

1 **Title: Efficacy of CDK4/6 inhibitors in preclinical models of malignant pleural
2 mesothelioma.**

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64 **Abstract**

65 There is no effective therapy for patients with malignant pleural mesothelioma (MPM)
66 who progressed to platinum-based chemotherapy and immunotherapy. Here, we
67 investigate the antitumor activity of CDK4/6 inhibitors using *in vitro* and *in vivo*
68 preclinical models of MPM. Based on publicly available transcriptomic data of MPM,
69 patients with *CDK4* or *CDK6* overexpression had shorter overall survival. Treatment
70 with abemaciclib or palbociclib at 100 nM significantly decreased cell proliferation in all
71 cell models. Both CDK4/6 inhibitors significantly induced G1 cell cycle arrest thereby
72 increasing cell senescence and increased the expression of interferon signaling
73 pathway and tumor antigen presentation process in culture models of MPM. *In vivo*
74 preclinical studies showed that palbociclib significantly reduced tumor growth and
75 prolonged overall survival in a platinum-naïve and platinum resistant MPM mouse
76 model. Treatment of MPM with CDK4/6 inhibitors decreased cell proliferation, mainly
77 by promoting cell cycle arrest at G1 and by induction of cell senescence. Our
78 preclinical studies provide evidence for evaluating CDK4/6 inhibitors in the clinic for the
79 treatment of MPM.

80 **Keywords:** malignant pleural mesothelioma, CDK4/6 inhibitors, drug therapy, MPM *in*
81 *vivo* models.

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87 **Introduction**

88 Malignant pleural mesothelioma (MPM) is an aggressive, locally invasive and currently
89 not curable malignancy of the pleura, which is associated with occupational and para-
90 occupational exposure to asbestos (1). Although asbestos use is banned in many
91 countries, asbestos-insulated buildings are present throughout the world and some
92 countries are still manufacturing and using large quantities of asbestos (2).

93 Treatment options are limited for patients with advanced MPM (3). Palliative
94 chemotherapy consisting of platinum and pemetrexed is the established standard of
95 care for MPM in patients with advanced disease with ECOG performance status of 0-2
96 (4). The addition of bevacizumab to chemotherapy modestly improved overall survival,
97 but this treatment is not available in all countries (5). To date, no treatment has yet
98 been shown to improve survival in the relapsed setting, resulting in a high unmet need
99 for effective therapies in previously treated patients with MPM. There are currently no
100 approved targeted therapies for mesothelioma. Single agent immunotherapy has
101 demonstrated limited efficacy in the relapsed setting in a randomized phase III clinical
102 trial (6). Dual immune checkpoint inhibition of PD1 and CTLA-4 has recently
103 demonstrated superiority to platinum plus pemetrexed in the first-line setting in the
104 CheckMate-743 study and is likely to change the treatment landscape in MPM (7).

105 Characterization of the genomic landscape of MPM has revealed a high frequency of
106 recurring focal and arm-level deletions, reflecting a predominant loss of tumor
107 suppressor genes in MPM (8). Cyclin dependent kinase inhibitor 2A (CDKN2A)
108 deletions are found in 56-70% of MPM and are associated with shorter overall survival
109 (9,10). The CDKN2A/ARF locus (9p21) encodes for two cell cycle regulatory proteins:
110 p14ARF and p16INK4a, the latter being a negative regulator of cyclin-dependent
111 kinase 4/6 (CDK4/6) (11,12). In a recent clinical trial of personalized therapy in
112 advanced NSCLC, CDKN2A loss was associated with sensitivity to CDK4/6 inhibitors

113 (11,13). Considering the high frequency of *CDKN2A* deletions in MPM and the fact that
114 cell cycle deregulation is a hallmark of this disease, we postulated that CDK4/6
115 inhibitors might constitute a novel therapeutic approach in MPM. In the last decade,
116 several selective CDK4/6 inhibitors, abemaciclib, ribociclib and palbociclib, have been
117 approved for the treatment of metastatic breast cancer (14-16).

118 In the present work, we report that *CDK4* or *CDK6* overexpression in primary tumors
119 conferred a more aggressive behavior in patients with MPM based on publicly available
120 transcriptomic data. We assessed the efficacy of CDK4/6 inhibitors both *in vitro* in MPM
121 cell models and *in vivo* in subcutaneous and orthotopic xenografts to investigate their
122 potential in the treatment of MPM.

123

124 **Results**

125 **Overexpression of CDK4 and CDK6 are associated with poor prognosis in** 126 **patients with MPM**

127 Patients with *CDK4* overexpression (i.e., above the median) had significantly shorter
128 overall survival in both cohorts (12.6 and 13.3 months, respectively) compared with
129 patients with lower expression (23.5 and 25.9 months respectively). *CDK4*
130 overexpression remained statistically significant after adjusting by age, gender, tumor
131 stage and histologic subtype in each dataset, as well as in the combined analysis of
132 both series (HR=2.10 [95% CI 1.53–2.88]; p=4.2e-06; **Figure 1A**). Patients with *CDK6*
133 overexpression (i.e., above the median) had significantly shorter overall survival (12.6
134 months) compared with patients with lower expression (20.3 months; p=0.00026) in the
135 Bueno cohort and there was a trend toward shorter overall survival in the TCGA
136 dataset (15 versus 23.6 months; p=0.060). Nevertheless, *CDK6* overexpression
137 remained statistically significant in the combined analysis after adjusting by age,

138 gender, tumor stage and histologic subtype in the Bueno cohort, and also in the
139 combined cohort (HR=1.74 [95% CI 1.32–2.29]; p=5.4e-05; **Figure 1B**).

