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1 **HTLV-1 TRANSACTIVATOR TAX EXPLOITS THE XPB SUBUNIT OF TFIID**  
2 **DURING VIRAL TRANSCRIPTION**

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16

17 **Keywords:** Retrovirus, oncoprotein, transcription, TFIID, promoter opening

18

19 **Short title:** XPB is a cofactor of HTLV-1 Tax

20 **ABSTRACT**

21 Human T-cell lymphotropic virus type 1 (HTLV-1) Tax oncoprotein is mandatory for viral  
22 gene expression. Tax transactivates the viral promoter by recruiting specific transcription  
23 factors but also by interfering with general transcription factors involved in the preinitiation  
24 step, such as TBP, TFIIA and TFIID. However, data are lacking regarding Tax interplay with  
25 TFIIH, which intervenes during the last step of preinitiation. We previously reported that  
26 XPB, the TFIIH subunit responsible for promoter opening and promoter escape, is required  
27 for Tat-induced Human-Immunodeficiency Virus promoter transactivation. Here, we  
28 investigated whether XPB may also play a role in HTLV-1 transcription. We report that  
29 endogenous XPB binds to Tax and is recruited on proviral LTR in HTLV-1-transformed T  
30 cells but also in HTLV-1-immortalized primary T cells. In contrast, XPB recruitment at the  
31 LTR is not detected in Tax-negative HTLV-1-infected T cells and is strongly reduced upon  
32 Tax downregulation. XPB overexpression does not affect basal HTLV-1 promoter activation  
33 but enhances Tax-mediated transactivation. Conversely, inducing XPB degradation strongly  
34 reduces Tax-mediated transactivation. Importantly, this inhibition can be fully compensated  
35 by overexpressing wild-type XPB but not a XPB mutant defective for the ATPase activity  
36 responsible for promoter opening. Finally, XPB downregulation inhibits proliferation of Tax-  
37 positive but not Tax-negative HTLV-1- T cell lines. These findings reveal that XPB is a novel  
38 cellular co-factor hijacked by Tax to facilitate HTLV-1 transcription.

39 **IMPORTANCE**

40 HTLV-1 is considered the most potent human oncovirus and is also responsible for severe  
41 inflammatory disorders. HTLV-1 transcription is taken in charge by RNA polymerase II and  
42 is controlled by the viral oncoprotein Tax. Tax transactivates the viral promoter first *via* the  
43 recruitment of CREB and its co-factors to the LTR. However, how Tax controls subsequent  
44 steps of the transcription process remains unclear. In this study, we explore the link between

45 Tax and the XPB subunit of TFIID that governs, *via* its ATPase activity, the promoter  
46 opening step of transcription. We demonstrate that XPB is a novel physical and functional  
47 partner of Tax, recruited on the HTLV-1 LTR and required for viral transcription. These  
48 findings extend the mechanism of Tax transactivation to the recruitment of TFIID and  
49 reinforce the link between XPB and transactivator-induced viral transcription.

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## 60 INTRODUCTION

61

62 Human T-lymphotropic virus type 1 (HTLV-1) is the etiologic agent of adult T-cell  
63 leukemia/lymphoma (ATL), a very aggressive malignant proliferation of CD4+ T  
64 lymphocytes (1, 2). In addition, HTLV-1 is also associated to various inflammatory disorders,  
65 notably HTLV-1-associated myelopathy/tropical spastic paraparesis (HAM/TSP)(3).

66 The HTLV-1 genome encodes for structural, enzymatic, regulatory and auxiliary proteins.  
67 Among them, the regulatory protein Tax is a major player for disease development (4, 5).  
68 Indeed, Tax is an oncoprotein able to induce leukemia or lymphoma in transgenic mice (6) as  
69 well as immortalization of primary human CD4+ T cells *in vitro* (7). Tax is also the  
70 transactivator of the viral promoter located in the 5'LTR, thereby controlling its own  
71 production as well as that of all sense HTLV-1 transcripts (8).

72 Transcription is an ordered process that proceeds through multiple stages including binding of  
73 specific transcription factors to the promoter, assembly of the preinitiation complex (PIC),  
74 promoter opening and escape, RNA polymerase II (Pol II) pausing, elongation and  
75 termination (reviewed in (9, 10)). Tax controls the first step by recruiting the specific  
76 transcription factor CREB at viral CREB-response elements (vCRE) located in the U3 region  
77 of the 5'LTR (8, 11). This event was initially believed to be the only mechanism by which  
78 Tax achieved maximal transcription. However, further data pointed towards additional key  
79 roles of Tax on the subsequent steps of transcription (12). Indeed, Tax was also shown to  
80 recruit to the LTR the general transcription factors (GTF) TBP (13), TFIIA (14), TFIID (15)  
81 involved in PIC assembly as well as the elongation factor pTEF-b (16, 17). In contrast, data  
82 are lacking regarding the specific involvement of TFIIH, which ensures transition between  
83 preinitiation and elongation, in the context of Tax-dependent transcription.

84 TFIIH is a complex playing a dual role in DNA repair and transcription. It consists in five  
85 non-enzymatic proteins, the CDK-activation kinase CAK (cyclin H, CDK7 and Mat1) and the  
86 XPD and XPB enzymes (18). Within TFIIH, the ATPase and translocase *Xeroderma*  
87 *Pigmentosum* type B (XPB) plays a key role in transcription (19). XPB acts as a molecular  
88 wrench able to melt double stranded DNA, allowing opening and insertion of the sequence  
89 around the transcription start into the active site of Pol II (19-22). The ATPase activity of  
90 XPB is critical for the DNA opening while translocase activity is committed to promoter  
91 escape (23-25). The ATPase activity of XPB is carried by the helicase domain 1 motif I and is  
92 regulated by other regions of the protein, notably the helicase domain 1 R-E-D motif (24, 26,  
93 27).

94 XPB plays a complex role in transcription that has only been clarified recently. Indeed,  
95 Alekseev *et al.* demonstrated that XPB causes a regulatory block during preinitiation,  
96 imposed by its translocase/helicase activity, then subsequently relieved by its own ATPase  
97 activity (21, 28). Strikingly, this mechanism appears to be dispensable for basal transcription  
98 while in contrast, transcription induced by trans-retinoic acid or cytokines was shown to be  
99 sensitive to XPB downregulation (29, 30). This elucidation of XPB function has been greatly  
100 facilitated by the use of a drug, Spironolactone (SP), originally described as an aldosterone  
101 antagonist and later on identified as a compound able to induce rapid degradation of XPB  
102 (30). Of note, ability to induce XPB degradation is not related to aldosterone signaling since  
103 the SP derivative Eplerenone (EPL) antagonizes aldosterone signaling like SP but has no  
104 impact on XPB (30). Strikingly, SP is believed to induce the degradation of XPB within  
105 preformed TFIIH complexes, allowing XPB depletion while preserving TFIIH integrity (21,  
106 30). A recent study showing that SP-induced XPB degradation depends on its prior  
107 phosphorylation by CDK7 provides the molecular explanation for this selectivity (31).

108 In a previous study, we demonstrated that XPB is required for Tat-mediated human  
109 immunodeficiency virus type 1 (HIV-1) promoter activation (32). This prompted us to  
110 investigate the possibility that XPB could also contribute to HTLV-1 transcription. In this  
111 study, we investigated the potential interaction between Tax and XPB as well as the impact of  
112 XPB on HTLV-1 promoter transactivation and viral transcription.

113 **RESULTS**

114

115 **XPB binds to Tax**

116 Since Tax was previously shown to interact with certain GTFs, we examined whether it may  
117 also interact with XPB. Co-immunoprecipitation experiments were first performed in 293T  
118 cells cotransfected with an XPB-coding plasmid along or not with a Tax expressor or empty  
119 vector. Immunoprecipitation of Tax allowed the recovery of XPB only in Tax cotransfected  
120 cells (Fig. 1A, lane 4). The same experiment was repeated in C8166 T cells that endogenously  
121 produce Tax and XPB. Immunoprecipitation with the anti-Tax antibody allowed the recovery  
122 of XPB while only background signal was found upon precipitation with control IgG (Fig.  
123 1B). Hence, XPB binds to Tax in both overexpression and endogenous conditions.

124

125 **XPB is recruited at proviral LTR in a Tax-dependent manner**

126 Whether XPB is recruited at the HTLV-1 LTR was examined by chromatin  
127 immunoprecipitation (ChIP) experiments conducted in either Tax positive (C8166) or Tax  
128 negative/low (TL-Om1, MT-1) HTLV-1-transformed T cell lines. TL-Om1 T cells do not  
129 expressed Tax at either RNA or protein level (33) while MT-1 T cells were recently shown to  
130 produce Tax protein only in a fraction of cells and in a transient manner (34). ChIP  
131 experiments were also performed on CB-CD4/HTLV-1 T cells generated upon *in vitro*  
132 activation of PBMC obtained from a HAM/TSP patient (35). Importantly, CB-CD4/HTLV-1  
133 T cells remain dependent of exogenous IL-2 and present the same Tax or HBZ intracellular  
134 distribution than fresh PBMC from HAM/TSP patients (36).

135 Following chromatin immunoprecipitation with a control (IgG) or anti-XPB antibody,  
136 recovered DNA fragments were subjected to PCR using primers amplifying either the R or  
137 U5 region of the LTR located downstream the transcription site start. The I $\kappa$ B $\alpha$  (*NFKBIA*)



138 promoter region, at which XPB was shown to be recruited (29), was amplified as positive  
139 control. In addition, the non-related  $\alpha$ -satellite region was also amplified as negative control.  
140 In both C8166 and CB-CD4/HTLV-1 T cells, XPB recruitment was observed at the R and U5  
141 LTR regions (Fig. 2A). In contrast, no LTR-specific signal (R or U5 region) was detected for  
142 either TL-Om1 or MT-1 T cells (Fig. 2B), strongly suggesting that XPB recruitment to the  
143 LTR depends on Tax. ChIP experiments were validated by the fact that for all T cell lines,  
144 positive XPB signals were found at the I $\kappa$ B $\alpha$  promoter but not at the  $\alpha$ -satellite region (Fig.  
145 2A and 2B). Of note, Tax-negative HTLV-1-transformed T cells were shown to maintain  
146 permanent NF- $\kappa$ B activation despite the absence of Tax (37), explaining the positive XPB  
147 signal found at the I $\kappa$ B $\alpha$  promoter for both TL-Om1 and MT-1 T cells.

148 If Tax is required for XPB recruitment to the LTR, downregulating Tax expression should  
149 lower the amount of XPB bound to the promoter. To address this hypothesis, we tried to  
150 deplete Tax *via* siRNA in C8166 T cells but obtained only little decrease in global Tax level  
151 (data not shown). Instead, we used chaetocin, an HSP90 inhibitor (38), since such inhibitors  
152 were previously shown to induce rapid Tax degradation (39). Treating C8166 T cells with  
153 chaetocin massively reduced Tax protein level without any effect on endogenous XPB (Fig.  
154 2C). Tax downregulation coincided with a statistically significant reduction of the level of  
155 XPB bound to the HTLV-1 LTR (Fig. 2D, left panel). In contrast, XPB was detected at the  
156 same level at the I $\kappa$ B $\alpha$  promoter (Fig. 2D, right panel), showing that chaetocin did not  
157 prevent XPB recruitment at chromatin in a general manner.

158 Collectively, these findings strongly suggest that XPB is recruited on the HTLV-1 LTR in a  
159 Tax-dependent manner.

