 other tissues³⁷⁻⁴⁰, and miR-27a is significantly downregulated in chemotherapy resistant blastemal Wilms
258 tumors.⁴¹ Since several miRNA processing genes are recurrently mutated in subsets of Wilms tumors, it
259 is possible that PHB overexpression is caused by miRNA dysregulation, potentially including miR-27a.
260 Future studies will be needed to determine the mechanisms of potential regulation of *PHB* expression by
261 miRNAs and causes of its pathogenic overexpression. Likewise, additional studies will be needed to
262 determine the prevalence and function of PHB in highly chemotherapy resistant anaplastic WT.

263 We found urine PHB to be elevated in the majority of favorable histology WT patients whose
264 disease ultimately relapsed (Figure 2B). These diagnostic urine PHB levels were generally orders of
265 magnitude higher in patients with ultimately relapsed WT as compared to cured patients (Figure 2B).
266 However, in primary tumor tissue samples, PHB was significantly but modestly overexpressed in relapsed
267 WT as compared to cured WT and normal kidney tissue (Figure 3, Supplemental Figure 5). Thus, urine
268 PHB elevation may be due to increased WT cell invasion and PHB release into renal tubules, as suggested
269 by the increased invasiveness of colorectal and lung carcinomas with PHB overexpression.⁴²⁻⁴⁴ This
270 possibility is further supported by the relatively higher frequency of abdominal WT relapse in patients
271 with elevated urine PHB (Figure 2E). Additional studies will be needed to establish the mechanisms and
272 significance of this possible phenomenon, and its relationship with abnormal mitochondrial structure and
273 function induced by PHB overexpression. However, if PHB overexpression indeed causes increased WT
274 cell invasion, then augmenting local control measures such as additional lymph node dissection and
275 radiation therapy may be helpful.

276 Our findings implicate the interaction between PHB and the mitochondrial proteases OMA1 and
277 YMEL1 in the dysregulation of mitochondrial cristae function and apoptotic cytochrome c release. It is
278 possible that the ring complex formed by PHB and PHB2 affects the OPA1 GTPase that remodels
279 mitochondrial cristae by sequestering the inner mitochondrial membrane OMA1 and YMEL1 proteases
280 within microdomains which are unable to access OPA1.^{21,45} As a result, PHB overexpression would impair
281 the release of cytochrome c from mitochondrial cristae, blocking the initiation of mitochondrial apoptosis,
282 as well as altering the dynamics of mitochondrial morphogenesis, which could further contribute to
283 alterations in apoptosis.^{28-31,46} In addition, although the PHB complex is associated with the inner
284 mitochondrial membrane, it has been shown to interact with BAX and BAK that comprise the apoptotic
285 MOMP pore.^{20,47} Thus, in addition to modulating cytochrome c release at crista junctions, PHB
286 overexpression may also impair the formation or function of the MOMP pore. Third, PHB overexpression
287 may impair apoptosis because the properties of the mitochondrial outer membrane govern the ability of
288 the predominantly cytosolic BAX to insert into the mitochondrial outer membrane as well as its ability for
289 subsequent activation by BH3-only proteins.^{48,49} Notably, this impaired BAX membrane insertion would
290 be expected in smaller, hyper-fragmented mitochondria produced as a result of mitochondrial fission.⁴⁸
291 Lastly, PHB overexpression can also affect the energetic and metabolic mitochondrial functions, as well as
292 its other cellular functions, such as regulation of cytosolic signaling. For example, PHB has been reported
293 to interact with the mitochondrial respiratory machinery and thus it is also possible that PHB mediated
294 overexpression co-opts mitochondrial respiration.²⁶ An analogous mechanism was described wherein
295 inhibitory factor 1 mediated a decrease in OMA1 proteolysis and resulted in impaired Opa1 cleavage by
296 maintaining ATP levels thereby reducing glutathione consumption and inactivating peroxiredoxin 3 during
297 apoptosis.⁵⁰ Importantly, given that rocaglamides and aurilide can interact with PHB, it is possible that
298 their derivatives can be developed to specifically interfere with the oncogenic functions of PHB in WT and
299 other tumors.⁵¹⁻⁵⁴

300 In all, PHB-mediated evasion of apoptosis through dysregulation of mitochondrial cristae
301 structure represents a previously unanticipated mechanism by which WT cells resist cell death, thereby
302 causing therapy failure and WT relapse. Non-invasive monitoring of urine prohibitin offers an immediately
303 accessible biomarker to identify and treat patients at risk for WT relapse, which should be investigated in
304 future prospective clinical trials.

305

306

307 **Methods**

308 ***Specimens***

309 Urine and tumor specimens were obtained from the Children's Oncology Group and Memorial
310 Sloan Kettering Cancer Center, as part of institutional review board-approved research studies, with
311 informed subject consent.

312 ***Mass Spectrometry***

313 Urine specimens were fractionated and the protein composition of the fractions was identified by
314 using high-resolution mass spectrometry as described previously¹³. Briefly, individual five ml urine
315 aliquots were fractionated using ultracentrifugation, protein precipitation, and denaturing polyacrylamide
316 gel electrophoresis, and protein fractions were reduced, alkylated and trypsin digested. Urine protein
317 fractions were subjected to liquid chromatography tandem mass spectrometry using a nanoflow HPLC
318 system (Eksigent, Dublin, CA) coupled to the hybrid linear ion trap-Fourier transform ion cyclotron
319 resonance mass spectrometer (LTQ FT Ultra, Thermo Scientific, Waltham, MA). Resultant spectra were
320 processed to extract the 200 most intense peaks and searched against the human International Protein
321 Index database (version 3.69) by using MASCOT version 2.1.04 (Matrix Science). Assessment of
322 identification accuracy was carried out by searching a decoy database composed of reversed protein
323 sequences of the target IPI database. Only proteins identified on the basis of two or more unique peptides
324 were included in the analysis, at a false discovery rate of <1% at the peptide level. Mass spectrometry
325 data are openly available at PeptideAtlas (<http://www.peptideatlas.org/PASS/PASS00248>).

326 ***PHB ELISA***

327 Enzyme linked immunosorbent assay (ELISA) against human PHB was constructed using the
328 sandwich capture method. The capture antibody was a rabbit polyclonal antibody against the C-terminal

329 domain and the detection antibody was a mouse monoclonal antibody paired with the capture antibody
330 and labeled with biotin. The blocking buffer was composed of 1% bovine serum albumin in phosphate-
331 buffered saline. Recombinant human prohibitin was produced in *E.coli* as a single, non-glycosylated His-
332 tagged protein. Streptavidin-horseradish peroxidase with tetramethylbenzidine as a substrate was used
333 for detection, as available from Novatein Biosciences (BG-HUM11702; Woburn, MA, United States).