140 As previously reported (9,10), low expression of *CDKN2A* was associated with shorter
141 overall survival in both cohorts and was independently associated with worse prognosis
142 in the combined cohort including Bueno and TCGA (HR=0.49 [95% CI 0.36–0.66];
143 p=3.4e-06; **Supplementary Figure S1A**). In the TCGA cohort, only two tumors
144 harbored an *RB1* homologous deletion, while *CDKN2A/p16* deletion was a common
145 event present in 34 out of 74 cases (46%).

146 *CDKN2A* copy number was assessed in an independent cohort of 79 MPM acquired at
147 radical surgery involving extended pleurectomy decortication. Patient
148 clinicopathological characteristics are outlined in **Table 1**. Homozygous loss of 9p21.3
149 encompassing *CDKN2A* was observed in 40 samples (50.6%), while copy number
150 loss/LOH was observed in 18 (22.7%). *CDKN2A* homozygous loss was associated with
151 shorter median overall survival (10.98 months) compared to euploid *CDKN2A* (45.8
152 months; HR=0.37 [95% CI 0.22 - 0.62]; p=0.0002; **Supplementary Figure S1B**).
153 *CDKN2A* copy number loss/LOH was associated with shorter median overall survival
154 (8.52 months) compared to wild-type *CDKN2A* (45.8 months; HR=0.18 [95% CI 0.08-
155 0.40]; p=0.0001). There were no statistically significant differences in overall survival
156 among patients harboring *CDKN2A* homozygous deletion compared to those with
157 *CDKN2A* copy number loss/LOH (HR=0.89 [95% CI 0.49-1.59]; p=0.158).

158 **Genomic characterization of patient-derived MPM models and baseline
159 expression of genes involved in cell cycle in MPM cell lines**

160 Clinicopathological characteristics and main genomic alterations are shown in **Table 2**.
161 In all three patient-derived cell lines, *CDKN2A/p16* was deleted and *NF2* was wild type,
162 while *BAP1* was mutated in ICO_MPM1 (p.K651Yfs*1) and ICO_MPM2 (p.R60X).

163 Additional information about their mutational profile is provided in **Supplementary**
164 **Table S1.**

165 We examined by Western blot the expression levels of CDK4, CDK6, cyclin D1,
166 CDKN2A/p16 and RB proteins in five commercial and in the three patient-derived MPM
167 cell lines (**Figure 2A**). p16 expression was not detected in any cell line, while CDK4
168 was highly expressed in MSTO-211H, H28, H2052 and H2452 and in all primary cell
169 lines. CDK4 expression was lower in H226, but levels were still perceptible. High CDK6
170 expression was detected in MSTO-211H, H28, H226 and ICO_MPM2 whereas its
171 expression in H2052, H2452, ICO_MPM1 and ICO_MPM3 was lower. Five out of eight
172 cell lines showed high expression of cyclin D1 and the other three expressed lower, but
173 detectable levels. None of the cell lines showed loss of RB expression. Additional
174 information about their mutational profile is provided in **Supplementary Table S2.**

175 **Antiproliferative effect of CDK4/6 inhibitors on human MPM cell lines**

176 All MPM cell lines treated with increasing concentrations of abemaciclib or palbociclib
177 for 72 hours, showed a decrease in cell number (**Figure 2B and Supplementary**
178 **Figure S2**). Treatment with abemaciclib and palbociclib at 100 or 500 nM significantly
179 reduced cell number in comparison to control in all cell lines tested ($p<0.05$). At lower
180 doses (10 nM), the decrease in cell number was statistically significant in six out of
181 eight cell lines after treatment with abemaciclib ($p<0.01$), while it was significantly
182 reduced in all cell lines after palbociclib treatment ($p<0.05$).

183 The reduction in cell number after exposure to CDK4/6 inhibitors at 100 nM was nearly
184 50% (mean $54.5\% \pm 5.5$ with abemaciclib and mean $53.4\% \pm 4.9$ with palbociclib). At
185 500 nM, a reduction of 64.3% and 64.1% was observed with abemaciclib and
186 palbociclib respectively. MSTO-211H was the most sensitive cell line to both CDK4/6
187 inhibitors at 100 nM and 500 nM doses. All primary cell lines were sensitive to CDK4/6
188 inhibitors regardless of whether they had been derived from a patient who was

189 chemotherapy-naïve or who had received prior chemotherapy. ICO_MPM2, which was
190 derived from a chemotherapy-naïve patient, was the most sensitive primary cell line to
191 palbociclib with a cell number reduction of $45.3\% \pm 5.2$ at 100 nM (**Figure 2B**). These
192 antiproliferative effects were confirmed by cell colony formation assay and crystal violet
193 staining (data not shown). The ability to form colonies was completely blocked when
194 MSTO-211H, H226, H2052 and ICO_MPM1 were treated with abemaciclib and
195 palbociclib at 250 and 500 nM (**Figure 2C**).