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162

163 **XPB is involved in Tax-mediated but not basal LTR activation**

164 To assess whether XPB recruitment at the viral promoter impacts LTR activation, luciferase  
165 assays were performed in uninfected Jurkat T cells. We used an approach described by Elinoff  
166 et al., based on XPB-overexpression in cells treated with SP in order to allow endogenous  
167 XPB degradation (29). Eplerenone (EPL) was used as a control drug. Jurkat T cells were  
168 transfected with the HTLV-1 LTR (U3R-Luc) reporter construct and pRL-TK normalization  
169 plasmid together with a control (basal) or Tax (transactivation) plasmid and with or without  
170 the XPB expressor, then treated with DMSO, EPL or SP for 24 hours. Neither SP treatment  
171 nor XPB overexpression affected basal activation of the U3R-Luc construct (Fig. 3, upper  
172 panel, bars 3 and 4), as compared to control cells (bar 1). In contrast, Tax-induced  
173 transactivation was reduced by 50% in SP-treated cells as compared to DMSO-treated cells  
174 (Fig. 3, upper panel, bars 7 and 9). The level of transfected Tax was similar in presence of  
175 either DMSO or SP (Fig. 3, lower panel, lanes 7 and 9), indicating that SP influenced neither  
176 Tax production from a CMV promoter nor Tax stability. Overexpressing XPB together with  
177 Tax allowed to recover an XPB level close to the endogenous level (lanes 1 and 12), even  
178 though overexpressed XPB was also partly sensitive to SP treatment (lanes 10 and 12). We  
179 noticed that the level of intracellular XPB recovered upon XPB plasmid transfection was  
180 higher in presence than in absence of Tax (lanes 6 and 12). This may be due to the ability of  
181 Tax to transactivate the CMV promoter driving XPB expression, although higher XPB level  
182 was not found in DMSO or EPL-treated Tax-transfected cells. Alternatively, this may indicate  
183 that overexpressed Tax may somehow protects XPB from degradation triggered by SP.  
184 Importantly, this XPB recovery fully reversed the inhibitory effect of SP on Tax-induced LTR  
185 transactivation, independently on Tax level (Fig. 3, upper panel, bar 12).  
186 These findings show that XPB is required for Tax-induced HTLV-1 LTR activation in T cells.  
187 In addition, the rescue effect of XPB overexpression confirms that SP acts on promoter

188 activation in a XPB dependent manner, which validates SP as a relevant tool to analyze the  
189 impact of XPB downregulation on transcription.

190

191 **The R-E-D domain of XPB is required for LTR transactivation and endogenous Tax**  
192 **production**

193 To confirm that XPB is required for LTR transactivation by Tax, luciferase assays were  
194 performed in C8166 T cells that produce Tax endogenously. In addition, we took advantage  
195 of the ability of XPB to compensate SP-mediated XPB degradation to characterize the XPB  
196 activity required for LTR transactivation. XPB contains various functional domains (25). In  
197 particular, the R-E-D motif (Fig. 4A) was shown to be required for optimal ATPase activity  
198 and promoter opening (26). We then used the XPB-E473A protein mutated in the R-E-D  
199 region and two other XPB mutants retaining transcriptional activity but either defective  
200 (F99S) or normal (T119P) for DNA repair activity (27). Importantly, the three mutants were  
201 previously shown to be still properly incorporated within the TFIIH complex (26, 27).  
202 Moreover, coimmunoprecipitation experiments performed in cotransfected 293T cells  
203 demonstrated that each mutant remains capable of interacting with Tax (Fig. 4B).

204 Luciferase assays were then performed in HTLV-1-infected C8166 T cells transfected with  
205 the reporter plasmids and one of the XPB construct in presence of DMSO, EPL or SP. As  
206 expected, treating C8166 T cells with SP induced XPB downregulation, which coincided with  
207 reduced production of endogenous Tax (Fig. 4C). In contrast, SP treatment did not affect the  
208 production of phospho-CREB or that of specific protein 1 (Sp1), known to modulate Tax-  
209 induced or basal LTR activation (40) (Fig. 4C). Strong reduction in LTR transactivation was  
210 found in SP-treated control cells (Fig. 4D, upper panel, bar 3). Overexpressing wild-type (wt)  
211 XPB, XPB-F99S or XPB-T119P reversed the effect of SP on LTR activation by Tax (Fig. 4D,  
212 upper panel, bars 6, 9 and 12). In contrast, despite XPB-E473A was capable of increasing the

213 level of intracellular XPB like wt XPB and the two other mutants (Fig. 4D, lower panel, lane  
214 15), this mutant was unable to rescue LTR transactivation in SP-treated cells (Fig. 4D, upper  
215 panel, bar 15). Immunoblot analysis showed that overexpressing wt XPB, XPB-F99S or XPB-  
216 T119P increased the level of endogenous Tax in SP-treated C8166 T cells (Fig. 4C, lower  
217 panel, lanes 6, 9 and 12). In contrast, no such increase was observed for XPB-E473A (Fig.  
218 4D, lower panel, compared lane 15 to lane 1).

219 These results show that XPB is involved in Tax-mediated LTR transactivation in the context  
220 of integrated proviruses and further indicate that the R-E-D domain of XPB, regulating its  
221 ATPase activity, is involved in this process.

222

### 223 **SP-mediated XPB downregulation inhibits viral transcription**

224 We next directly investigated the impact of XPB downregulation on HTLV-1 mRNA  
225 production by RTqPCR experiments. C8166 and MT-4 HTLV-1-transformed T cells as well  
226 as CB-CD4/HTLV-1-immortalized T cells were treated with DMSO, SP or EPL for 24 hours.  
227 Of note, C8166 T cells exhibit a defect in viral RNA export and therefore do not produce Gag  
228 proteins while they still produce Gag at the mRNA level (41). SP treatment inhibited the  
229 production of Gag mRNA in C8166 (Fig. 5A), MT-4 (Fig. 5B, left panel) and HTLV-1-  
230 immortalized CB-CD4/HTLV-1 (Fig. 5C, left panel) T cells. In both MT-4 and CB-  
231 CD4/HTLV-1 T cells, this was accompanied by a reduction in Gag protein production (Fig.  
232 5B and 5C, right panels).

233 To further study the link between HTLV-1 RNA production and XPB, we quantified the level  
234 of HTLV-1 Gag mRNA in the course of SP treatment. C8166 T cells were treated with  
235 DMSO, EPL or SP up to 6 hours. In agreement with previous data (30), XPB decrease can  
236 already be seen 30 min post-treatment with a maximal reduction at 120 min (Fig. 5D).  
237 Reduction of Gag mRNA began at 30 min (Fig. 5E, left panel), coinciding with the beginning

238 of XPB downregulation (Fig. 5D). Moreover, a solid positive correlation was found between  
239 the level of Gag mRNA and the amount of XPB protein over the course of SP treatment (Fig.  
240 5E, right panel). Importantly, no significant variation in the level of HPRT and EEF1G  
241 housekeeping gene mRNAs was observed in the course of SP treatment (Fig. 5F), confirming  
242 that SP does not act as a general inhibitor of Pol II-mediated transcription.

243

### 244 **SP-mediated XPB downregulation inhibits growth of Tax-positive HTLV-1-infected T** 245 **cells**

246 We finally studied the effect of XPB downregulation on the growth of HTLV-1-infected T  
247 cells. Cells were treated every day with DMSO or with EPL or SP and the number of living  
248 cells was quantified by the MTT method after 72h of culture. As compared to DMSO and  
249 EPL, SP reduced the viability of C8166 (Fig. 6A) and MT-4 (Fig. 6B) T cells in a dose-  
250 dependent manner. The same treatments were applied on Tax negative/low HTLV-1-infected  
251 T cells (MT-1, TL-Om1) and uninfected T cells (Jurkat). Neither SP nor EPL impacted  
252 viability of TL-Om1 (Fig. 6C) or Jurkat (Fig. 6E) T cells. Interestingly, SP at 10  $\mu$ M slightly  
253 decreased viability of MT-1 T cells (Fig. 6D), in agreement with the transient expression of  
254 Tax by this cell line (34). Importantly, SP treatment also reduced viability of CB-CD4/HTLV-  
255 1 T cells in a dose-dependent manner (Fig. 6F), demonstrating that its cytotoxic effect also  
256 applied on HTLV-1-immortalized primary T cells.

257 These data show that the effect of XPB downregulation on HTLV-1 RNA production  
258 translates into inhibition of proliferation of Tax-positive HTLV-1-infected T cells, reinforcing  
259 the link between Tax expression and XPB function.

260

261

262 **DISCUSSION**

263 As emphasized in recent reviews, HTLV-1 is considered the most potent cancer-associated  
264 virus and still remains a significant threat to human health (42, 43). Deciphering the  
265 mechanisms by which the HTLV-1 transactivator Tax regulates HTLV-1 gene expression is  
266 therefore a central issue for both fundamental and therapeutic aspects. In this study, we  
267 describe a novel physical and functional interaction between Tax and the XPB subunit of the  
268 general transcription factor TFIID.

269 First, we found that Tax coprecipitates with XPB in cotransfected 293T cells as well as in  
270 HTLV-1-infected T cells, in which the two proteins are produced endogenously. Second, we  
271 showed that endogenous XPB is bound to the HTLV-1 LTR in Tax-positive but not Tax-  
272 negative HTLV-1-transformed T cells, suggesting that XPB recruitment is mediated by Tax.  
273 Importantly, XPB recruitment at the LTR was also observed in HTLV-1-immortalized T cells  
274 generated from PBMC from an HAM/TSP patient. The role of Tax was confirmed by data  
275 showing that inducing Tax degradation significantly reduced XPB recruitment at the LTR. Of  
276 note, we checked that chaetocin treatment used to induce Tax degradation did not affect XPB  
277 stability. Furthermore, chaetocin did not prevent XPB recruitment at a cellular promoter,  
278 showing that XPB functionality was preserved. These data provide direct evidence that XPB  
279 is a novel partner of Tax recruited by Tax at the LTR of integrated viral genomes in an  
280 HTLV-1-transformed T cell line as well as in *in vivo*-infected T cells.

281 To assess the functional role of XPB, we next studied the impact of XPB overexpression on  
282 HTLV-1 LTR activation using a reporter construct. We found that overexpressing XPB in  
283 uninfected Jurkat T cells increases luciferase production only in presence of Tax, showing  
284 that XPB is involved in Tax-induced but not basal LTR activation. Conversely, inducing XPB  
285 degradation using the validated drug SP significantly reduces Tax-mediated LTR  
286 transactivation in Jurkat T cells with no impact on Tax stability. SP-mediated XPB

287 downregulation also inhibits LTR transactivation mediated by endogenous Tax in HTLV-1-  
288 transformed T cells, while the level of CREB or Sp1 was not affected. Of note, no significant  
289 change in Tax-mediated LTR transactivation is observed upon treatment with EPL, arguing  
290 against a role of aldosterone signaling modulation in LTR inhibition. The importance of XPB  
291 is also attested by the fact that XPB overexpression is sufficient to reverse the negative effect  
292 of SP on LTR transactivation in either Tax-transfected Jurkat T cells or HTLV-1-infected  
293 C8166 T cells. This compensation effect gave us the opportunity to identify the domain of  
294 XPB involved in Tax-mediated HTLV-1 transcription. Thus, we found that wild type XPB as  
295 two XPB mutants defective for DNA repair but retaining transcriptional activity, fully  
296 compensate SP-mediated XPB downregulation in C8166 T cells. In contrast, no compensation  
297 is achieved with a mutant bearing a mutation in the R-E-D domain regulating XPB ATPase  
298 activity (26). This strongly suggests that the ATPase-dependent activity of XPB, necessary for  
299 the promoter opening activity, is indeed the one cooperating with Tax during HTLV-1  
300 transcription.