334 ***Immunohistochemistry and Immunofluorescence***

335 Immunohistochemistry was performed using established methods as described previously.⁵⁵
336 Images were analyzed using the Halo imaging analysis software (Indica Labs; Corrales, NM, United States).
337 24,862,509 cells in total were counted and scored from 0+ to 3+ based on PHB expression. Confocal
338 immunofluorescence microscopy was performed using cells plated in 4-well glass Millicell EZ slides fixed
339 in 4% paraformaldehyde and washed with PBS prior to imaging. PHB and CoxIV antibodies used are listed
340 in the Western Blotting section below, and were stained at 2.5 and 1.2 µg/mL, respectively. Images were
341 acquired using the Leica TCS SP5 II (Leica Microsystems Inc., Buffalo Grove, IL, United States).

342 ***Cell culture***

343 HEK293T and BJ cells were obtained from the American Type Culture Collection (Manassas, VA,
344 United States). WTCLS1 cells were obtained from the Leibniz Institute - Deutsche Sammlung von
345 Mikroorganismen und Zellkulturen (Braunschweig, Germany). CCG-9911 cells were a gift from Benjamin
346 Tycko at Columbia University (New York, New York, United States). WiT49 cells were a gift from Herman
347 Yeger at University of Toronto (Toronto, Ontario, Canada). The identity of all cell lines was verified by STR
348 analysis and lack of Mycoplasma contamination was confirmed by Genetica DNA Laboratories (Burlington,
349 NC, United States). BJ cells were cultured in DMEM; WTCLS1 and CCG-9911 cells were cultured in IMDM;
350 and WiT49 cells were cultured in DMEM F-12. All media included 10% fetal bovine serum, 100 U/mL

351 penicillin, 100 µg/mL streptomycin, and 1% glutamine, as maintained in a humidified atmosphere at 37°C
352 and 5% CO₂.

353 ***Plasmids***

354 For RNA interference, pLKO.1 vectors targeting PHB were obtained from the RNAi Consortium:
355 TRCN0000029204 (referred to as shPHB4), TRCN0000029206 (referred to as shPHB6), and
356 TRCN0000029208 (referred to as shPHB8). PHB was overexpressed using pLX304 vector, as obtained from
357 the DNASU repository. All plasmids were verified by restriction endonuclease mapping and Sanger
358 sequencing, and are available from Addgene (https://www.addgene.org/Alex_Kentsis/).

359 ***Lentivirus Transduction***

360 Lentivirus particles were produced using HEK293T cells with the psPAX2 and pMD2.G packaging
361 plasmids, as described previously.¹⁶ Cell transduction was performed using the multiplicity of infection of
362 10 in the presence of 8 µg/ml hexadimethrine bromide. Transduced cells were selected using puromycin
363 (3 µg/mL) for the pLKO.1 vectors or with blasticidin (3 µg/mL) for the pLX304 vectors. Transduced cells
364 were cloned using limiting dilution.

365 ***Western Blotting***

366 Western blotting was carried out as described.¹⁴ PHB antibody used was a rabbit polyclonal
367 antibody (1:1000, H-80) from Santa Cruz Biotechnology (Dallas, TX, United States). OMA1 antibody used
368 was a mouse monoclonal antibody (1:1000, H-11) from Santa Cruz Biotechnology (Dallas, TX, United
369 States). YME1L antibody used was a rabbit polyclonal antibody (1:1000, AP4882a) from Abgent (Suzhou
370 city, Jiangsu Province, China). Opa1 antibody used was a mouse monoclonal antibody (1:1000, 18/Opa-1)
371 from BD Biosciences (Franklin Lakes, NJ, United States). For loading controls, β-actin mouse monoclonal
372 antibody (1:5000, 8H10D10) from Cell Signaling Technology (Beverly, MA, United States), β-tubulin rabbit

373 polyclonal antibody (1:2500, T2200) from Millipore Sigma (St.Louis, MO, United States), and Cox IV rabbit
374 polyclonal antibody (1:1000, 4844) from Cell Signaling Technology (Beverly, MA, United States) were used.
375 The secondary antibodies used in this study include IRDye 680RD goat anti-rabbit and IRDye 800CW goat
376 anti-mouse secondary antibodies, both at 1:15,000 dilution and obtained from Li-cor (Lincoln, NE, United
377 States). Imaging and quantification was performed using the Li-Cor Odyssey Imaging System (Lincoln, NE,
378 United States).

379 ***Electron Microscopy***

380 Fresh 1 cm³ pieces of tissue were fixed in 2.5% glutaraldehyde, 4% paraformaldehyde, 0.02%
381 picric acid in 0.1 M sodium cacodylate buffer overnight at 4°C, washed, and then post fixed with osmium
382 tetroxide reduced with potassium ferricyanide for 1 hour at room temperature, washed, and
383 dehydrated in graded ethanol. Blocks generated using Embed 812 (Electron Microscopy Sciences,
384 Hatfield, PA) resin were cut at 65 nm and mounted on copper grids, stained with uranyl acetate and lead
385 citrate, and imaged using the JEM-1400 electron microscope (JEOL, Tokyo, Japan) as described
386 previously.⁵⁶

387 ***Statistics***

388 Exploratory simple logistic regression models were fit to determine the optimal cut-off point for
389 urine PHB and normalized PHB, which was the ratio of PHB and urine concentrations of creatinine, at
390 which the odds of having relapse was maximized. We also used the Youden index, aimed at maximizing
391 the sensitivity and specificity simultaneously, to find an optimal cut-off point. The Youden index is the
392 maximum of (sensitivity + specificity – 1) over all threshold values of PHB and normalized PHB and allows
393 evaluation of a diagnostic test with respect to its true positive and true negative rates.⁵⁷

394 Based on the results of these two criteria, two series of logistic regression models were used to
395 evaluate whether PHB and normalized PHB (dichotomized by the optimal cut-off point) could predict
396 Wilms tumor relapse. The first series was performed for the entire sample, considering either of the two
397 PHB variables only. The second series were performed for patients with Wilms tumor. In addition to the
398 PHB variables, three possible confounders were also included in the multivariate logistic regression
399 models: Stage (I, II, or III), Histology (Blastema, Favorable Histology Wilms, Mixed Cell Wilms, or Epithelial),
400 and Therapy (None vs. Any Chemotherapy). Backward selection was used to determine the most
401 parsimonious model.

402 Fisher's Exact tests were also applied to assess if the PHB or normalized PHB values categorized
403 by the optimal cut-off point differed significantly among the three groups and the different relapse sites.

404 All statistical analyses and figures were performed using SAS version 9.2 (Cary, NC, United
405 States), Origin version 9.1 (Northampton, MA, United States), and Graph Pad version 7.01 (LaJolla, CA,
406 United States).