196 **Effect of CDK4/6 inhibitors on cell cycle in human MPM cell lines**

197 Three cell lines selected for expressing high levels of CDK4 and CDK6 proteins
198 (MSTO-211H, H28 and ICO_MPM3) were evaluated for alterations in cell cycle
199 progression after 24-hour treatment with 250 or 500 nM abemaciclib or palbociclib.
200 Compared with control, cells treated with abemaciclib or palbociclib were arrested at
201 G1 phase (**Figure 3A**).

202 At 500 nM, the fraction of cells at G0/G1 phase increased to 13% and 11% in MSTO-
203 211H, to 24% and 26% in H28 and to 23% and 28% in ICO_MPM3 after abemaciclib or
204 palbociclib treatment, respectively ($p<0.001$). In addition, a significant decrease in cell
205 percentage in the G2/M phase ($p<0.001$) and in S phase ($p<0.001$) was observed in
206 the three cell lines after treatments at 250 nM and 500 nM compared to non-treated
207 cells (**Supplementary Figure S3**). The percentage of subG1 fraction significantly
208 increased from 1.38% in MSTO-211H control cells to $2.32\% \pm 0.6$ after treatment
209 ($p<0.001$, **Supplementary Figure S3**). In H28, the percentage of subG1 fraction
210 significantly decreased from 3.36% to $1.63\% \pm 0.2$ after treatment ($p<0.001$,
211 **Supplementary Figure S3**). In ICO_MPM3, the percentage of cells in subG1 remained
212 unchanged from 0.90 in control cells to $0.94\% \pm 0.1$ under all treatments except with
213 250 nM palbociclib, where there was a small, but statistically significant increase (0.9%
214 vs 1.07%; $p<0.05$, **Supplementary Figure S3**). These small biological differences in

215 cells with subG1 DNA content suggest that there is no increment in classical apoptosis
216 after abemaciclib or palbociclib at different exposure concentrations.

217 **Effect of CDK4/6 inhibitors on cell death and senescence in human MPM cell**
218 **lines**

219 As a next step, we investigated whether treatment with CDK4/6 inhibitors could induce
220 cell death in MPM cells. MSTO-211H, H28 and ICO_MPM3 cells were treated with
221 different concentrations of abemaciclib and palbociclib, as single agents or in
222 combination with the apoptosis inhibitor QVD for 72 hours and cell death was
223 quantified by FACS (**Figure 3B**). Neither inhibitor was able to significantly increase the
224 levels of apoptosis in MSTO-211H, H28 and ICO_MPM3 cells at any of the doses
225 tested. At the highest dose (500 nM), the percentage of apoptotic cells reached 12%
226 with abemaciclib and 8% with palbociclib in MSTO-211H cells, 2% after abemaciclib
227 and 3% after palbociclib in H28 cells, and around 6% after either treatment in
228 ICO_MPM3 cells.

229 To investigate whether CDK4/6 inhibitors promote senescence, both treated and
230 control MSTO-211H, H28 and ICO_MPM2 cells were stained using β -galactosidase. A
231 significant increase in the percentage of senescent cells was detected in all cell lines
232 treated with different concentrations of abemaciclib or palbociclib ($p<0.001$, **Figure 3C**).
233 Specifically, the proportion of senescent SA- β -gal positive MSTO-211H cells increased
234 from 18% to 54% with 250 nM abemaciclib and to 61% with 500 nM abemaciclib and to
235 52% with 250 nM palbociclib and to 59% with 500 nM palbociclib. Likewise, an
236 increase of senescent cells was also observed in H28 cells treated with 250 nM or 500
237 nM of either inhibitor. In ICO_MPM2 cells, the percentage of SA- β -gal positive cells
238 increased from 12% in control cells to 41% after abemaciclib and to 46% after
239 palbociclib treatments at 250 and 500 nM, respectively.

240 **Gene-expression profiling in cell lines and xenografts treated with CDK4/6
241 inhibitors**

242 To determine the functional consequences of CDK4/6 inhibitor treatment, we
243 performed transcriptomic analysis of MSTO-211H cells treated with abemaciclib or
244 palbociclib at 250 nM for 72 hours. In addition, tumor xenografts treated with palbociclib
245 were also evaluated. After treatment with either CDK4/6 inhibitor, a significant
246 downregulation in the expression levels was observed in the MSTO-211H cell line for
247 genes related with cell cycle, such as regulation of transcription genes involved in G1-S
248 transition of mitotic cell cycle, nucleus organization and mitotic spindle assembly and
249 organization (**Supplementary Figure S4 and Supplementary Table S3**). On the other
250 hand, there was a significant upregulation of genes related to interferon signaling
251 pathways, lymphocyte migration and chemotaxis, complement activation and antigen
252 presentation pathways, such as MHC protein complex. Furthermore, the transcriptomic
253 analysis of palbociclib-treated tumors xenografts mice showed similar results (data not
254 shown).