301 Importantly, we also provide evidence that inducing XPB degradation had major  
302 consequences on viral RNA expression and viability of HTLV-1-infected T cells. Indeed, we  
303 showed that SP reduces the production of HTLV-1 Gag mRNA and that there is a solid  
304 correlation between the level of Gag mRNA and the level of XPB. Moreover, we found that  
305 as compared to EPL, SP inhibits the proliferation of HTLV-1-infected T cells. This was  
306 observed in C8166 and MT-4 T cells but also in HTLV-1-immortalized CB-CD4/HTLV-1 T  
307 cells, proving that the effect of XPB downregulation is not restricted to HTLV-1-transformed  
308 T cells. In contrast, SP had no effect on either uninfected T cells or Tax-negative HTLV-1-  
309 infected T cells. This reinforces the functional link between XPB and Tax and confirms the  
310 key role of Tax in the survival of Tax-positive HTLV-1-infected T cells (44). These findings

311 also reveal that *via* its ability to downregulate XPB, SP is a potent inhibitor of Tax-induced  
312 HTLV-1 gene expression as well as Tax-driven T cell proliferation.

313 Since XPB is member of a complex of general transcription factors, one could assume that its  
314 downregulation would block transcription in a general manner. However, the role of XPB is  
315 more complex. Indeed, while XPB appears to be dispensable for basal transcription, it is  
316 required for transcription induced by certain stimuli. In good agreement with this, TFIIH was  
317 shown to be at least partially dispensable in the case of promoters with preformed  
318 transcription bubbles (45) while the promoter opening step, controlled by XPB, is considered  
319 an important regulatory step for inducible promoters (46). We found here that SP-mediated  
320 degradation of XPB impacts Tax-mediated but not basal HTLV-1-LTR activity in Jurkat T  
321 cells. Noteworthy, we previously reported that SP inhibits Tat-dependent but not basal  
322 transcription of the HIV-1 LTR (32). Our data therefore provide new evidence for a role of  
323 XPB in inducible viral transcription by showing that XPB is also involved in HTLV-1 RNA  
324 production.

325 Our demonstration that Tax interacts with XPB, raises the issue of whether XPB could also  
326 directly interact with Tat to accomplish its function on the HIV-1 LTR promoter. In this line,  
327 it would be also of interest to study the recruitment of XPB on the HIV-1 LTR sequence. Both  
328 HIV-1 Tat (47) and HTLV-1 Tax (16) interact with pTEF-b but, in contrast to Tat, Tax is able  
329 as well to recruit TFIIA and TFIID to the promoter. These findings, along with our present  
330 data, support a model in which Tax not only recruits specific transcription factors to the  
331 promoter but controls as well subsequent steps of the transcription process by successively  
332 recruiting at least one subunit of each GTF complex acting together with RNA Pol II (Fig. 7).  
333 This provides another example of the powerful ability of Tax to manipulate cellular  
334 machineries.



335 In conclusion, this study demonstrates that XPB is a member of the Tax-dependent  
336 transcription complexes assembled at the HTLV-1 LTR. Our data also suggest that the  
337 promoter opening step of transcription plays a key role in HTLV-1 gene expression. These  
338 findings provide new insights on the molecular players governing HTLV-1 transcription and  
339 may open new avenues of research for the development of therapeutic interventions targeting  
340 HTLV-1 transcription.

341 **MATERIALS AND METHODS**

342

343 **Cells and transfection**

344 HEK-293T (American Type Culture Collection CRL-3216) were grown in Dulbecco's  
345 modified Eagle's medium supplemented with 10% fetal calf serum (Dutcher), 2 mM  
346 glutamine, 1 mM pyruvate and antibiotics (Invitrogen) and were transfected using the  
347 phosphate calcium procedure. Uninfected CD4+ Jurkat T-cells (kindly provided by S.  
348 Emiliani, Institut Cochin, France) were grown in RPMI 1640 medium supplemented as above.  
349 The HTLV-1-infected CD4+ T-cell lines C8166 and MT-4 (NIH AIDS Research and  
350 Reference Reagent Program, USA), TL-Om1 and MT-1 (kindly provided by Dr. Harhaj, Johns  
351 Hopkins School of Medicine, Baltimore, USA) were grown in supplemented RPMI 1640  
352 containing also 25mM glucose, 20 mM HEPES and 5mL of 100X non-essential aminoacid  
353 solution (Invitrogen). T cell lines were transfected using the DMRIE-C reagent (Roche).  
354 HTLV-1-immortalized CB-CD4/HTLV-1 T cells generated from peripheral blood  
355 mononuclear cells of a TSP/HAM patient have been described in (35). These cells were  
356 grown in supplemented RPMI medium in the presence of 50U/ml of IL-2 (Roche, France).

357 **Plasmids**

358 The pSG5M empty vector and pSG5M-Tax plasmids were described elsewhere (48). The  
359 U3R-Luc (Firefly) plasmid was kindly provided by A. Kress (Germany). The normalization  
360 plasmid pRL-TK (Renilla) was obtained from Promega. Human XPB cDNA was cloned from  
361 total RNA extracted from Jurkat T cells by using the RNeasy Mini Kit (Qiagen). One µg of  
362 total RNA was subjected to reverse transcription using the Maxima Reverse Transcriptase  
363 (Thermo Fisher Scientific). PCR amplification was performed on a fraction of RT products  
364 with the high fidelity Platinum Taq DNA Polymerase (Invitrogen) using the oligonucleotides

365 XPB-BamHI Fw (5' GCGCCTCGAGGATCCACCATGGGCAAAAGAGACCGAGGC 3') and  
366 XPB NheI Rev (5' GCGCACGCGTGC GGCCGCTAGCTCATTTCCTAAAGCGCTTGAAG 3')  
367 and products were then cloned in the pCR-Blunt II-TOPO vector (Invitrogen). The XPB insert  
368 was then digested with BamHI and NheI and cloned into the pcDNA3 vector (Invitrogen).  
369 XPB mutagenesis was performed on the pcDNA3-XPB plasmid by PCR amplification with  
370 the high fidelity proof reading Pfu Turbo DNA Polymerase (Stratagene) using the following  
371 primers: F99S (Fw: 5' CAAATATGCCCAAGACTCCTTGGTGGCTATTGC 3', F99S Rev: 5'  
372 GCAATAGCCACCAAGGAGTCTTGGGCATATTTG 3); T119P (Fw: 5'CATGAGTACAAACTA  
373 CCTGCCTACTCCTTG 3', T119P Rev: 5' CAAGGAGTAGGCAGGTAGTTTGTACTCATG 3');  
374 K346R (Fw: 5' CCCTGCGGTGCTGGAAGGTCCCTGGTTGGTGTC 3', K346R Rev:  
375 5'CACACCAACGGGACCTTCCAGCACCGCAGGG 3'); E473A (Fw: 5'GCGACCCTCGTCCGCG  
376 CAATGACAAAATTGTG 3', E473A Rev: 5'CACAATTTTGTTCATCTGCGCGGA CGAGGGTCGC  
377 3'). Sequencing of the wt and mutated plasmids showed that the XPB ORF was identical in  
378 each cDNA excepted for the presence of the introduced mutation.

379

### 380 **Antibodies and reagents**

381 The anti XPB monoclonal antibody from Novusbio (NB10061060) was used for ChIP  
382 experiment. The following other primary antibodies were used in immunoblots: anti-XPB  
383 (Santa Cruz, s19), anti-pCREB-Ser133 (Millipore, CS 204400), anti-Sp1 (Abcam ab13370),  
384 anti-GAPDH (Santa Cruz, sc32233), anti-gammatubulin (Abcam ab16504), anti-lamin A/C  
385 (Cell signaling, 2032S) and anti-IgG rabbit (Millipore PP64B). HRP-conjugated anti-human,  
386 anti-mouse and anti-rabbit IgG (Promega) were used as secondary antibodies. Spironolactone  
387 (SP), Eplerenone (EPL) and Chaetocin (all from Sigma) were diluted in dimethyl sulfoxide  
388 (DMSO) as 10 mM stock solutions.

389

390

391 **Luciferase assays**

392 T cells ( $3 \times 10^5$ /24 well in duplicate) were cotransfected using the DMRIE-C reagent (Roche)  
393 with 100 ng of the U3R-Luc plasmid, 10 ng of pRL-TK and 250 ng of the control, Tax or  
394 XPB plasmid/well. After 48 hours, cells were lysed in 100  $\mu$ L of Passive lysis buffer  
395 (Promega). Luciferase activities were quantified using the Dual Luciferase Assay System  
396 (Promega) and Firefly activity values were normalized to that of Renilla activity.

397

398 **Immunoprecipitation and immunoblot**

399 293T cells ( $1.5 \times 10^6$  cells in 10 cm dish) were transfected with 6 $\mu$ g of the control, Tax or XPB  
400 plasmid and lysed 48h post-transfection. Transfected 293T cells or C8166 T cells ( $5 \times 10^6$ )  
401 were lysed in 500  $\mu$ L of RIPA buffer (50 mM Tris-HCl pH8, 1% NP40, 0.5% deoxycholate,  
402 0.1% SDS and 150 mM NaCl) supplemented with protease inhibitor and benzonase nuclease  
403 (Sigma). 500 $\mu$ g of the lysates were incubated overnight with 3 $\mu$ g of primary antibodies at 4°C  
404 and 10 $\mu$ g of the lysates were used for western blot analysis. Immunocomplexes were then  
405 captured on protein A/G-agarose beads (Thermoscientific 20421) 1h at 4°C. Sepharose beads  
406 were then washed 5 times in wash buffer (120 mM NaCl, 20mM Tris-HCl pH8, 0.2 mM NaF,  
407 0.2 mM EGTA, 0.2% deoxycholate, 0.5% NP40) before elution in 50  $\mu$ L of Laemmli buffer  
408 (0.3 M Tris-HCl pH6.8, 10% SDS, 20% Glycerol, 0.04% Bromophenol Blue, DTT 100 mM).  
409 Immunoprecipitated proteins or total cell lysates were separated on 4-15% SDS-PAGE,  
410 transferred to nitrocellulose membranes (0.45  $\mu$ m) and blotted with specific antibodies.  
411 Images were acquired using a Fusion Fx camera (Vilber Lourmat). Band quantification was  
412 performed with the Image J software after subtraction of the background.

413

414 **RNA extraction and RT-qPCR**

415 Total RNAs were prepared with the Nucleospin RNAII kit (Macherey Nagel, France) and 1 $\mu$ g

416 was reverse-transcribed using the Maxima first strand cDNA synthesis kit (Thermo Scientific,  
417 France). Real-time PCR were performed on 1/10 of the reverse transcription reaction. HTLV-  
418 1 genomic RNA (gRNA) and housekeeping control RNAs were amplified using the Sybr  
419 Green method with the following primers: unspliced Gag mRNA (region 2036 to 2224, Fw  
420 5'CAGAGGAAGATGCCCTCCTATT 3', Rev: 5' GTCAACCTGGGCTTTAATTACG 3');  
421 Total sense RNA (Fw: TTCCCAGGGTTTGGACAGAG, Rev:  
422 GATGGGGTCCCAGGTGATCT); EEF1G (Fw: AGATGGCCCAGTTTGATGCTAA, Rev:  
423 GCTTCTCTTCCCGTGAACCCT), HPRT (Fw: TGACACTGGCAAACAATGCA, Rev:  
424 GGTCCTTTTCACCAGCAAGCT). PCR conditions were as followed: pre-incubation 95° 5  
425 min x1; amplification x45: denaturation 95° 10 sec; annealing 60° 20 sec; extension 72° 10  
426 sec; acquisition, melting curve, cooling. The normalized quantity (NQ) of each mRNA was  
427 determined by normalizing their level to that of the housekeeping genes EEF1G and HPRT  
428 according to the following formula:  $NQ=2^{-(cp-((cpEEF1G+cpHPRT)/2))}$ .