407 **Author Contributions**

408 MO contributed to the study design, data collection, experiments, and interpretation of results.
409 AK, SA, MB, AH, IM, S. Gunasekera, LG, GB, and JR performed experiments. TH, YH, AN, YYC, PC, and S.
410 Gadd assisted with data analysis. MLQ, TH, JD, EP, EM, HS contributed to the interpretation of results. EM,
411 HS, and AK contributed to the study design, data analysis, and interpretation. AK and MO wrote the
412 manuscript, with contributions from other authors.

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422

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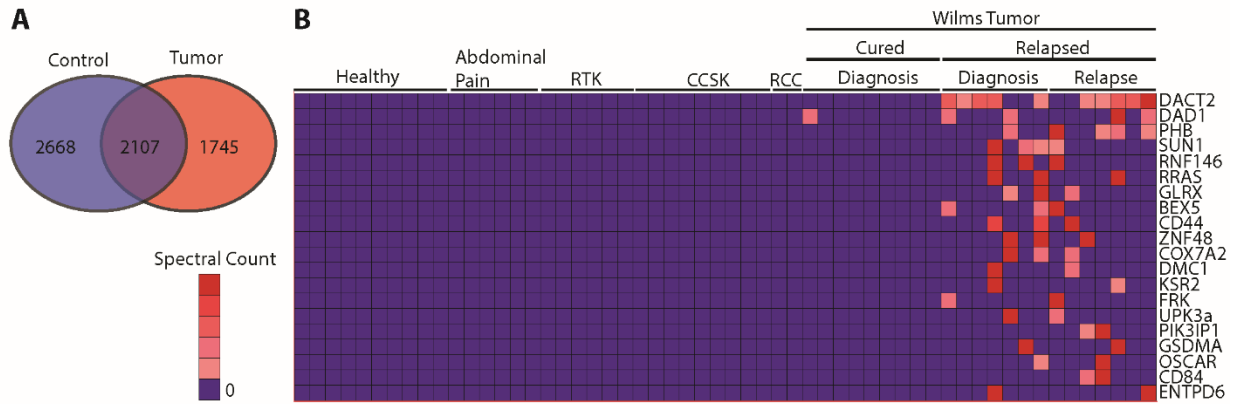
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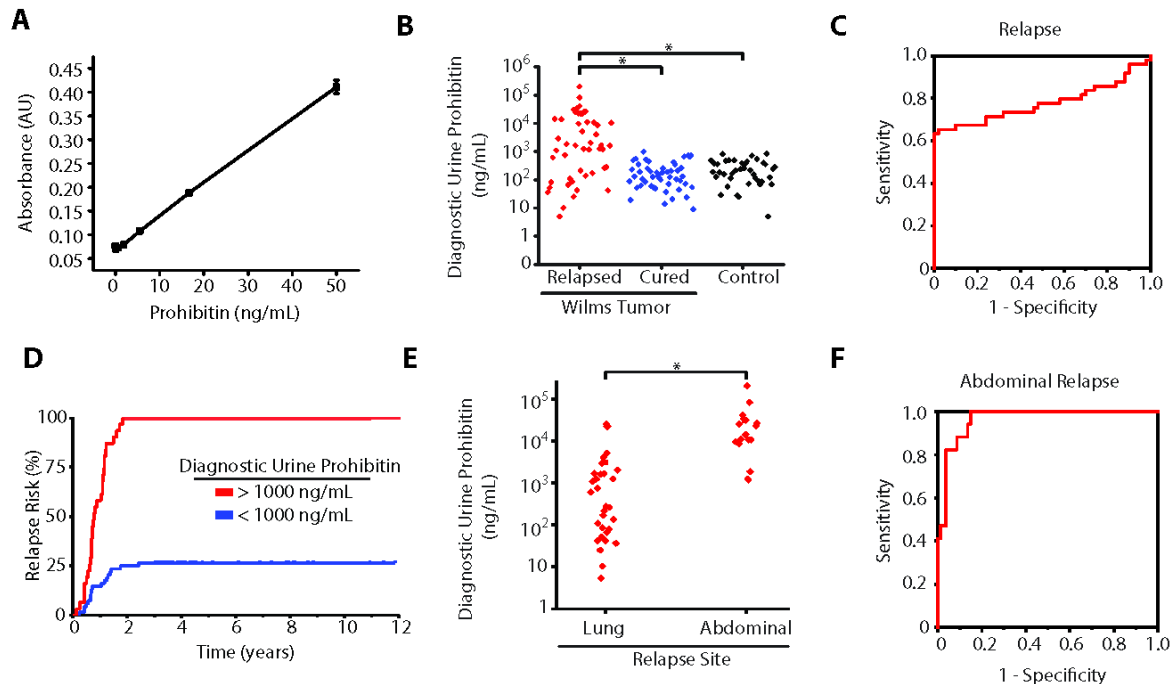
561

562 **Figure 1. Using high accuracy mass spectrometry to profile the urine proteomes of childhood**
563 **kidney tumors reveals markers of relapse and chemoresistance.**

564 **(A)** This venn diagram demonstrates the distribution of unique proteins identified in the children
565 without renal tumors (Blue) compared to those with tumors (Red) (n = 6520 proteins).

566 **(B)** The 20 proteins which were most highly enriched in Wilms tumors that relapsed are shown
567 in this heat map (n=56 samples); RTK = Rhabdoid tumor of the kidney, CCSK = Clear cell sarcoma
568 of the kidney, RCC = Renal cell carcinoma.

569



570

571 **Figure 2. Elevated urine prohibitin at diagnosis is a specific biomarker of relapse in favorable**
572 **histology Wilms tumors.**

573 (A) Enzyme linked immunosorbance assay (ELISA) comparing known prohibitin levels (ng/mL)
574 with measured absorbance via ELISA.

575 (B) Diagnostic urine prohibitin levels (ng/mL) in favorable histology Wilms tumor patients who
576 relapsed (Red, n = 49) are compared with those who were cured (Blue, n = 50) and normal
577 controls (Black, n = 40). Odds ratio of relapse for patients with diagnostic urine prohibitin > 1000
578 ng/mL = 153 (95% CI = 19.6 - 1000).