255 **Palbociclib reduced tumor growth in *in vivo* preclinical tumor models improving
256 overall survival in mice with orthotopically implanted MPM tumors**

257 The effect of palbociclib *in vivo* was examined by implanting subcutaneously MSTO-
258 211H cells into the right flanks of athymic mice. After 26 days of treatment, the mean
259 volume of tumors implanted subcutaneously in vehicle-treated mice was 1816 ± 795.2
260 mm^3 ; in cisplatin plus pemetrexed-treated mice was $1647.1 \pm 733.8 \text{ mm}^3$ whereas for
261 palbociclib-treated mice it was $524.2 \pm 236.6 \text{ mm}^3$ (**Figure 4A and Supplementary
262 Figure S5A**). Differences among palbociclib and the two other cohorts were already
263 statistically significant at day 16 ($p=0.043$, **Supplementary Figure S5B**). At mice
264 sacrifice, 26 days post-treatment, a significant decrease in the tumor weight was
265 observed for palbociclib-treated mice respect to vehicle and combined chemotherapy-

266 treated mice (0.35 vs 1.1 and 1.13 gr; p=0.01 and p=0.007, respectively, **Figure 4B**
267 and **4C**). No differences were observed at histologic level (**Supplementary Figure**
268 **S6**). The body weight of the mice was monitored to evaluate the potential side effects
269 of treatments (**Supplementary Figure S5C**). In those mice treated with palbociclib, no
270 body weight loss was observed during the experiment, suggesting that palbociclib did
271 not exert significant systemic toxicity at the doses used in this study.

272 To preclinically investigate the efficacy of palbociclib as second-line treatment in MPM
273 tumors refractory to conventional chemotherapy, we re-implanted one of the
274 subcutaneous tumors derived from MSTO-211H cells previously treated with cisplatin
275 plus pemetrexed. After 40 days of treatment, no vehicle-treated mice were alive (0/11;
276 0%); only three platinum-treated mice were alive (3/11; 27.3%), while seven
277 palbociclib-treated mice were still alive (7/11; 63.6%) (**Figure 4D**). Animals (93.9%)
278 were sacrificed due to dyspnea or excessive weight loss (31/33). Overall survival
279 analysis showed a significant reduction in the risk of death for palbociclib-treated mice
280 compared with vehicle (HR=0.04 [95% CI 0.01-0.17]) or with cisplatin (HR=0.11 [95%
281 CI 0.03-0.41]).

282 Those mice that were alive after 40 days of treatment (n=10) were maintained without
283 treatment and followed up until endpoint. After six days of stopping treatments, all the
284 remaining platinum-treated mice (n=3) were dead, whereas two out of seven
285 palbociclib-treated mice were still alive after two months without receiving any
286 treatment. Palbociclib treatment did not exert any substantial change in body weight
287 between the first and the last day of treatment (**Supplementary Figure S5D**).
288 Representative pictures of MSTO-211H orthotopic tumors from each group of
289 treatment are shown in **Figure 4E** and **Supplementary Figure S7**. Histopathological
290 analysis of the MPM tumor xenografts grown orthotopically in mice accurately

291 reproduced the natural history of mesothelioma (**Figure 4F and Supplementary**
292 **Figure S8**).

293

294

295 **Discussion**

296 MPM is a rapidly fatal neoplastic disease in which therapeutic options are limited and
297 there are no effective second-line treatment available. We investigated the role of
298 CDK4/6 inhibition in MPM because cell cycle deregulation is a relevant hallmark in this
299 disease. In this regard, *CDKN2A/p16* deletion is a common genomic event associated
300 to worse clinical outcome in MPM (9,10). Based on publicly available gene expression
301 data of MPM, we found that overexpression of *CDK4* or *CDK6* is associated with
302 shorter overall survival. The unfavorable prognostic role of *CDKN2A/p16* deletion was
303 confirmed in an independent cohort of MPM. Together these findings suggest that cell
304 cycle deregulation may confer an aggressive biological behavior in mesothelioma and
305 let us to hypothesize that treatment with CDK4/6 inhibitors might be an effective
306 treatment in MPM.

307 The efficacy of palbociclib has been previously studied in *in vitro* models of MPM (17).
308 However, the antitumor activity of CDK4/6 inhibitors has not yet been evaluated using
309 primary patient-derived cell models of MPM neither *in vivo* models of MPM. In our
310 work, we assessed the efficacy of two CDK4/6 inhibitors, abemaciclib and palbociclib,
311 in a subset of five commercial and three primary patient-derived cell culture models
312 obtained from pleural effusions of patients with MPM (one chemotherapy-naïve and
313 two after progression to standard first-line chemotherapy). Furthermore, we performed
314 not only *in vivo* basic subcutaneous drug response studies in xenografts derived from
315 one chemotherapy-naïve MPM cell line, but also advanced studies by means of

316 orthotopic implanted xenograft from a cell line-derived tumor previously treated with
317 cisplatin plus pemetrexed. Remarkably all the cell lines were sensitive to palbociclib
318 and to abemaciclib. Treatment with abemaciclib or palbociclib significantly reduced cell
319 proliferation, as evaluated by cell number counting or by colony formation ability, in all
320 the cell lines including in the primary ones derived from pleural liquid from patients
321 resistant to chemotherapy. Interestingly, these *in vitro* experiments underscore two
322 important points: i) no substantial differences were found in the antiproliferative effect
323 of both inhibitors; and ii) the sensitivity to CDK4/6 inhibitors was not correlated with the
324 endogenous expression levels of CDK4 or CDK6.