429

### 430 **CHIP experiments**

431 Before the experiment,  $10^7$  cells were crosslinked using 1.1% Formaldehyde (Electron  
432 Microscopy Sciences) for 8 minutes at room temperature. Chromatin was then sheared using a  
433 Bioruptor Pico sonicator to obtain fragments of approximately 300 bp. IP were performed  
434 using the ChIP-IT high sensitivity kit (Active motif) on 10 µg of chromatin using 4 µg of  
435 specific or control antibodies and 10% of chromatin was kept for inputs. qPCR were  
436 conducted with the following primers: a-sat (Fw: CTGCACTACCTGAAGAGGAC, Rev:  
437 GATGGTTCAACACTCTTACA), IκBα (SimpleChIP® Human IκBα Promoter Primers  
438 #5552, Cell Signaling Technology), LTR R region (Fw: CGCATCTCTCCTTCACGCGC,  
439 Rev: CGGTCTCGACCTGAG) or LTR U5 region (Fw: GACAGCCCATCCTATAGCACTC,  
440 Rev: CTAGCGCTACGGGAAAAGATT).

441 **Cell viability assay**

442 Cell viability was quantified by measuring the rate of mitochondrial reduction of yellow  
443 tetrazolium salt MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (Sigma)  
444 to insoluble purple crystals. Cells were cultivated for 72h with DMSO, EPL or SP and MTT  
445 solution (25  $\mu$ L of a solution at 5 mg/mL) was added to each well for 2 hours. The supernatant  
446 was then removed and 50  $\mu$ L of DMSO added to dissolve formazan crystal. Optical densities  
447 (OD) were measured at 590 nm with a Tecan infinite Pro 2000 spectrophotometer.

448

449 **Statistical analysis**

450 Statistical analyses were conducted with the GraphPad Prism 6 software. Two-group  
451 comparison was done using the paired t test and multiple-group analysis with the one-way  
452 ANOVA Tukey's multiple comparisons test. Correlation analysis was done using the Pearson  
453 test. Statistical significance was defined for p-values < 0.05.

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455

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467

468 **FIGURE LEGENDS**

469

470 **Figure 1. XPB binds to Tax.**

471 (A) Coprecipitation of Tax and XPB in cotransfected 293T cells. Total proteins prepared 24  
472 hours post-transfection were analyzed by immunoblot before (Lysates) or after anti-Tax  
473 immunoprecipitation (IP Tax). Data correspond to one representative experiment out of two.  
474 (B) Coprecipitation of endogenous Tax and XPB produced in HTLV-1-transformed C8166 T  
475 cells. Immunoprecipitated proteins (IP Tax, left panel) or total proteins obtained before  
476 (input) or after (flowthrough) IP (right panels) were analyzed by immunoblot. Data  
477 correspond to one representative experiment out of two. Ig: signal corresponding to  
478 immunoglobulins used for the IP.

479

480 **Figure 2. Endogenous XPB is recruited at proviral LTR in a Tax-dependent manner**

481 (A,B) ChIP experiments to detect XPB recruitment at various genomic loci. Sonicated  
482 chromatin prepared for (A) Tax-positive C8166 and CB-CD4/HTLV-1 or (B) Tax-  
483 negative/low MT-1 and TL-Om1 HTLV-1-infected T cells were used before (input) or after  
484 immunoprecipitation with control IgG or the anti-XPB antibody. PCR reactions were then  
485 performed using primers specific for the R or U5 region of the HTLV-1 LTR or for the  $\text{I}\kappa\text{B}\alpha$   
486 promoter (positive control) and the  $\alpha$ -satellite regions (negative control). PCR amplification  
487 gave positive signals for both R and U5 regions in the four T cell lines (18 to 22 PCR cycles  
488 as compared to 37 to 45 for water), confirming that they all carried integrated HTLV-1  
489 genomes. Data correspond to means  $\pm$  SEM of two independent experiments performed in  
490 triplicate. (C) Effect of Tax downregulation on XPB recruitment to the HTLV-1 promoter.  
491 C8166 T cells were treated with 100 nM of chaetocin for 24 hours. Left panel shows the  
492 effect of chaetocin on the levels of endogenous Tax and XPB analyzed by immunoblot (one



493 representative experiment out of two). **(D)** Effect of chaetocin treatment on XPB recruitment  
494 to either the LTR or the  $\text{I}\kappa\text{B}\alpha$  promoter. CHIP analysis was performed as in (A). Data  
495 correspond to means  $\pm$  SEM of one experiment performed in triplicate out of 2. Statistical  
496 significance: ns: not significant, \*:  $p < 0.05$ , \*\*:  $p < 0.01$ , \*\*\*:  $p < 0.001$ , \*\*\*\*\*:  $p < 0.0001$ .

497

### 498 **Figure 3. XPB is involved in Tax-mediated but not basal HTLV-1 LTR activation**

499 Effect of XPB overexpression on HTLV-1 LTR activation in Jurkat T cells. Cells were  
500 transfected with the LTR U3R-Luc and pRL-TK reporter plasmids along with control (basal),  
501 Tax (transactivation) or the XPB plasmid and then treated with DMSO or with EPL or SP at  
502 10  $\mu\text{M}$  for 24 hours. Upper panel: relative luciferase activity calculated by normalizing  
503 Firefly/Renilla ratios to that of DMSO-treated Tax-transfected cells (set to 1). Data are means  
504  $\pm$  SEM of three independent experiments performed in duplicate. Lower panel: Tax and XPB  
505 expression levels detected by immunoblot. Data are from one representative experiment out of  
506 two. Statistical significance: \*:  $p < 0.05$ , \*\*:  $p < 0.01$ .

507

### 508 **Figure 4. The R-E-D domain of XPB is required for LTR transactivation and** 509 **endogenous Tax production**

510 **(A)** Schematic representation of the XPB protein and position of the XPB mutations. **(B)**  
511 Interaction of Tax with wild type XPB or XPB mutants. 293T cells were cotransfected with  
512 one of the XPB constructs along with a control or Tax expressor. Total proteins prepared 24  
513 hours post-transfection were separated before (lysates) or after the anti-Tax  
514 immunoprecipitation (IP Tax). Data correspond to one representative experiment out of two.  
515 **(C)** Immunoblots performed in HTLV-1-transformed C8166 T cells to analyze expression  
516 levels of XPB, Tax, phospho-CREB (Ser133) and Specific factor 1 (Sp1) upon SP treatment.  
517 **(D)** Capacity of wt or mutated XPB proteins to rescue SP-mediated inhibition of either LTR

518 transactivation or endogenous Tax production. HTLV-1-transformed C8166 T cells were  
519 transfected with the LTR U3R-Luc and pRL-TK reporter plasmids and one of the XPB  
520 construct and were then treated with DMSO or with EPL or SP at 10  $\mu$ M for 48 hours. Upper  
521 panel: relative luciferase activity calculated by normalizing Firefly/Renilla ratios to that of  
522 DMSO-treated control cells (set to 1). Data are means  $\pm$  SEM of five independent  
523 experiments performed in duplicate. Lower panel: Tax and XPB expression levels detected by  
524 immunoblot. Data are from one representative experiment out of three. Statistical  
525 significance: ns: not significant, \*\*\*\*:  $p < 0.0001$ .

526

527 **Figure 5. XPB downregulation inhibits viral transcription**

528 (A) C8166 and (B) MT-4 HTLV-1-transformed T cells or (C) HTLV-1-immortalized CB-  
529 CD4/HTLV-1 T cells were treated with DMSO or with SP or EPL at 10  $\mu$ M for 24 hours. The  
530 level of unspliced Gag mRNA was quantified by RTqPCR and normalized to the level of  
531 housekeeping genes (left panels). For MT-4 and CB-CD4/HTLV-1 T cells, the level of Gag  
532 protein (p19) was also analyzed by immunoblot (right panels). Data correspond to one  
533 representative experiment out of two or three. (D-F) Time-course experiment to quantify the  
534 level of Gag mRNA over the course of SP treatment. C8166 T cells were either untreated  
535 (NT) or treated with DMSO or with SP or EPL at 10  $\mu$ M. (D) The level of XPB was analyzed  
536 at indicated times by immunoblot in half of the cells. At each time-point, the intensity of the  
537 XPB signal in EPL or SP-treated cells was compared to that of DMSO-treated cells (set to 1).  
538 Data correspond to one representative experiment out of three. (E) The other half of the cells  
539 was used to quantify the level of Gag mRNA. Left panel shows the SP/DMSO ratios  
540 calculated from the level of RNA normalized to the level of housekeeping genes (NQ). Right  
541 panel shows correlation between the level of XPB protein quantified from (A) and the  
542 SP/DMSO ratios shown in the left panel. (F) Effect of SP on the levels of housekeeping gene

543 mRNAs. Data show the SP/DMSO ratios for HPRT or EEF1G calculated from relative  
544 quantities using the formula:  $Q=2^{-C_p}$ . Data correspond to one representative experiment  
545 performed in triplicate out of 3.

546

547 **Figure 6. XPB downregulation reduces viability of Tax-positive HTLV-1-infected T**  
548 **cells.**

549 (A) C8166, (B) MT-4, (C) TL-om1, (D) MT-1 and (E) Jurkat transformed T cells or (F)  
550 HTLV-1 immortalized CB-CD4/HTLV-1 were treated every day with DMSO (0) or with EPL  
551 or SP at indicated concentrations and cell viability was determined by the MTT method after  
552 3 days of culture. The viability values for SP or EPL were normalized to that of DMSO-  
553 treated cells (set as 100%). For each cell line, viability results correspond to two independent  
554 experiments performed in triplicate. Ns: not significant, \*:  $p<0.05$ , \*\*:  $p<0.01$ ; \*\*\*:  $p<0.001$ ,  
555 \*\*\*\*:  $p<0.0001$ .

556

557 **Figure 7. Model illustrating the capacity of Tax to target essential steps of the Pol II-mediated**  
558 **transcription process, including the promoter opening step controlled by the XPB subunit of**  
559 **TFIIH.**

560

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565 **REFERENCES**

- 566 1. Hermine O, Ramos JC, Tobinai K. 2018. A Review of New Findings in Adult T-cell  
567 Leukemia-Lymphoma: A Focus on Current and Emerging Treatment Strategies. *Adv*  
568 *Ther* 35:135-152.
- 569 2. Panfil AR, Martinez MP, Ratner L, Green PL. 2016. Human T-cell leukemia virus-  
570 associated malignancy. *Curr Opin Virol* 20:40-46.
- 571 3. Bangham CR, Araujo A, Yamano Y, Taylor GP. 2015. HTLV-1-associated  
572 myelopathy/tropical spastic paraparesis. *Nat Rev Dis Primers* 1:15012.
- 573 4. Curren R, Van Duyne R, Jaworski E, Guendel I, Sampey G, Das R, Narayanan A,  
574 Kashanchi F. 2012. HTLV tax: a fascinating multifunctional co-regulator of viral and  
575 cellular pathways. *Front Microbiol* 3:406.
- 576 5. Kfoury Y, Nasr R, Journo C, Mahieux R, Pique C, Bazarbachi A. 2012. The  
577 multifaceted oncoprotein Tax: subcellular localization, posttranslational modifications,  
578 and NF-kappaB activation. *Adv Cancer Res* 113:85-120.
- 579 6. Hasegawa H, Sawa H, Lewis MJ, Orba Y, Sheehy N, Yamamoto Y, Ichinohe T,  
580 Tsunetsugu-Yokota Y, Katano H, Takahashi H, Matsuda J, Sata T, Kurata T,  
581 Nagashima K, Hall WW. 2006. Thymus-derived leukemia-lymphoma in mice  
582 transgenic for the Tax gene of human T-lymphotropic virus type I. *Nat Med* 12:466-  
583 72.
- 584 7. Bellon M, Baydoun HH, Yao Y, Nicot C. 2010. HTLV-I Tax-dependent and -  
585 independent events associated with immortalization of human primary T lymphocytes.  
586 *Blood* 115:2441-8.
- 587 8. Nyborg JK, Egan D, Sharma N. 2010. The HTLV-1 Tax protein: revealing  
588 mechanisms of transcriptional activation through histone acetylation and nucleosome  
589 disassembly. *Biochim Biophys Acta* 1799:266-74.