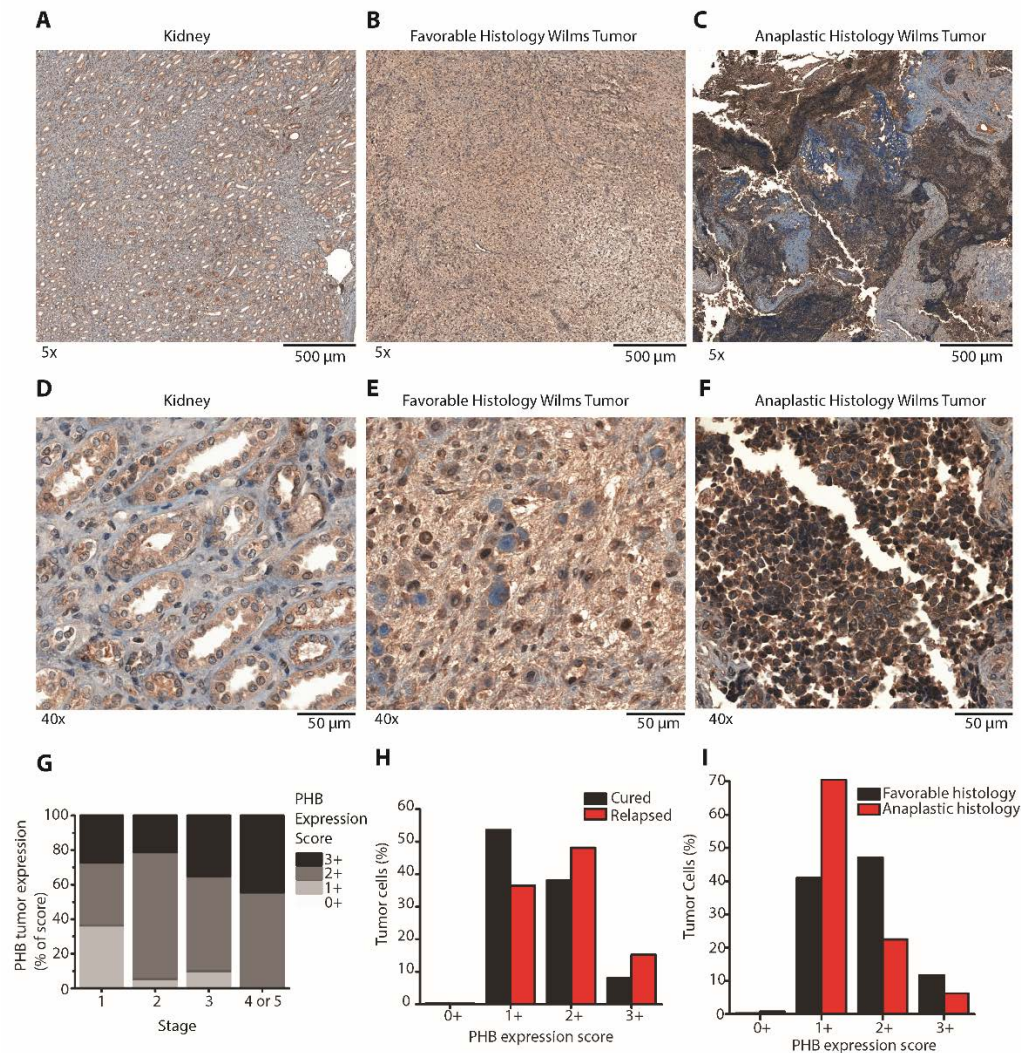
579 (C) A receiver operating characteristic curve demonstrates the prognostic power of diagnostic
580 urine prohibitin to predict relapse in favorable histology Wilms tumors at different sensitivity and
581 specificity with an area under the curve of 0.77 (95% confidence interval 0.64-0.99).

582 (D) Risk of relapse in patients with favorable histology Wilms tumors are stratified by those with
583 a diagnostic urine prohibitin > 1000 ng/mL (Red, n = 31) compared with those with a diagnostic
584 urine prohibitin < 1000 ng/mL (Blue, n = 68).

585 (E) Diagnostic urine prohibitin levels in relapsed favorable histology Wilms tumor patients are
586 stratified by site of relapse.

587 (F) A receiver operating characteristic curve demonstrates the prognostic power of diagnostic
588 urine prohibitin to predict abdominal relapse in favorable histology Wilms tumors at different
589 sensitivity and specificity with an area under the curve of 0.99 (95% confidence interval 0.99-1.0).

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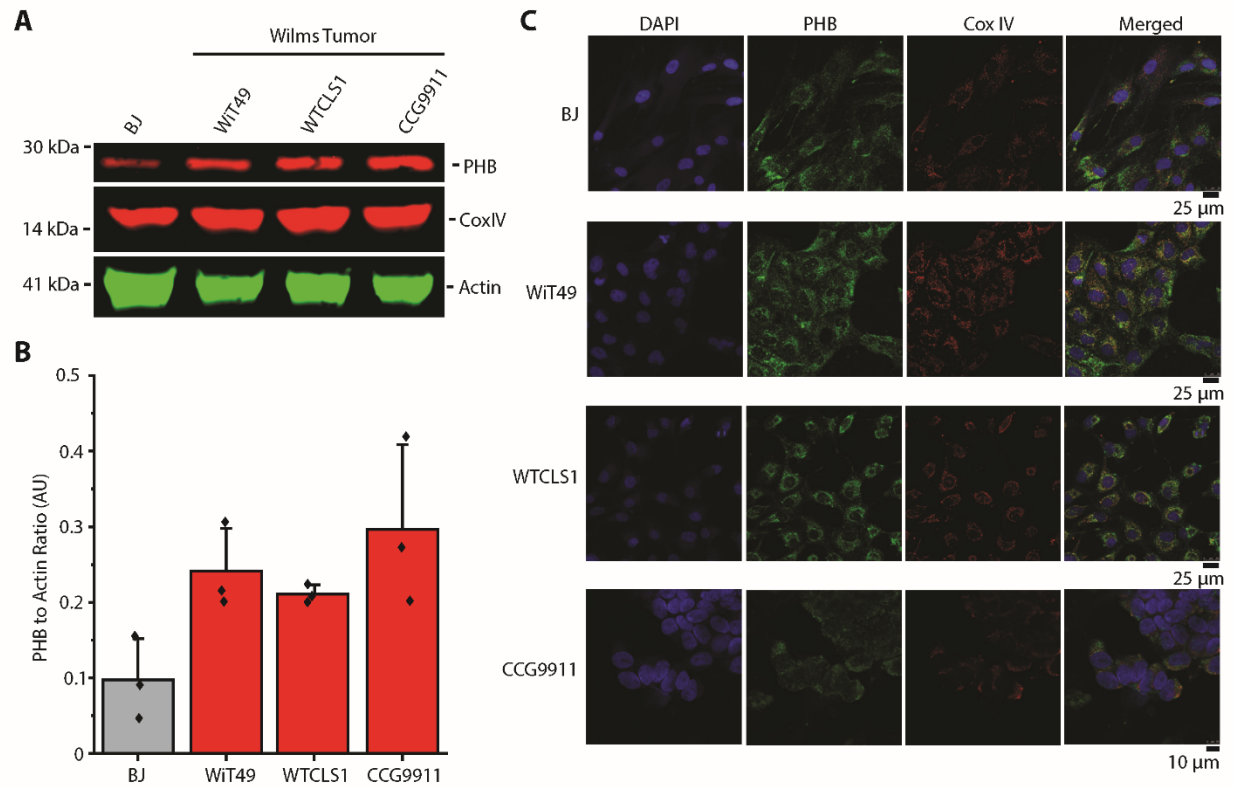
591

592 **Figure 3. Prohibitin is highly expressed in primary Wilms tumor samples.**

593 (A-F). PHB immunohistochemical (IHC) staining was performed on formalin fixed paraffin
 594 embedded primary Wilms tumor samples and compared with adjacent normal kidneys. A-C are
 595 5x magnified and E-F are 40x magnified. A and D include normal kidney. B and E include favorable
 596 histology Wilms tumors. C and F include anaplastic histology Wilms tumors.