325 Then, we assessed the impact of abemaciclib and palbociclib treatment on cell cycle
326 progression, cellular senescence and apoptosis induction. These experiments were
327 performed using three cell lines that were sensitive to both drugs, including a primary
328 cell line derived from a patient resistant to chemotherapy. As expected, the treatment
329 with abemaciclib and palbociclib caused cell cycle arrest at G1 phase but also
330 promoted cellular senescence. However, neither abemaciclib nor palbociclib activated
331 programmed cell death or apoptosis as indicated by negligible subG1 accumulation or
332 propidium iodide incorporation. The observed increase on cellular senescence induced
333 by both drugs could be linked to apoptosis resistance mechanisms (15,18). As
334 proposed by other groups (17,19,20), our results reinforce the cytostatic mechanism of
335 action of CDK4/6 inhibitors and underscore that these should be given sequentially
336 after completing chemotherapy treatment (21). However, the low cell death observed *in*
337 *vitro* does not eliminate the possibility that palbociclib, by inducing senescence in a few
338 cells, may promote *in vivo* cytotoxicity mediated by Natural Killer cells. This
339 phenomenon has been described in lung cancer, in which Natural Killers participate in
340 tumor reduction upon treatment with MEK inhibitors and palbociclib (22,23).

341 In order to explore potential activation of compensatory pathways, we performed gene

342 set enrichment analysis of the transcriptome of MSTO-211H cells treated with
343 abemaciclib or palbociclib *in vitro* or subcutaneously implanted in mice. This
344 experiment showed downregulation of genes involved in G1-S transition of mitotic cell
345 cycle, nucleus organization and mitotic spindle assembly and organization. In
346 concordance with studies conducted in other tumor types, genes encoding interferon
347 signaling and antigen presentation pathways were upregulated after CDK4/6
348 pharmacological inhibition (20). In melanoma, CDK4/6 inhibition activates p53 by
349 lowering PRMT5 which leads to altered MDM4 splicing and significantly reduced
350 protein expression (24,25). Other studies performed in breast cancer cell lines and
351 transgenic mice models have shown that abemaciclib treatment increased the
352 expression of antigen processing and presentation and even suppressed the
353 proliferation of regulatory T cells (16,20). Further studies evaluating the functional
354 consequences of the treatment with CDK4/6 inhibitors on the tumor immune contexture
355 are warranted in mesothelioma.

356 As both CDK4/6 inhibitors showed a similar pattern of response and effectiveness *in*
357 *vitro* and considering that palbociclib has a more convenient posology compared with
358 abemaciclib, we decided to perform *in vivo* experiments with palbociclib. To the best of
359 our knowledge, this is the first time that effectiveness of palbociclib was evaluated
360 using preclinical *in vivo* subcutaneous and orthotopic MPM tumor models. Among the
361 available cell line models, MSTO-211H cell line was selected for the *in vivo*
362 experiments because i) it expresses CDK4 and CDK6; ii) it is the most sensitive cell
363 line to palbociclib at 500 nM; and iii) it was tumorigenic in athymic mice. Our results
364 showed that palbociclib reduced tumor size in a subcutaneous mouse model of chemo-
365 naïve MSTO-211H cells compared with standard chemotherapy (cisplatin plus
366 pemetrexed). An increased expression of pro-apoptotic proteins after long-term
367 chemotherapy treatment could explain the chemoresistance in this model (26). We
368 tried to replicate a situation representing treatment after progression to platinum-based

369 chemotherapy by generating an orthotopic tumor mouse model and implanting in the
370 pleura small solid fragments of MSTO-211H xenografted tumors previously treated with
371 chemotherapy. In this advanced model of MPM, palbociclib significantly increased the
372 overall survival of mice compared with cisplatin-based chemotherapy or vehicle; the
373 benefits from treatment persisted even after stopping the treatment. Our results
374 reinforce the potential use of palbociclib as a second-line treatment for patients with
375 MPM that is resistant or has relapsed after standard chemotherapy doublet treatment.
376 Interestingly, the extended response of palbociclib treatment, even after stopping
377 treatment, could result from an effect modulating on the immune system response;
378 however, this still needs to be elucidated.

379 Some limitations of our study are the absence of a wide range of available commercial
380 MPM cell lines and the need for preclinical *in vivo* models representing the
381 heterogeneity of the disease. However, in our study we have combined commercial,
382 primary patient-derived lines as well as orthotopic models where mesothelioma grows
383 in its corresponding microenvironment and can recapitulate the disease behavior.

384 A phase II clinical study of abemaciclib in patients harboring p16ink4a deficient,
385 relapsed MPM has recently completed accrual (NCT03654833). CDK4/6 inhibition in
386 this cohort has been associated radiological responses however the underlying
387 molecular correlates of response are under investigation. Accordingly, whole exome
388 sequencing of the trial cohort is planned to uncover genomic determinants of response.

389 In conclusion, our data support that treatment with CDK4/6 inhibitors, abemaciclib or
390 palbociclib, can reduce cell proliferation and induce cellular senescence in MPM cell
391 lines and palbociclib can increase overall survival of mice with orthotopically implanted
392 MPM cells. A remarkable and sustained response to palbociclib was observed in
393 xenografts of MPM tumor resistant to cisplatin and pemetrexed which was then
394 implanted orthotopically in the pleural space of mice. Transcriptomic analysis of cell

395 lines and xenografted tumors treated with CDK4/6 inhibitors showed an increased
396 expression of interferon signaling pathway and antigen presenting processes,
397 suggesting that CDK4/6 inhibitors may favor potential response to immunotherapy. Our
398 results warrant further evaluation of CDK4/6 inhibitors as a second-line treatment in
399 patients with advanced MPM that has failed standard platinum-based chemotherapy.