- 590 9. Chen FX, Smith ER, Shilatifard A. 2018. Born to run: control of transcription  
591 elongation by RNA polymerase II. *Nat Rev Mol Cell Biol* 19:464-478.
- 592 10. Nogales E, Louder RK, He Y. 2017. Structural Insights into the Eukaryotic  
593 Transcription Initiation Machinery. *Annu Rev Biophys* 46:59-83.
- 594 11. Lemasson I, Polakowski NJ, Laybourn PJ, Nyborg JK. 2002. Transcription factor  
595 binding and histone modifications on the integrated proviral promoter in human T-cell  
596 leukemia virus-I-infected T-cells. *J Biol Chem* 277:49459-65.
- 597 12. de la Fuente C, Kashanchi F. 2004. The expanding role of Tax in transcription.  
598 *Retrovirology* 1:19.
- 599 13. Caron C, Rousset R, Beraud C, Moncollin V, Egly JM, Jalinot P. 1993. Functional and  
600 biochemical interaction of the HTLV-I Tax1 transactivator with TBP. *EMBO J*  
601 12:4269-78.
- 602 14. Clemens KE, Piras G, Radonovich MF, Choi KS, Duvall JF, DeJong J, Roeder R,  
603 Brady JN. 1996. Interaction of the human T-cell lymphotropic virus type 1 tax  
604 transactivator with transcription factor IIA. *Mol Cell Biol* 16:4656-64.
- 605 15. Anderson MG, Scoggin KE, Simbulan-Rosenthal CM, Steadman JA. 2000.  
606 Identification of poly(ADP-ribose) polymerase as a transcriptional coactivator of the  
607 human T-cell leukemia virus type 1 Tax protein. *J Virol* 74:2169-77.
- 608 16. Zhou M, Lu H, Park H, Wilson-Chiru J, Linton R, Brady JN. 2006. Tax interacts with  
609 P-TEFb in a novel manner to stimulate human T-lymphotropic virus type 1  
610 transcription. *J Virol* 80:4781-91.
- 611 17. Cho WK, Zhou M, Jang MK, Huang K, Jeong SJ, Ozato K, Brady JN. 2007.  
612 Modulation of the Brd4/P-TEFb interaction by the human T-lymphotropic virus type 1  
613 tax protein. *J Virol* 81:11179-86.

- 614 18. Rimel JK, Taatjes DJ. 2018. The essential and multifunctional TFIIH complex. *Protein*  
615 *Sci* 27:1018-1037.
- 616 19. Compe E, Egly JM. 2016. Nucleotide Excision Repair and Transcriptional Regulation:  
617 TFIIH and Beyond. *Annu Rev Biochem* 85:265-90.
- 618 20. Fishburn J, Tomko E, Galburt E, Hahn S. 2015. Double-stranded DNA translocase  
619 activity of transcription factor TFIIH and the mechanism of RNA polymerase II open  
620 complex formation. *Proc Natl Acad Sci U S A* 112:3961-6.
- 621 21. Alekseev S, Nagy Z, Sandoz J, Weiss A, Egly JM, Le May N, Coin F. 2017.  
622 Transcription without XPB Establishes a Unified Helicase-Independent Mechanism of  
623 Promoter Opening in Eukaryotic Gene Expression. *Mol Cell* 65:504-514 e4.
- 624 22. Kim TK, Ebright RH, Reinberg D. 2000. Mechanism of ATP-dependent promoter  
625 melting by transcription factor IIH. *Science* 288:1418-22.
- 626 23. Tirode F, Busso D, Coin F, Egly JM. 1999. Reconstitution of the transcription factor  
627 TFIIH: assignment of functions for the three enzymatic subunits, XPB, XPD, and  
628 cdk7. *Mol Cell* 3:87-95.
- 629 24. Lin YC, Choi WS, Gralla JD. 2005. TFIIH XPB mutants suggest a unified bacterial-  
630 like mechanism for promoter opening but not escape. *Nat Struct Mol Biol* 12:603-7.
- 631 25. Oksenyich V, Coin F. 2010. The long unwinding road: XPB and XPD helicases in  
632 damaged DNA opening. *Cell Cycle* 9:90-6.
- 633 26. Oksenyich V, Bernardes de Jesus B, Zhovmer A, Egly JM, Coin F. 2009. Molecular  
634 insights into the recruitment of TFIIH to sites of DNA damage. *EMBO J* 28:2971-80.
- 635 27. Coin F, Oksenyich V, Egly JM. 2007. Distinct roles for the XPB/p52 and XPD/p44  
636 subcomplexes of TFIIH in damaged DNA opening during nucleotide excision repair.  
637 *Mol Cell* 26:245-56.

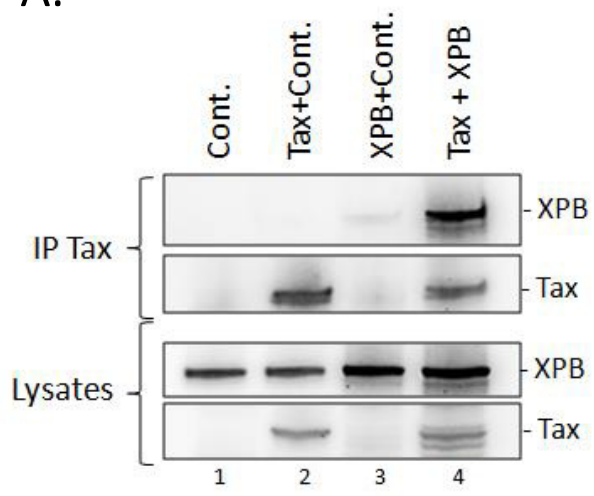
- 638 28. Sandoz J, Coin F. 2017. Unified promoter opening steps in eukaryotic gene  
639 expression. *Oncotarget* 8:84614-84615.
- 640 29. Elinoff JM, Chen LY, Dougherty EJ, Awad KS, Wang S, Biancotto A, Siddiqui AH,  
641 Weir NA, Cai R, Sun J, Preston IR, Solomon MA, Danner RL. 2018. Spironolactone-  
642 induced degradation of the TFIID core complex XPB subunit suppresses NF-kappaB  
643 and AP-1 signalling. *Cardiovasc Res* 114:65-76.
- 644 30. Alekseev S, Ayadi M, Brino L, Egly JM, Larsen AK, Coin F. 2014. A small molecule  
645 screen identifies an inhibitor of DNA repair inducing the degradation of TFIID and the  
646 chemosensitization of tumor cells to platinum. *Chem Biol* 21:398-407.
- 647 31. Ueda M, Matsuura K, Kawai H, Wakasugi M, Matsunaga T. 2019. Spironolactone-  
648 induced XPB degradation depends on CDK7 kinase and SCF(FBXL) (18) E3 ligase.  
649 *Genes Cells* doi:10.1111/gtc.12674.
- 650 32. Lacombe B, Morel M, Margottin-Goguet F, Ramirez BC. 2016. Specific Inhibition of  
651 HIV Infection by the Action of Spironolactone in T Cells. *J Virol* 90:10972-10980.
- 652 33. Hironaka N, Mochida K, Mori N, Maeda M, Yamamoto N, Yamaoka S. 2004. Tax-  
653 independent constitutive IkappaB kinase activation in adult T-cell leukemia cells.  
654 *Neoplasia* 6:266-78.
- 655 34. Mahgoub M, Yasunaga JI, Iwami S, Nakaoka S, Koizumi Y, Shimura K, Matsuoka M.  
656 2018. Sporadic on/off switching of HTLV-1 Tax expression is crucial to maintain the  
657 whole population of virus-induced leukemic cells. *Proc Natl Acad Sci U S A*  
658 115:E1269-E1278.
- 659 35. Ozden S, Cochet M, Mikol J, Teixeira A, Gessain A, Pique C. 2004. Direct evidence  
660 for a chronic CD8+-T-cell-mediated immune reaction to tax within the muscle of a  
661 human T-cell leukemia/lymphoma virus type 1-infected patient with sporadic  
662 inclusion body myositis. *J Virol* 78:10320-7.

- 663 36. Forlani G, Baratella M, Tedeschi A, Pique C, Jacobson S, Accolla RS. 2019. HTLV-1  
664 HBZ Protein Resides Exclusively in the Cytoplasm of Infected Cells in Asymptomatic  
665 Carriers and HAM/TSP Patients. *Front Microbiol* 10:819.
- 666 37. Mori N, Fujii M, Ikeda S, Yamada Y, Tomonaga M, Ballard DW, Yamamoto N. 1999.  
667 Constitutive activation of NF-kappaB in primary adult T-cell leukemia cells. *Blood*  
668 93:2360-8.
- 669 38. Song X, Zhao Z, Qi X, Tang S, Wang Q, Zhu T, Gu Q, Liu M, Li J. 2015.  
670 Identification of epipolythiodioxopiperazines HDN-1 and chaetocin as novel inhibitor  
671 of heat shock protein 90. *Oncotarget* 6:5263-74.
- 672 39. Gao L, Harhaj EW. 2013. HSP90 protects the human T-cell leukemia virus type 1  
673 (HTLV-1) tax oncoprotein from proteasomal degradation to support NF-kappaB  
674 activation and HTLV-1 replication. *J Virol* 87:13640-54.
- 675 40. Yao J, Grant C, Harhaj E, Nonnemacher M, Alefantis T, Martin J, Jain P, Wigdahl B.  
676 2006. Regulation of human T-cell leukemia virus type 1 gene expression by Sp1 and  
677 Sp3 interaction with TRE-1 repeat III. *DNA Cell Biol* 25:262-76.
- 678 41. Bhat NK, Adachi Y, Samuel KP, Derse D. 1993. HTLV-1 gene expression by  
679 defective proviruses in an infected T-cell line. *Virology* 196:15-24.
- 680 42. Martin F, Tagaya Y, Gallo R. 2018. Time to eradicate HTLV-1: an open letter to  
681 WHO. *Lancet* 391:1893-1894.
- 682 43. Tagaya Y, Gallo RC. 2017. The Exceptional Oncogenicity of HTLV-1. *Front*  
683 *Microbiol* 8:1425.
- 684 44. Dassouki Z, Sahin U, El Hajj H, Jollivet F, Kfoury Y, Lallemand-Breitenbach V,  
685 Hermine O, de The H, Bazarbachi A. 2015. ATL response to arsenic/interferon  
686 therapy is triggered by SUMO/PML/RNF4-dependent Tax degradation. *Blood*  
687 125:474-82.