597 (G). IHC was performed on a tissue microarray containing 59 primary WT samples and graded
 598 from 0+ to 3+ in a blinded manner. Quantification of IHC from the tissue microarray is shown
 599 and stratified by initial tumor stage.

600 (H-I). A second cohort of 38 primary WT patients was assessed (15 cured, 16 relapsed, 7 no information;
 601 24 favorable, 14 anaplastic WT). The expression of PHB was evaluated on a cell-by-cell basis using Halo
 602 imaging analysis software. 24,862,509 cells in total were counted and scored from 0+ to 3+ based on PHB
 603 expression. In panel H, PHB expression in the cells of Wilms tumors that ultimately relapsed are compared
 604 with those that were cured. Whereas in panel I, PHB expression in the cells of Wilms tumors that had
 605 favorable histology are compared with those with anaplastic histology.



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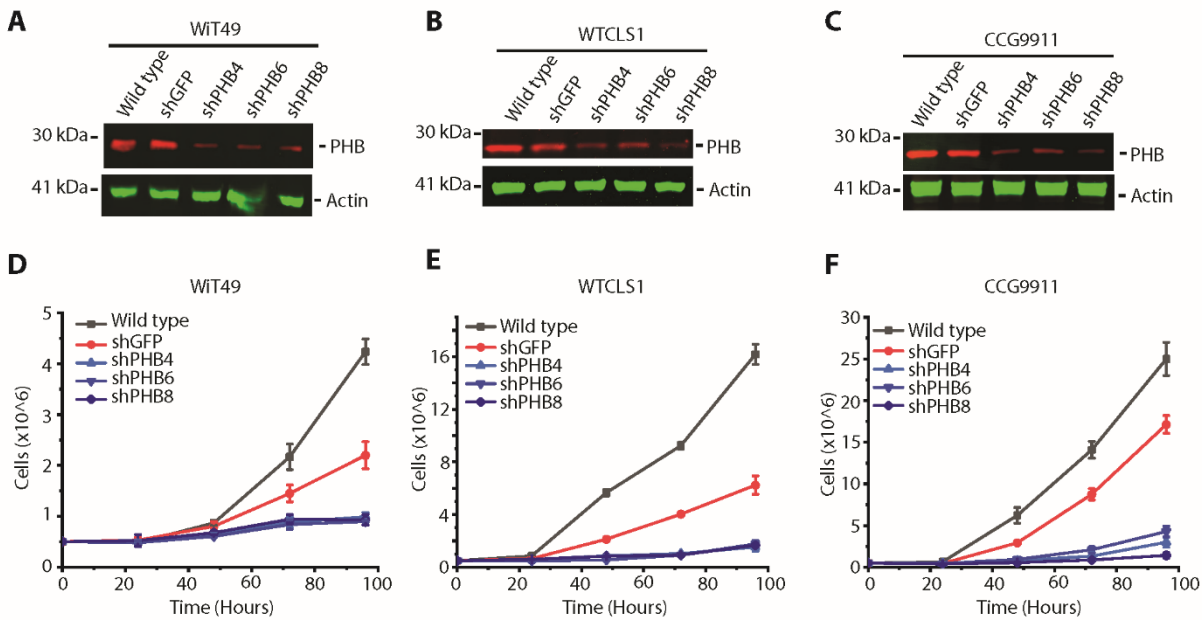
607 **Figure 4. Prohibitin is an abundant mitochondrial protein in Wilms tumor cell lines.**

608 (A). Our *in vitro* studies of PHB included a control fibroblast cell line (BJ) as well as three Wilms
609 tumor cell lines (WiT49, WTCLS1, and CCG9911). Endogenous PHB expression in the Wilms tumor
610 cell line is shown with Actin as a loading control and CoxIV as a mitochondrial loading control.

611 (B). PHB expression is compared in the different cell lines normalized to Actin in western blot
612 triplicates.

613 (C). Confocal imaging demonstrates colocalization of PHB (Green) with the inner mitochondrial
614 membrane marker CoxIV (Red) but not the nuclear marker Dapi (Blue) in paraformaldehyde fixed
615 cells.

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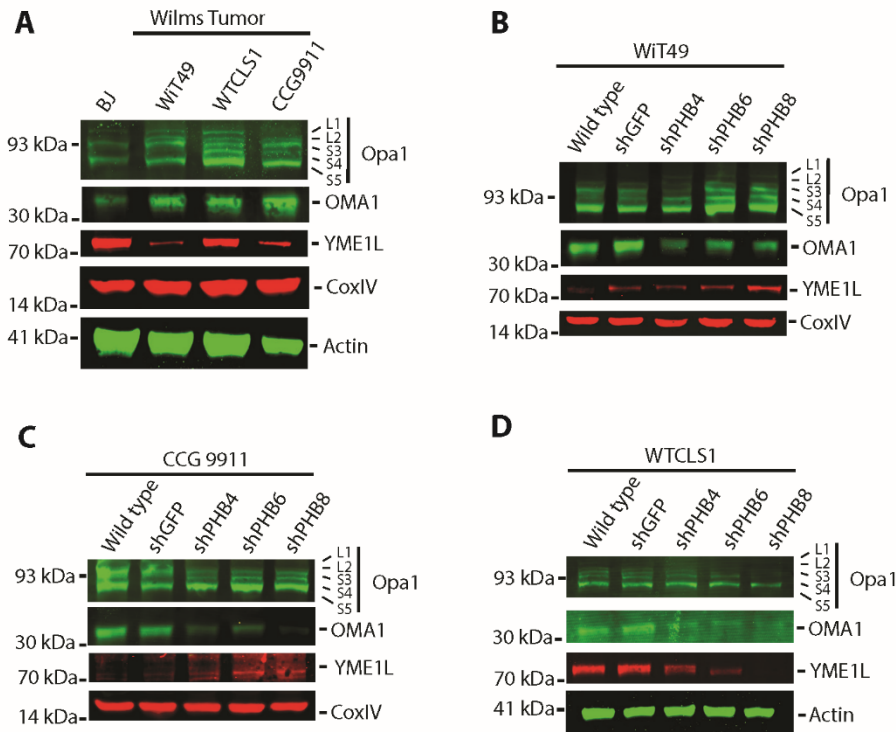


617

618 **Figure 5. Prohibitin is required for Wilms tumor growth and survival.**

619 (A-C). Western blots of wild type Wilms tumor cells (A, WIT49; B, WTCLS1; C, CCG9911) as well
620 as a nontargeting shGFP and three different shRNA hairpins targeting the PHB 3'UTR (shPHB4)
621 and CDS (shPHB6 and shPHB8). Cox IV is used for mitochondrial loading control and Actin is used
622 for whole cell loading control.