400

401 **Materials and methods**

402 **Cell culture and cell lines**

403 Five human MPM cell lines, including H28, H2452, H2052, MSTO-211H and H226
404 were purchased from the American Type Culture Collection (ATCC, Manassas,
405 Virginia). Three additional primary cell lines (ICO_MPM1, ICO_MPM2 and ICO_MPM3)
406 were derived from pleural effusions obtained from three patients with MPM.
407 ICO_MPM1 and ICO_MPM3, were derived from two patients who progressed to
408 standard chemotherapy with platinum and pemetrexed, while ICO_MPM2 was derived
409 from a chemotherapy-naïve patient. Primary cells were isolated and cultured as
410 previously described (27). All cell lines were incubated and maintained at 37°C in a
411 humidified chamber containing 5% CO₂.

412 **Patient and tissue samples**

413 Patients with confirmed histological diagnosis of malignant pleural mesothelioma were
414 scheduled for routine surgery involving extended pleurectomy decortication at the
415 Glenfield Hospital (University of Leicester). Patients were approached 24 hours prior to
416 their operation and provided with patient information regarding the research. All
417 patients signed informed consent prior to surgery. Seventy-nine patient MPM samples
418 were obtained at the time of surgery. Following surgery, all patients were longitudinally
419 tracked until disease progression with CT monitoring, and monitored for survival.

420

421 **Oncoscan Analysis**

422 DNA was extracted with the GeneRead DNA FFPE kit (Qiagen, Manchester, UK).
423 Eighty nanograms of genomic DNA were analyzed using the OncoScan FFPE Assay
424 Kit (Affymetrix, Wooburn Green High Wycombe, UK). The BioDiscovery Nexus Express
425 10.0 for OncoScan software was used to determine copy number alterations and loss
426 of heterozygosity (LOH).

427 **Antibodies and drugs**

428 Antibodies against total Rb (#9313), p-Rb (#8180), CDK4 (#12790), CDK6 (#13331),
429 cyclin D1 (#2922), p16 (#80772) and β -actin (#4970) were purchased from Cell
430 Signaling Technology (Danvers, Massachusetts) and were used following manufacturer
431 instructions for western blot.

432 Abemaciclib (LY2835219) was purchased from Selleckchem (Houston, Texas).
433 Palbociclib (PD0332991) was provided by Pfizer, Inc (San Diego, California). Cisplatin
434 and pemetrexed were obtained at the Catalan Institute of Oncology pharmacy.

435 ***In vitro* and *in vivo* drug experiments**

436 For *in vitro* experiments, cell lines were plated into 6-well plates and treated with
437 abemaciclib or palbociclib with 0 (control), 10, 100, 250 or 500 nM for 1, 3 or 15 days.
438 Doses below micromolar range, would be clinically well tolerated. For *in vivo* assays,
439 mice were randomly treated with i) vehicle, 200 μ l of 0.05 N sodium lactate pH 4.0 five
440 days a week; ii) cisplatin alone, 3.5 mg/kg once a week or combined with pemetrexed,
441 100 mg/kg twice a week; or iii) palbociclib, 150 mg/kg five days over seven days. Mice
442 were treated during twenty-six days for subcutaneous models or forty days for
443 orthotopic models.

444 **Western blot analysis**

445 Total cell lysates and western blotting were performed as previously described (28).

446 **Cell viability, cell cycle and apoptosis analysis**

447 Cell viability was evaluated by cell counting and colony formation assays as described
448 elsewhere (29). Cell cycle and apoptosis were analyzed as described in (30). A
449 minimum of 1×10^4 cells were analyzed per determination. All experiments were
450 repeated at least three times with similar results. P-values were adjusted usingFDR.

451 **Measurement of cellular senescence**

452 The evaluation of senescence-associated β -Galactosidase (SA- β -Gal) expression was
453 performed as previously described (17). Experiments were repeated at least three
454 times with similar results.

455 ***In vivo* MPM subcutaneous preclinical drug assays in nude mice**

456 To investigate the efficacy of palbociclib in the treatment of MPM, we used the MSTO-
457 211H cell line, derived from a patient who had not received prior chemotherapy and
458 able to grow in athymic mice. For subcutaneous xenograft development, 4×10^6
459 MSTO-211H cells growing exponentially were suspended in 300 μ l PBS and
460 subcutaneously inoculated into the right flanks of 30 four-week-old male athymic nude
461 mice (Envigo, Indiana, Indianapolis). Once the tumors reached a homogeneous
462 average volume size of 300–400 mm^3 , mice (n=28) were randomly assigned into four
463 groups (n=7 per group) and treated as described above. To evaluate efficacy, tumor
464 volumes ($V = \pi/6 \times L \times W^2$) were measured twice per week with calipers and the weight
465 of each animal was measured every day. After 26 days of treatment, mice were
466 euthanized by cervical dislocation and the tumors were excised, weighted and
467 processed for histologic and RNA studies following standard protocols. The mean

468 volume + SD were calculated using R software v.3.5.0 (31). Daily differences among
469 treatments were analyzed using Kruskal-Wallis tests, with FDR adjustment.