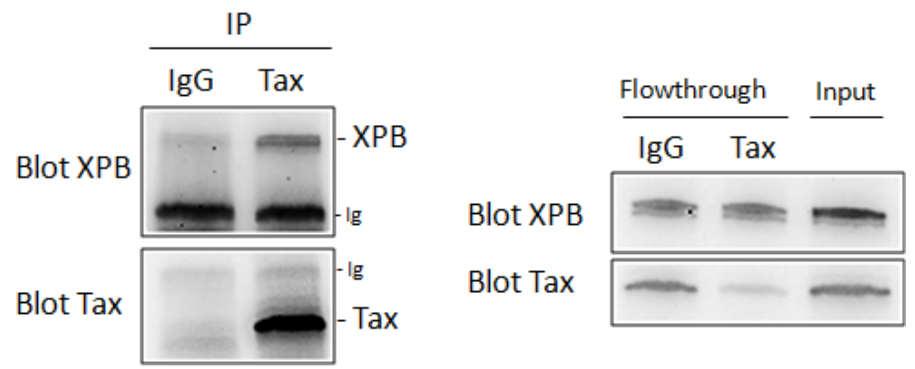


- 688 45. Hahn S. 2004. Structure and mechanism of the RNA polymerase II transcription  
689 machinery. *Nat Struct Mol Biol* 11:394-403.
- 690 46. Kouzine F, Wojtowicz D, Yamane A, Resch W, Kieffer-Kwon KR, Bandle R, Nelson  
691 S, Nakahashi H, Awasthi P, Feigenbaum L, Menoni H, Hoeijmakers J, Vermeulen W,  
692 Ge H, Przytycka TM, Levens D, Casellas R. 2013. Global regulation of promoter  
693 melting in naive lymphocytes. *Cell* 153:988-99.
- 694 47. Rice AP. 2017. The HIV-1 Tat Protein: Mechanism of Action and Target for HIV-1  
695 Cure Strategies. *Curr Pharm Des* 23:4098-4102.
- 696 48. Nasr R, Chiari E, El-Sabban M, Mahieux R, Kfoury Y, Abdulhay M, Yazbeck V,  
697 Hermine O, de The H, Pique C, Bazarbachi A. 2006. Tax ubiquitylation and  
698 sumoylation control critical cytoplasmic and nuclear steps of NF-kappaB activation.  
699 *Blood* 107:4021-9.
- 700

A.



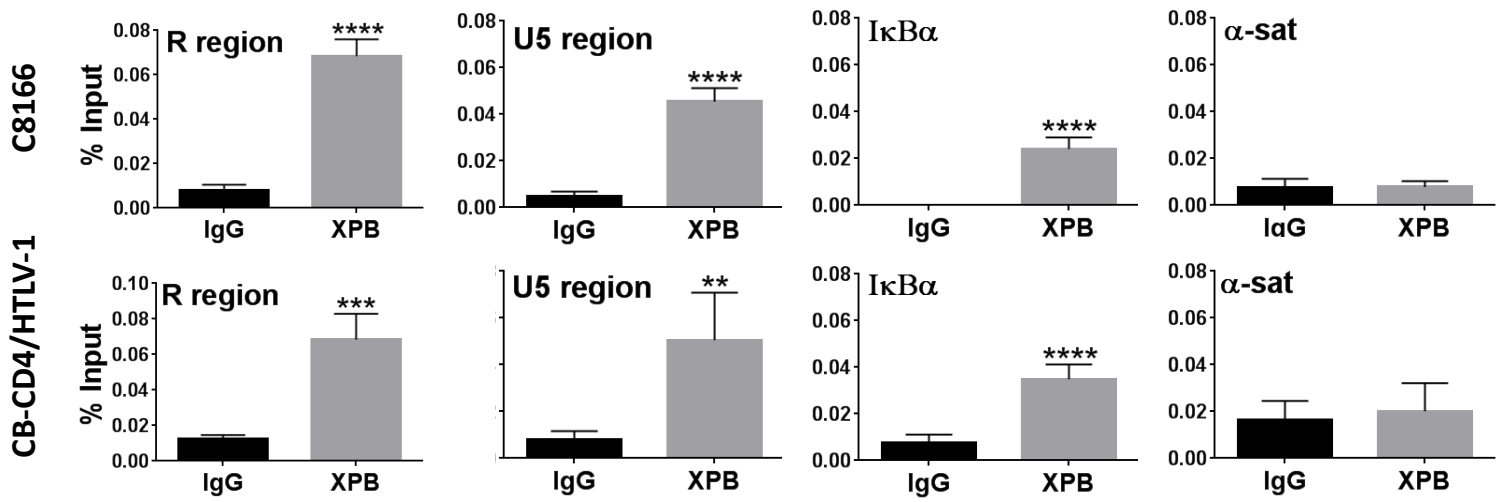
B.



**FIGURE 1**

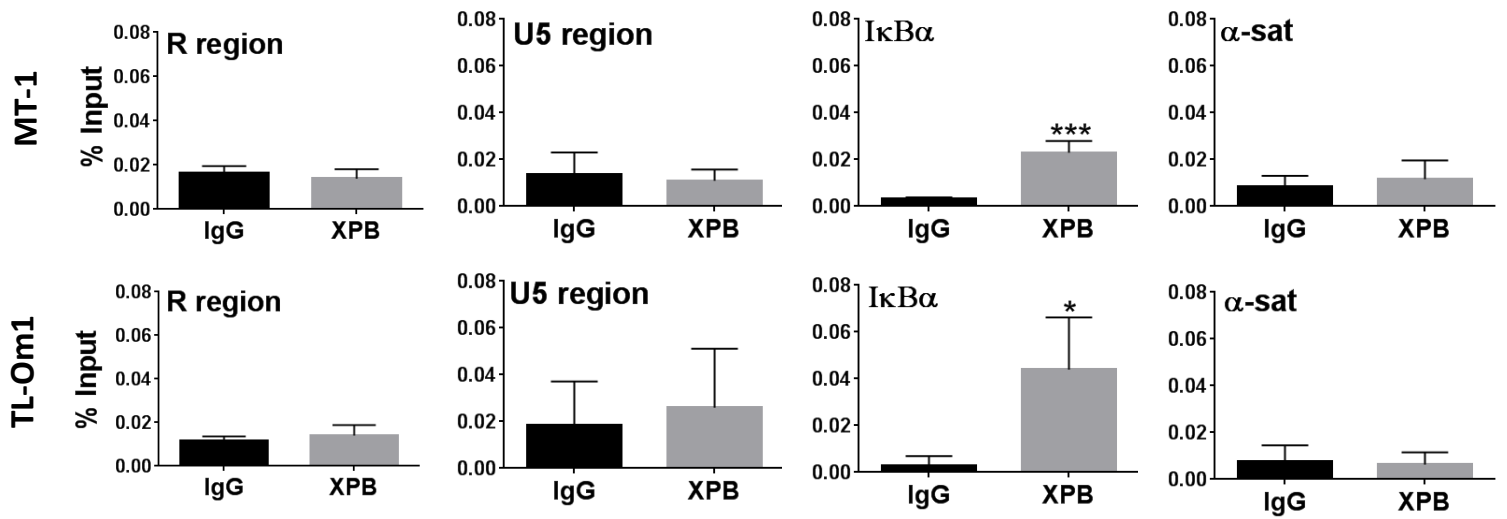
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## HTLV-1 LTR

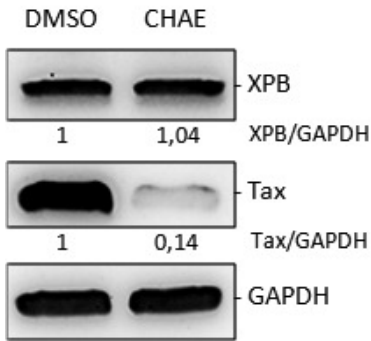


B.

## HTLV-1 LTR



C.



D.