623 (D-F). Cell growth over time in Wilms tumor cells (D, WIT49; E, WTCLS1; F, CCG9911) which are
624 wild type (Black), compared with those transduced with non-targeting shGFP (Red), and the three
625 PHB targeting shRNA (Blue).

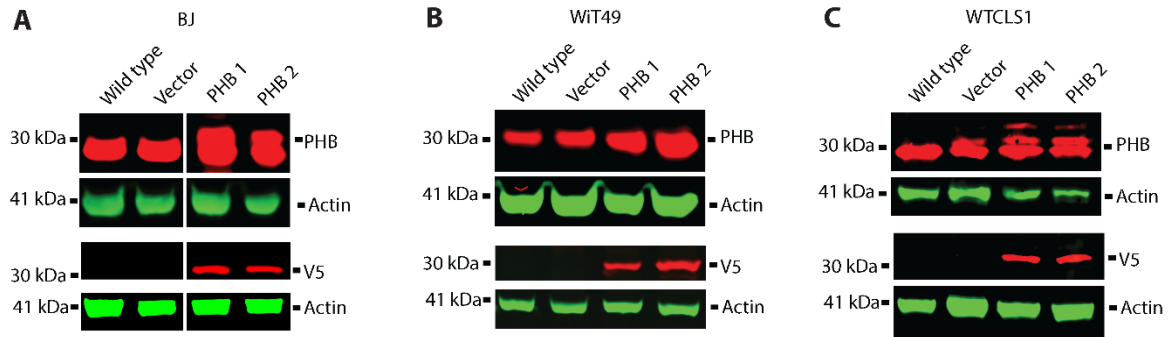


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Figure 6. Depletion of prohibitin results in alterations in mitochondrial intermembrane proteases and structural proteins involved in apoptosis and mitochondrial morphogenesis.

(A). Western blot of endogenous expression of Opa1, OMA1, and YME1L with Cox IV and Actin as mitochondrial and whole cellular loading controls, respectively.

(B-D). Western blots of Opa1, OMA1, and YME1L in Wilms tumor cells (B, WIT49; C, WTCLS1; D, CCG9911) comparing wild type cells with nontargeting shGFP and three different shRNA hairpins targeting the PHB 3'UTR (shPHB4) and CDS (shPHB6 and shPHB8). Loading controls as shown.



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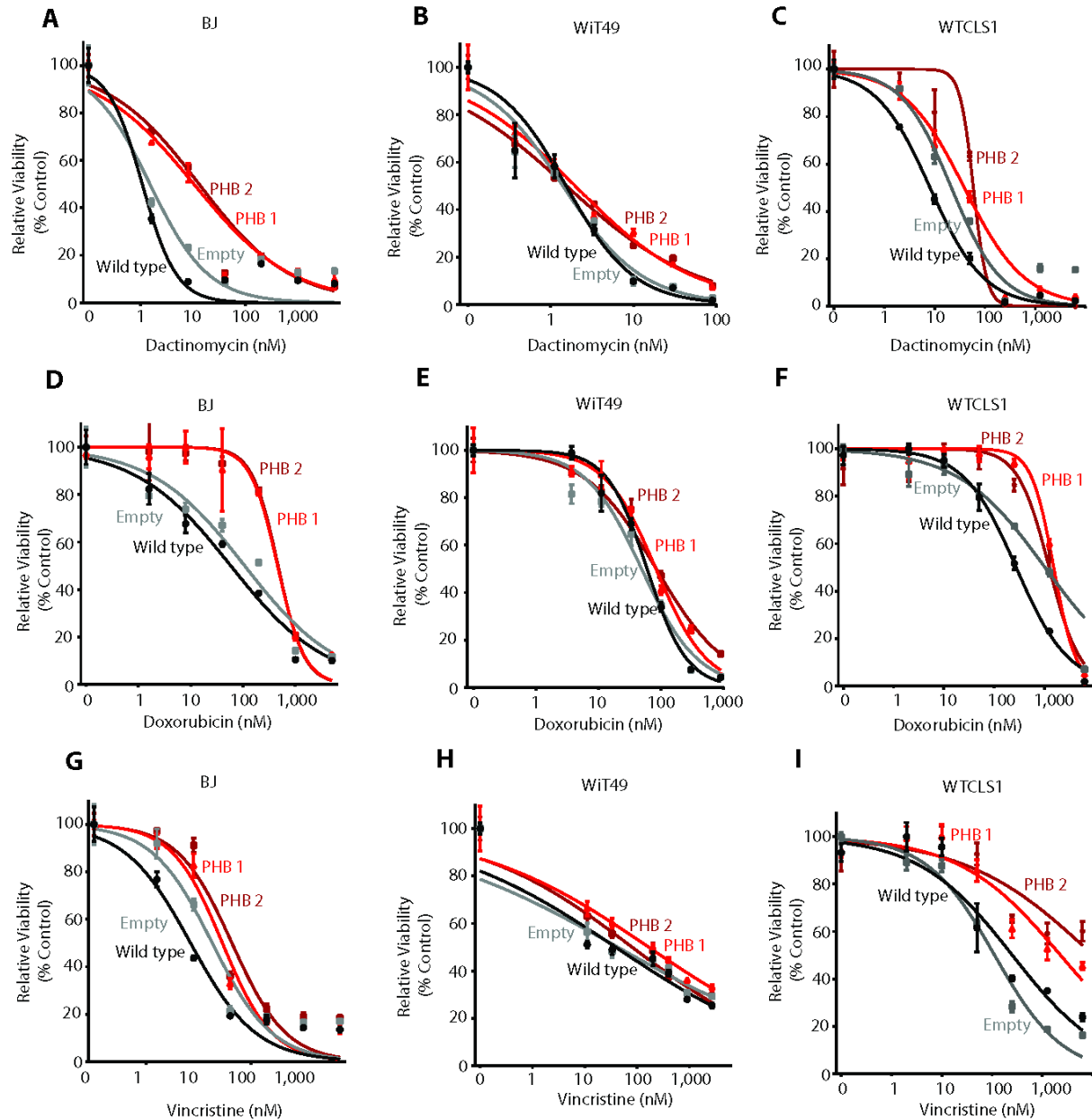
637 **Figure 7. Overexpression of prohibitin in Wilms tumor and control cell lines**

638 (A-C). Western blots of PHB and V5 in control (A, BJ) and Wilms tumor cells (B, WiT49; C, WTCLS1)

639 comparing wild type cells and those transduced with an empty vector with two different clones

640 transduced with a PHB expressing vector containing a V5 tag.