470 ***In vivo MPM orthotopic preclinical drug assays in tumors nude mice***

471 To investigate the efficacy of palbociclib in tumors after progression to standard first-
472 line chemotherapy, two subcutaneous tumors treated with cisplatin plus pemetrexed
473 from the previous experiments were aseptically isolated and implanted in 35 four-week-
474 old male athymic nude mice following our previously reported procedures (32). Thirty-
475 three mice were randomized into three groups (n=11 per group) and treated as
476 previously mentioned for forty days. Beyond 40 days, all live mice remained untreated
477 until human endpoint. Orthotopic tumors were collected from euthanized mice
478 presenting breathing problems and processed for histological studies. Survival curves
479 for each cohort of mice were calculated using the Kaplan-Meier method and the
480 differences between groups were compared using Cox proportional hazards model.

481 ***In silico analysis of publicly available RNA-sequencing data***

482 Public data from RNA-seq cohorts published by Bueno et al. (33) and The Cancer
483 Genome Atlas (TCGA-MESO) (8) were used to assess differences in survival. Gene
484 expression ($\log_2(\text{TPM})$) was stratified using the median, and Cox proportional-hazards
485 models adjusted for sex, stage, age and histology were fitted to assess differences in
486 survival using R software (31).

487 ***Whole Exome Sequencing (WES) and RNA sequencing (RNA-seq) analysis of
488 patient-derived cell lines***

489 Paired-end RNA sequencing was performed on an Illumina HiSeq 2500, with 100 bp
490 long reads. Genomic DNA and total RNA were submitted to the Centro National de
491 Análisis Genómico (CNAG, Barcelona, Spain), for WES and RNA-Seq library

492 preparation and sequencing. All statistical analyses were done using R software v.3.5.0
493 (31).

494 **Statistics**

495 Cell proliferation assay was assessed using Wilcoxon signed rank tests comparing
496 each treatment with vehicle condition, and adjusted using FDR correction. Differences
497 among treatment and vehicle conditions in the cell death experiment were evaluated
498 using Mann-Whitney U test for each comparison and Kruskal-Wallis test if 3 conditions
499 were simultaneously tested and adjusted afterward using FDR. Cell cycle and
500 senescence experiments were analyzed using proportion tests taking into account all
501 the cells counted in the abovementioned experiments. P-values were adjusted using
502 FDR. For *in vivo* experiments, the analysis of differences in body weight for orthotopic
503 xenografts was computed using a Mann-Whitney U test comparing the first and last
504 day of treatment in each treatment and adjusted with FDR. For subcutaneous
505 xenografts, a longitudinal analysis testing for differences in treatment slopes was done
506 using analysis of covariance. Regarding survival analysis, for public data (Bueno et al.
507 (33) and The Cancer Genome Atlas (8), Cox proportional-hazards models adjusted for
508 sex, stage, age, and histology were fitted to assess the differences between gene
509 expression (categorized using the median log2TPM value for each gene). For *in vivo*
510 experiments, a Cox proportional-hazards model was fitted to assess differences among
511 groups. Survival curves were plotted using Kaplan-Meier curves. P-value smaller than
512 0.05 was considered statistically significant. All statistical analyses were done using R
513 software v.3.5.0 (22).

514 **Ethics approval**

515 The retrospective cohort was approved by a National Ethical Committee, under the
516 references 4/LO/1527 (a translational research platform entitled *Predicting Drug and*
517 *Radiation Sensitivity in Thoracic Cancers – also approved by University Hospitals of*

518 *Leicester NHS Trust under the reference IRAS131283) and 14/EM/1159 (retrospective*
519 *cohort). Pleural effusions samples were obtained after patients signed the informed*
520 *consent approved by the Hospital de Bellvitge Ethical Committee (PR152/14). All the*
521 *animal experiments were performed in accordance with protocols approved by Animal*
522 *Research Ethics Committee at IDIBELL. This study was performed in accordance with*
523 *the principles outlined in the Declaration of Helsinki.*

524

525 For additional information about methodology see supplementary material.

526

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651 **Figure legends**

652 **Figure 1. Kaplan-Meier plots of overall survival (OS) in MPM patients according**
653 **to (A) CDK4 and (B) CDK6 gene expression levels based on data obtained from**
654 **Bueno et al. (left column) and Hmeljak et al. (middle column) cohorts or the**
655 **combination of both (right column).** High levels of *CDK4* or *CDK6* (red line) were
656 significantly associated with poor OS in patients with MPM. In each cohort, the high
657 and low expression levels were defined based upon the median. P-values and hazard

658 ratios (HR) were calculated by likelihood ratio test and multivariate Cox regression
659 analysis respectively.

660 **Figure 2. Quantification of the expression levels of key cell cycle regulators and**
661 **response to treatment with CDK4/6 inhibitors in a panel of commercial MPM cell**
662 **lines (MSTO-211H, H28, H226, H2052 H2452) and primary patient-derived cultures**
663 **(ICO_MPM1, ICO_MPM2, ICO_MPM3).** (A) Base line protein expression levels by
664 Western blot of CDK4, CDK6, cyclin D1, Rb, phosphor-RB and p16. (B) Number of
665 viable cells was determined *in vitro* by cell counting in the panel of cells after three
666 days of treatment with increasing concentrations (0, 10, 100, 500 nM) of abemaciclib or
667 palbociclib. Bar plots represent the means \pm SD of three measurements. Adjusted p-
668 values were calculated with Wilcoxon signed rank tests. In the graph, the p values are
669 reported with respect to 0 nM (*p < 0.05; **p < 0.01). (C) Colony formation assay
670 displaying treatment response to abemaciclib and palbociclib. A representative image
671 from 3 biological independent replicates is displayed.