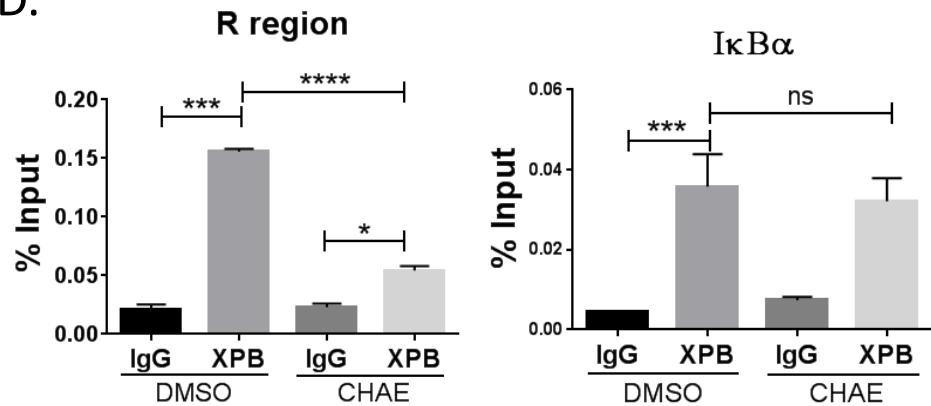
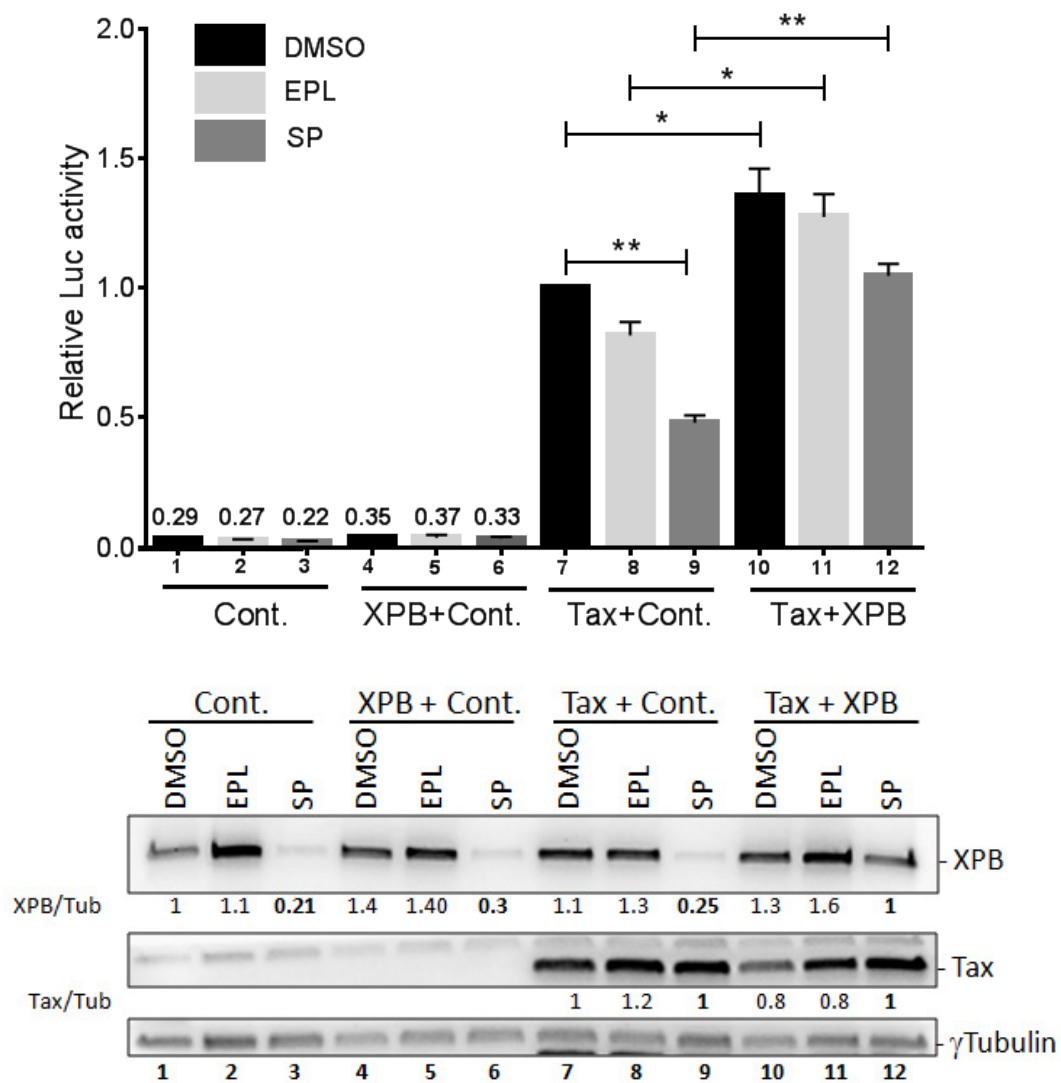
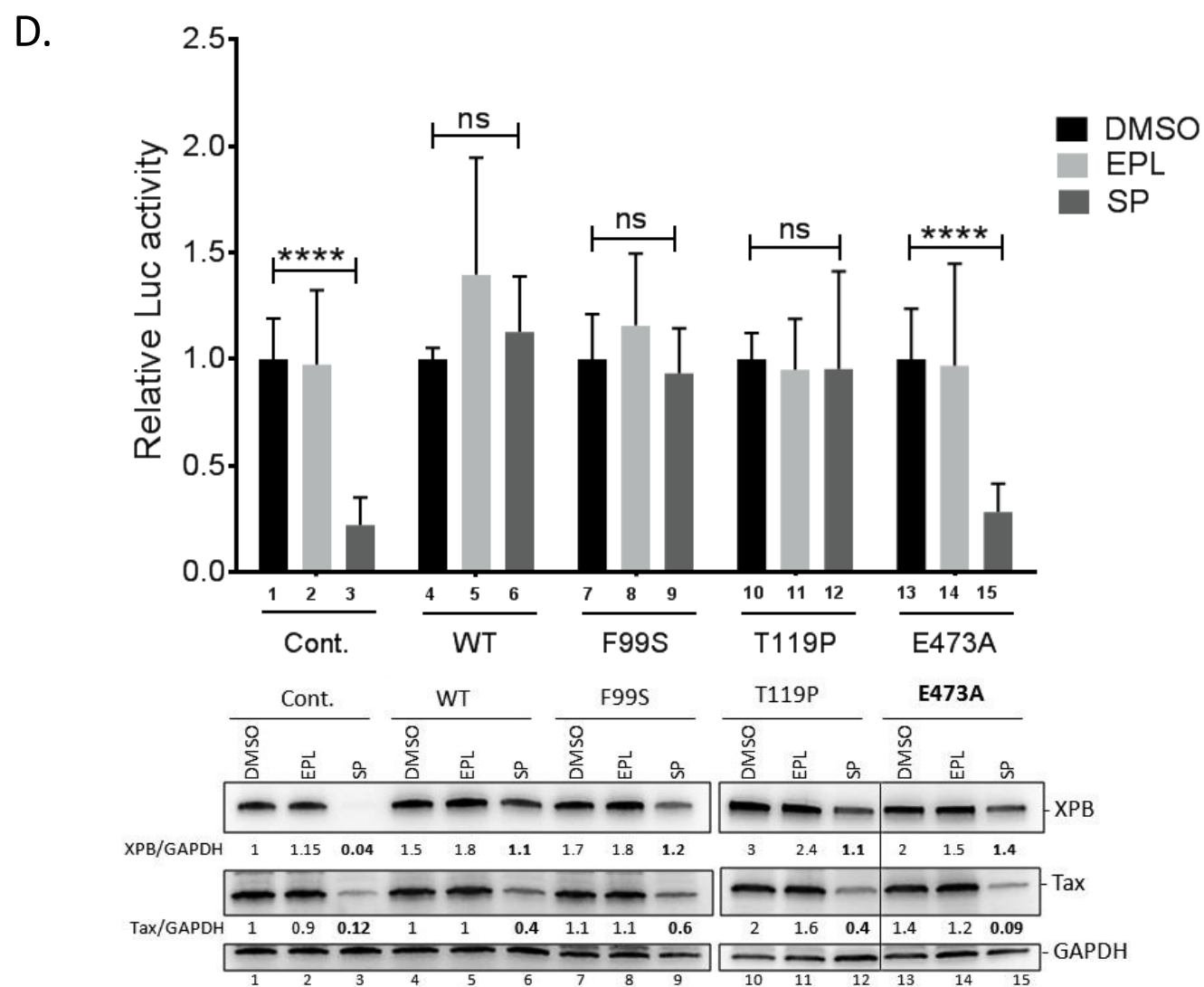
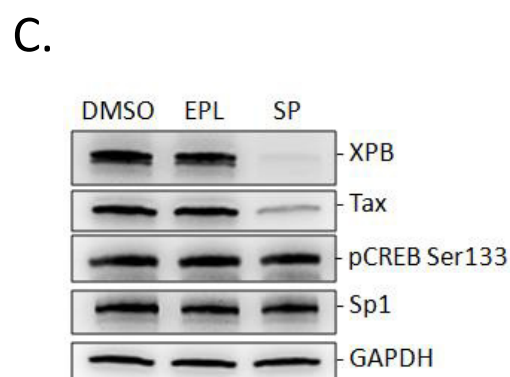
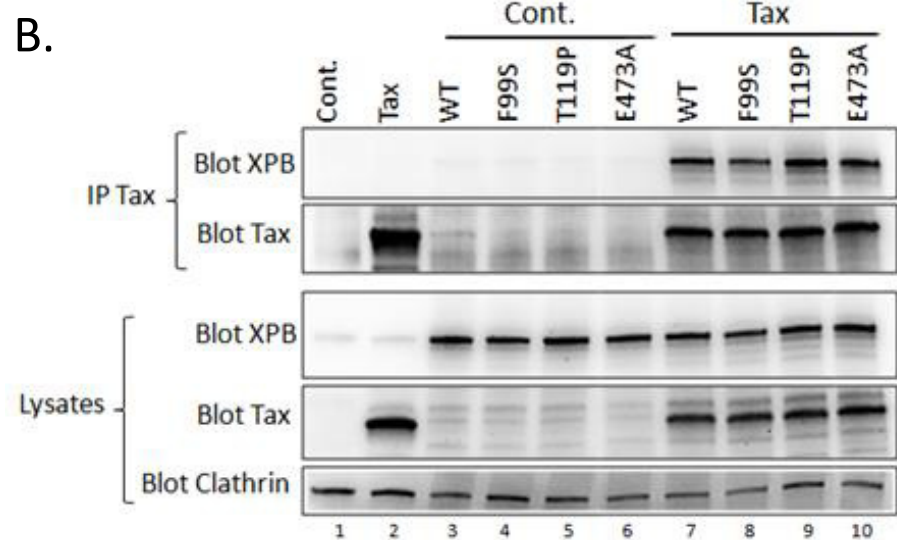
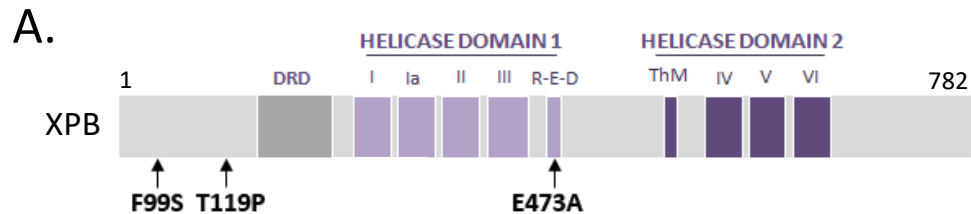


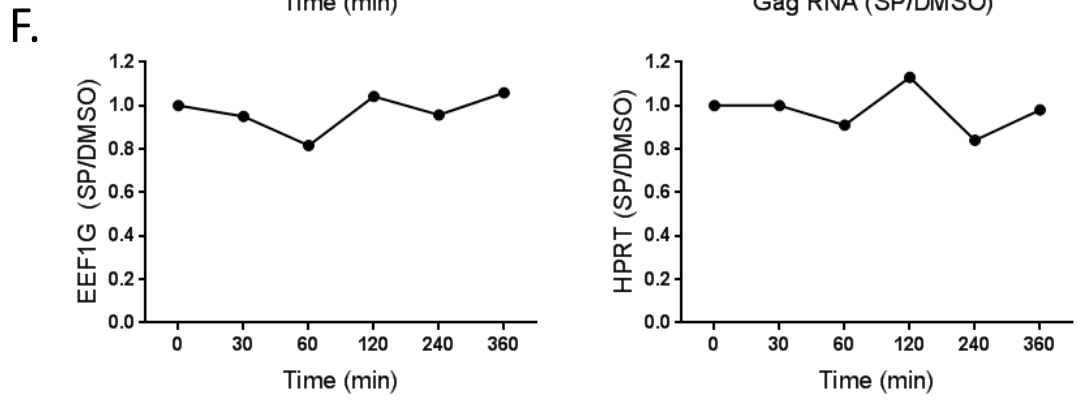
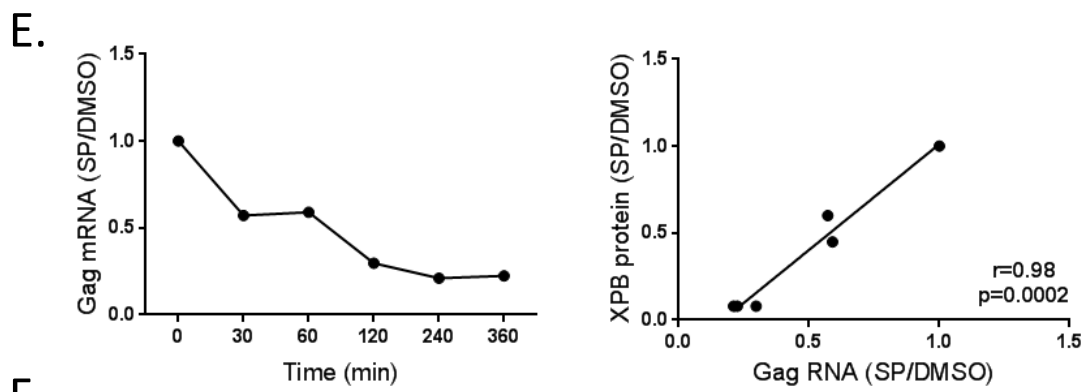
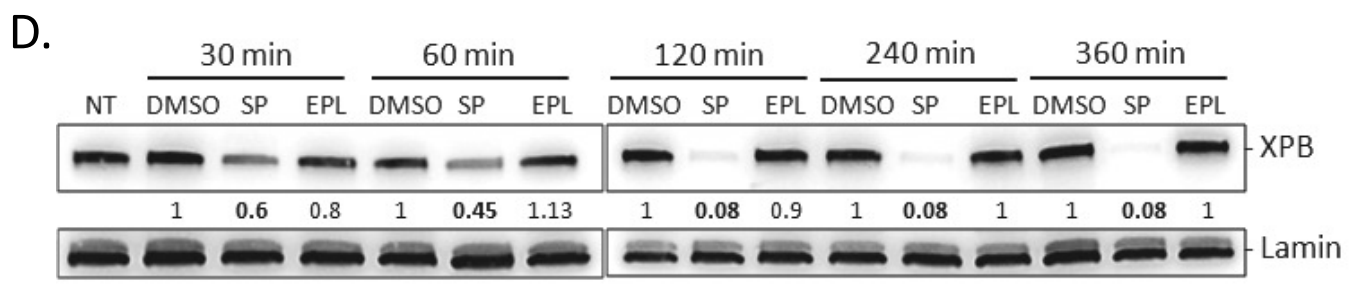
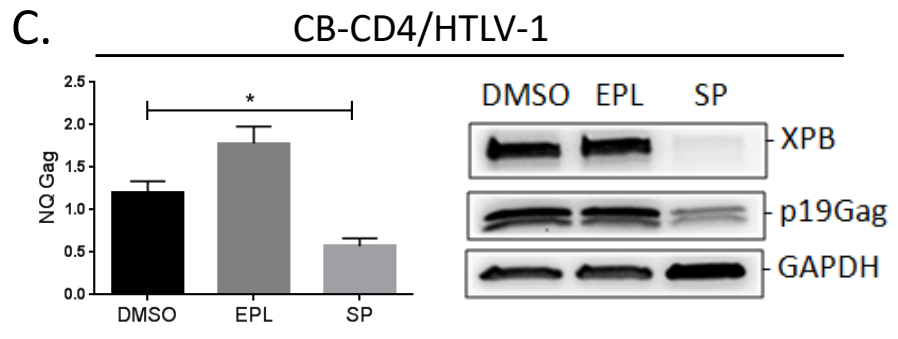
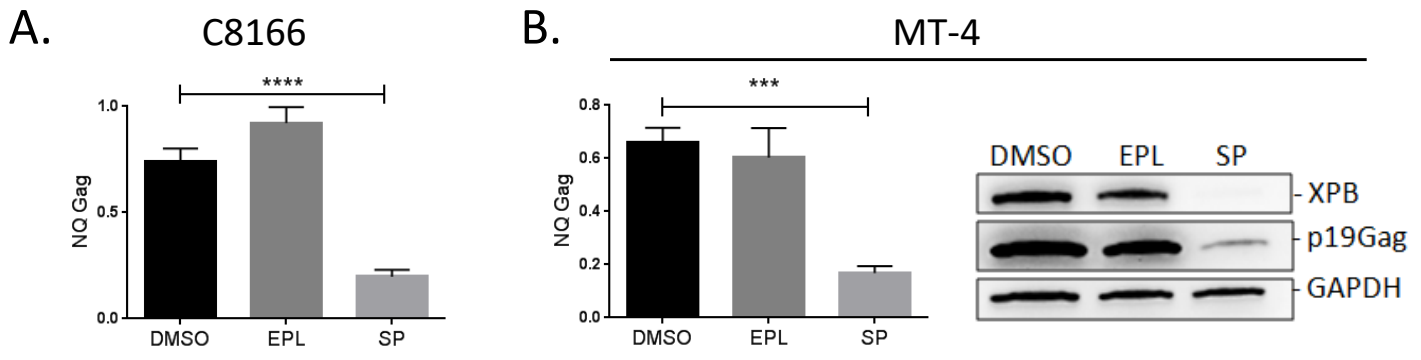
FIGURE 2