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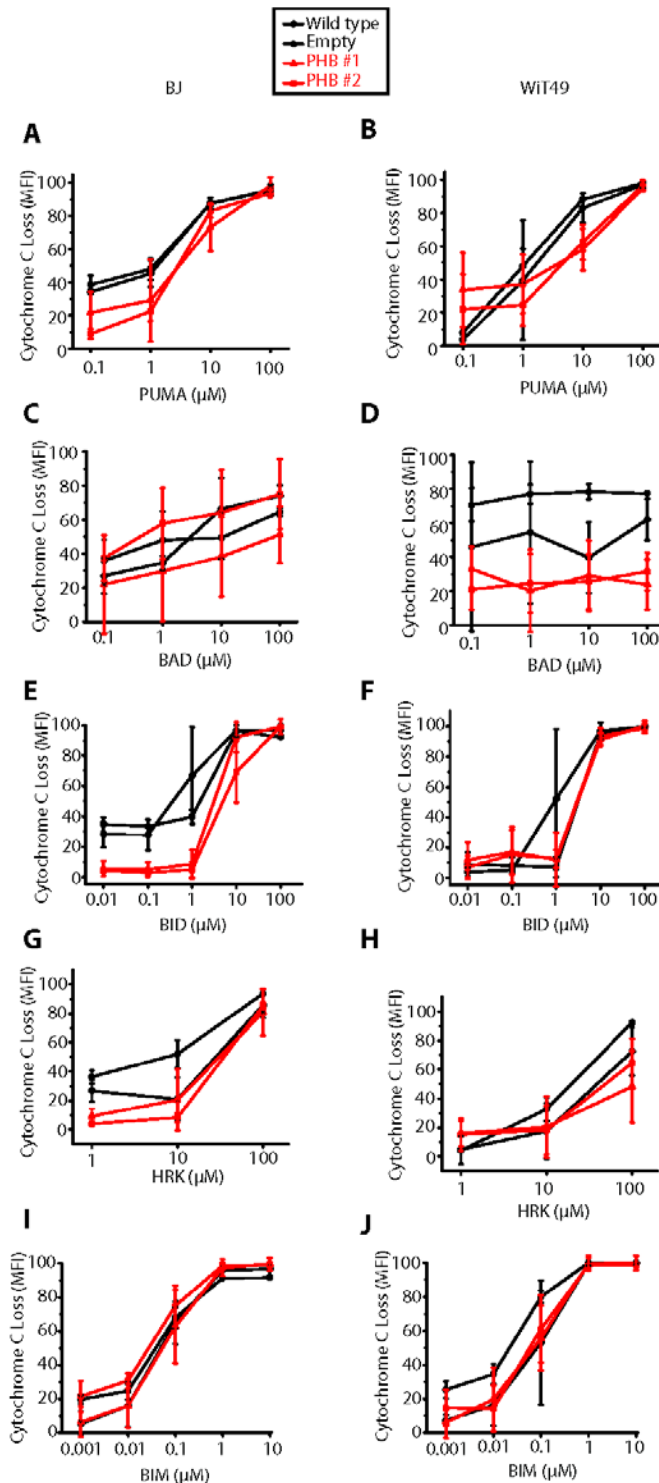


642

643 **Figure 8. Overexpression of prohibitin results in resistance to chemotherapy in both Wilms**
644 **tumor and control cells.**

645 (A-I). Dose response curve of BJ (D, G, J), WiT49 (E, H, K), and WTCLS1 (F, I, L) cells treated with
646 Dactinomycin (D-F), Doxorubicin (G-I), or Vincristine (J-L) for 72 hrs comparing wild type cells
647 (Black), empty vector transduced cells (Gray), as well as PHB transduced cells (Red, Dark Red).

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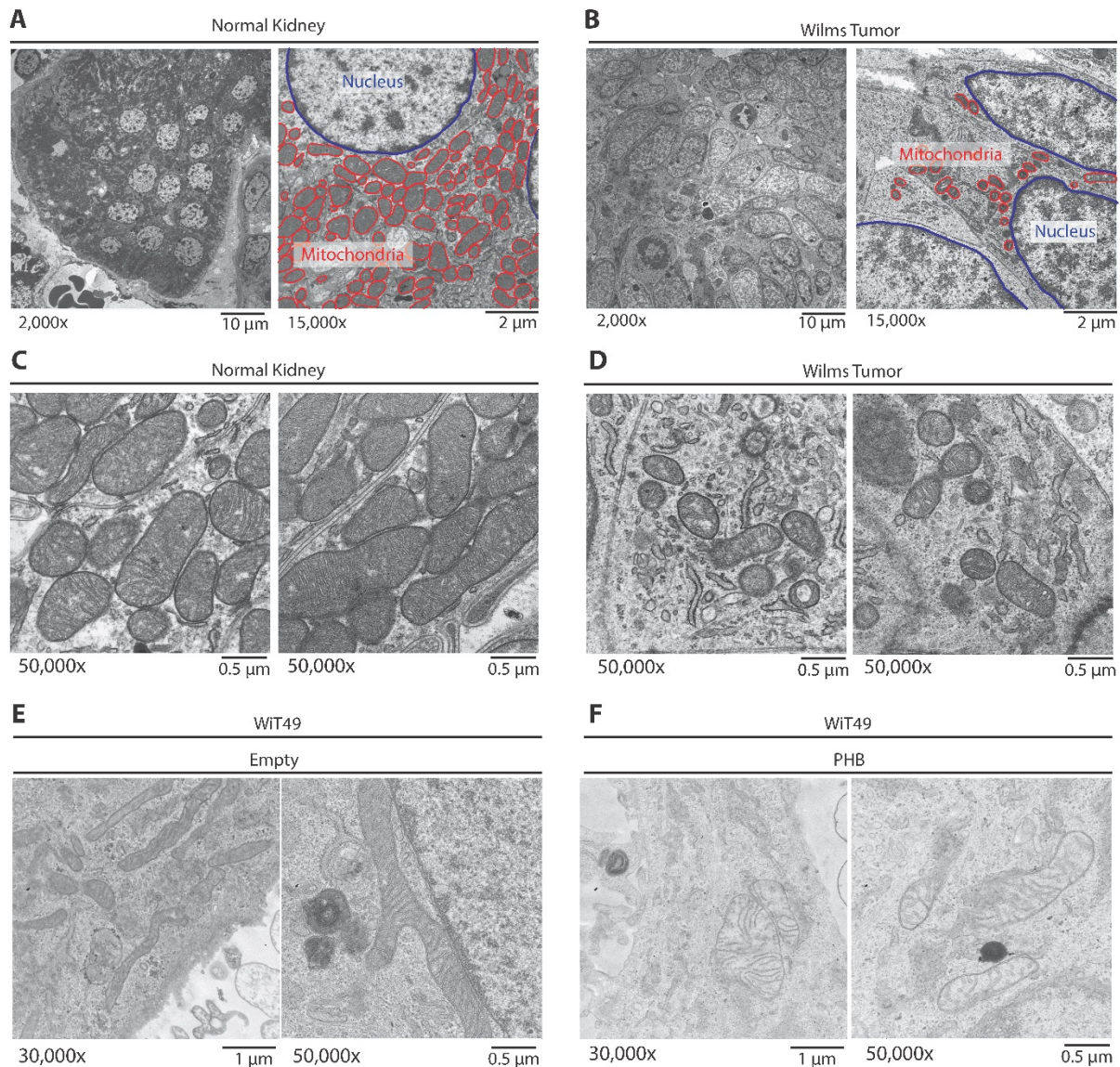


649

650 **Figure 9. BH3 profiling reveals globally decreased apoptotic priming in response to PHB**
651 **overexpression.**

652 (A-J). Cytochrome c loss in response to treatment with different pro-apoptotic peptides
653 comparing Wild type (Black Diamond), with Empty (Black Circles), and two PHB overexpressing
654 cell lines (Red Triangle, Red Square) in both BJ control fibroblasts and WiT49 Wilms tumors.

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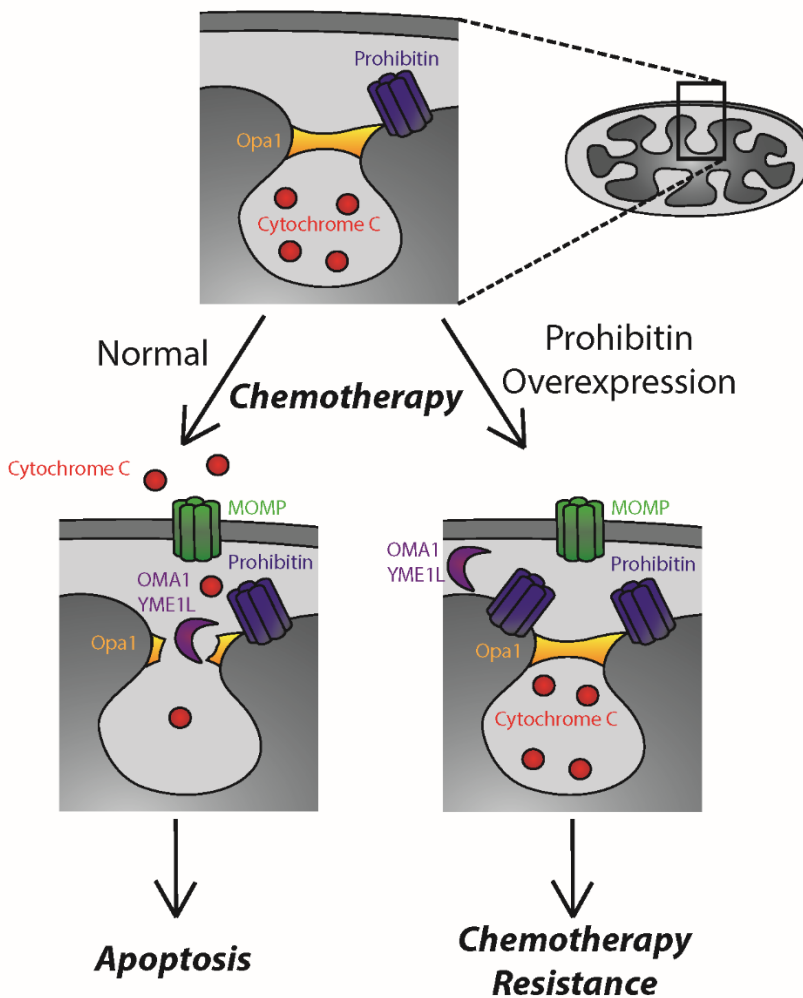
657 **Figure 10. Primary Wilms tumor samples exhibit fewer mitochondria and predominantly a**
658 **fission phenotype, as compared with adjacent normal kidneys.**

659 **(A-D).** Untreated favorable histology Wilms tumor was immediately fixed following nephrectomy
660 and imaged using a transmission electron microscope to evaluate mitochondrial morphology.
661 The normal kidney (Panel A, 2,000x magnification; Panel C, 50,000x magnification) is compared
662 with the Wilms tumor (Panel B, 2,000x magnification; Panel D, 50,000x magnification). Panels A
663 and B also highlight at 15,000x the size and number of the mitochondria (red) as compared with
664 the nucleus (blue).

665 **(E-F).** Characteristic mitochondria of a Wilms tumor cells (WiT49) treated with an empty vector
666 (E) compared with a PHB overexpressing vector (F).

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670 **Figure 11. PHB overexpression leads to failure to release cytochrome c from cristae junctions**
671 **despite the presence of a MOMP complex**

672 Prohibitin (Blue) forms a complex along the mitochondrial inner membrane that interacts with
673 several key regulators of apoptosis, including the Opa1 complex (Orange) located at cristae
674 junctional openings. The majority of cytochrome c (Red) is sequestered within these cristae and
675 in response to an apoptotic stimuli such as chemotherapy, the mitochondrial outer membrane
676 pore (MOMP) complex consisting of BAX and BAK is inserted into the mitochondrial outer
677 membrane. Upon proteolysis of the Opa1 complex, generally via OMA1 or other intermembrane
678 proteases (Purple), Cytochrome c is released into the cytosol where it results in the apoptotic
679 cascade. Our model proposes that due to the overexpression of PHB, in response to apoptotic
680 stimuli, intermembrane proteases are no longer able to access the Opa1 complex thereby
681 resulting in resistance to chemotherapy despite the presence of a MOMP pore in the outer
682 mitochondrial membrane, ultimately resulting in failure to undergo apoptosis and chemotherapy
683 resistance.