**FIGURE 3**



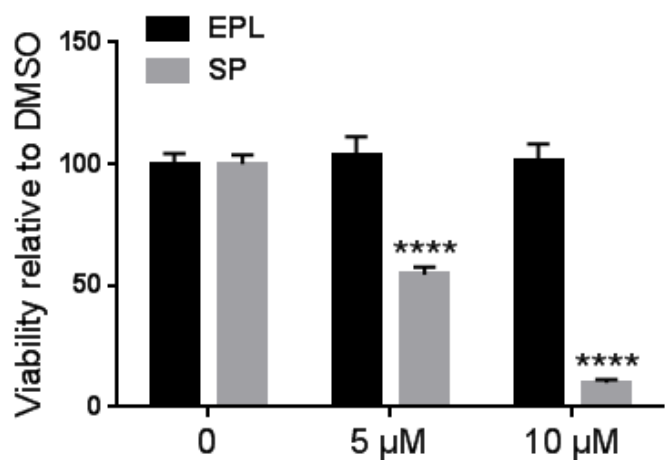
**FIGURE 4**



**FIGURE 5**

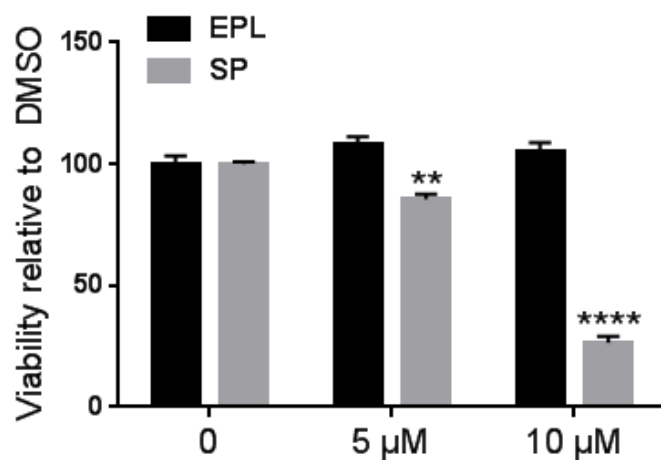
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C8166



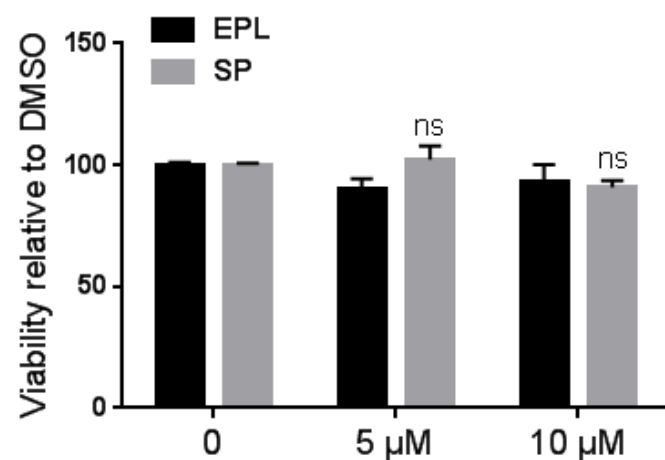
B.

MT-4



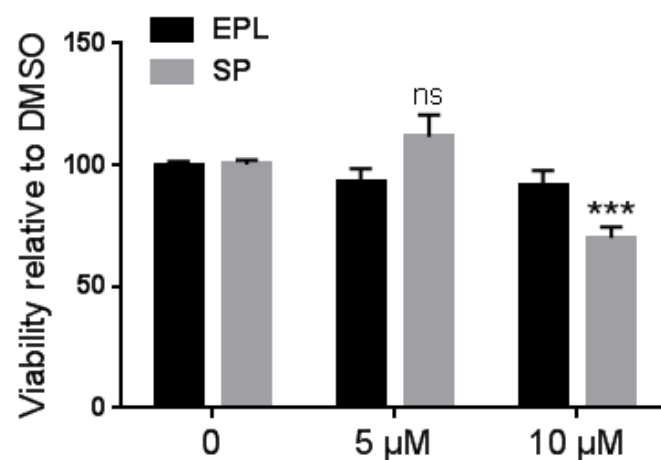
C.

TL-Om1



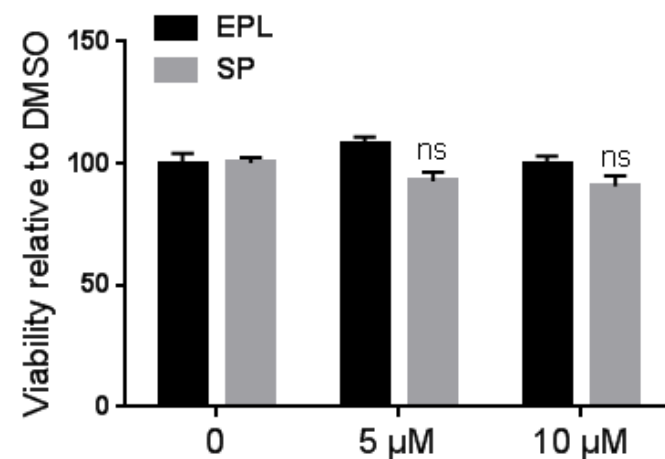
D.

MT-1



E.

Jurkat



F.

CB-CD4/HTLV-1

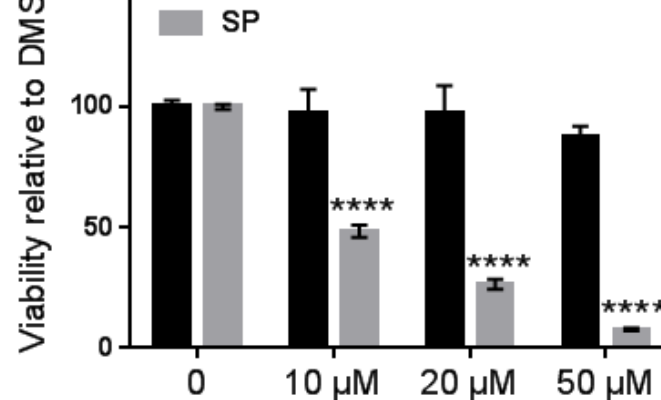
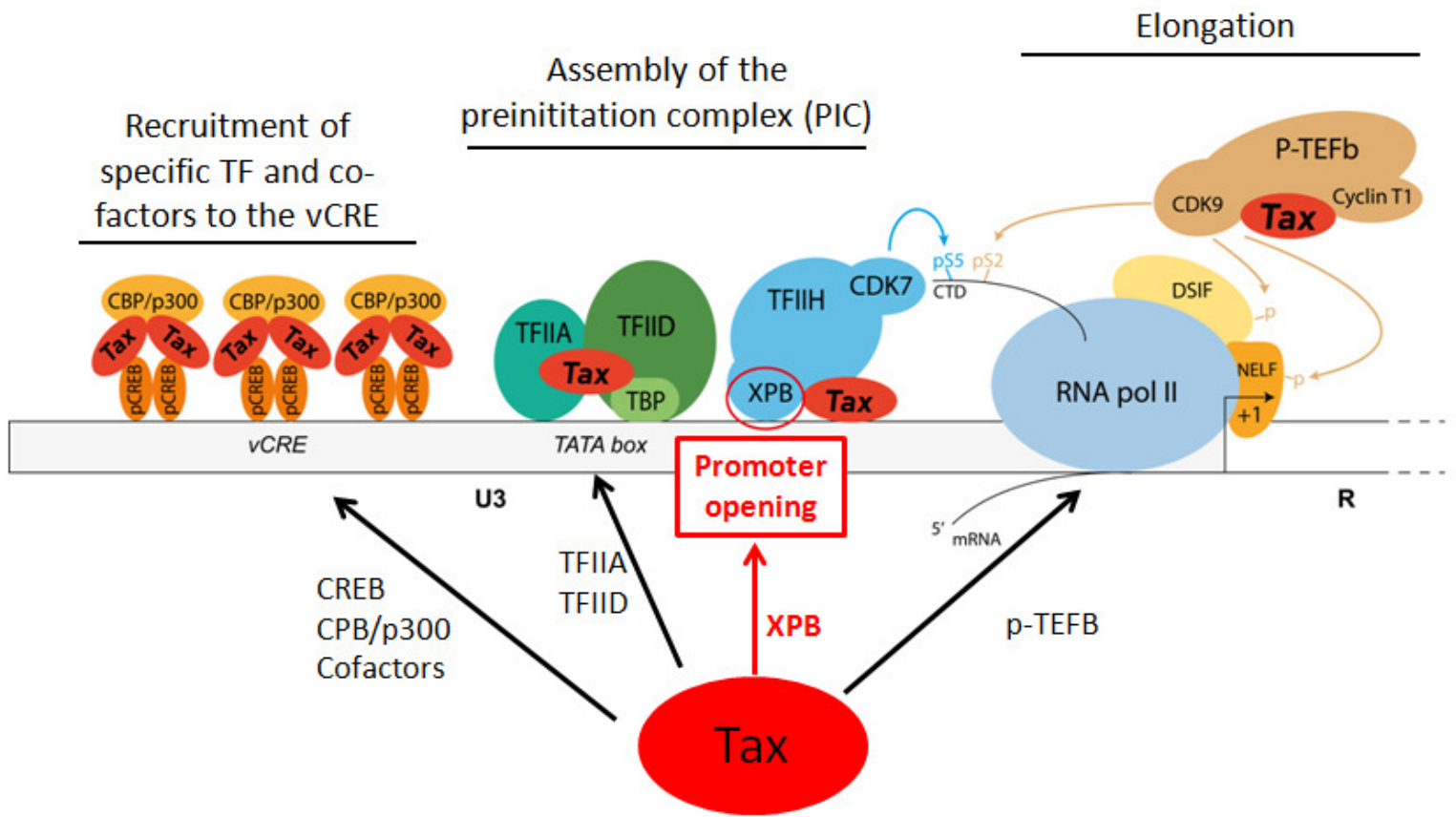


FIGURE 6



**FIGURE 7**