672 **Figure 3. Effects of cell line treatments with CDK4/6 inhibitors abemaciclib or**
673 **palbociclib at 0, 100, 250 or 500 nM doses to induce (A) cell-cycle arrest (B), cell**
674 **death and (C) senescence.** (A) MSTO-211H, H28 and ICO_MPM3 cells were
675 untreated and treated with both inhibitors during 24 hours and DNA content analyzed
676 by flow cytometry. Cell cycle arrest at G1 phase was induced by both CDK4/6 inhibitors
677 in the cell lines. (B) Likewise the same three cells were exposed to drugs for 72 hours
678 and cell death stained with propidium iodide (PI⁺ cells) analyzed by flow cytometry. Cell
679 death was slightly affected (up to 1-5%) by both drugs. To quantify the percentage of
680 non-apoptotic induced cell death, cells were treated with QVD (an apoptosis inhibitor).
681 Cell cycle phase distribution and cell death analysis were done using FlowJo software.
682 (C) A significant increase in the number of SA- β -Gal positive cells was detected in
683 MSTO-211H, H28 and ICO_MPM2 treated. Data are expressed as a percentage of

684 senescent cells obtained from the mean value \pm SD of three replicates. Adjusted p-
685 values less than 0.05 were considered significant.

686 **Figure 4. *In vivo* treatment with palbociclib in both subcutaneous and advanced**
687 **orthotopic MPM models.** A xenografted subcutaneous tumor model was
688 established by inoculation of MSTO-211H cells into the flanks of athymic nude mice.
689 Tumors' volume (*A*) was monitored by caliper measure every four days, and at the end
690 of the experiment, mice were sacrificed and (*B* and *C*) the tumors were removed,
691 weighted and photographed. An Advanced orthotopic model was generated by
692 implantation in the lung of mice (n=35) of small solid fragments (2-3 mm³) of previously
693 generated MSTO-211H subcutaneous cisplatin plus pemetrexed resistant tumor
694 xenograft. (*D*) Kaplan-Meier curves showing survival of MSTO-211H orthotopic tumor-
695 bearing mice. (*E*) Representative MSTO-211H images of orthotopic tumors dissected
696 from each group of treatment and (*F*) histological characterization on H&E sections
697 (Scale bars = 100 μ m). Orthotopic model accurately reproduce human MPM disease
698 characteristics as tumor grown from the site of implantation to all the pleural space.
699 Tumor mass area is delimited by white line. Asterisks indicated absence of apparent
700 macroscopic tumor at sacrifice, while residual cells were identified by H&E analysis.

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709 **Author contribution statement**

710 **EA:** Conceptualization, Methodology, Validation, Formal analysis, Investigation,
711 Resources, Data Curation, Writing – Original Draft, Writing – Review & Editing,
712 Visualization **AA:** Conceptualization, Software, Validation, Formal analysis, Resources,
713 Data Curation, Writing – Review & Editing, Visualization **MMI:** Methodology,
714 Investigation, Resources, Data curation **MHM:** Methodology, Validation, Investigation,
715 Data Curation **DC:** Conceptualization, Software, Validation, Formal analysis, Data
716 Curation **MG:** Conceptualization, Resources, Writing – Review & Editing **EP:**
717 Resources, Writing – Review & Editing **MS:** Resources, Writing – Review & Editing **SB:**
718 Software, Validation, Data Curation **AJS:** Resources, Writing – Review & Editing **AD:**
719 Resources, Writing – Review & Editing **RP:** Resources, Data Curation, Writing –
720 Review & Editing **SP:** Resources, Writing – Review & Editing **SA:** Resources, Writing –
721 Review & Editing **IE:** Resources, Writing – Review & Editing **RR:** Resources, Writing –
722 Review & Editing **RL:** Resources, Validation, Data Curation **AV:** Resources, Validation,
723 Data Curation **MV:** Resources, Validation, Data Curation **MSC:** Resources, Writing –
724 Review & Editing **DF:** Resources, Validation, Formal analysis, Investigation, Data
725 Curation, Writing – Review & Editing **CMP:** Conceptualization, Methodology,
726 Validation, Formal analysis, Investigation, Data Curation, Writing – Review & Editing,
727 Visualization **AV:** Conceptualization, Methodology, Validation, Formal analysis,
728 Investigation, Data Curation, Writing – Review & Editing, Visualization **XS:**
729 Conceptualization, Software, Formal analysis, Data Curation, Writing – Review &

730 Editing, Visualization **EN**: Conceptualization, Methodology, Validation, Formal analysis,
731 Investigation, Resources, Data Curation, Writing – Original Draft, Writing – Review &
732 Editing, Visualization, Supervision, Project administration, Funding acquisition.

733

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797 **Tables**798 **Table 1. Clinicopathological characteristics of patients.** (CI: confidence interval; CN: copy number; IMIG: International Mesothelioma
799 Interest Group; IQR: interquatile range; LOH: loss of heterozygosity).

800

	Homozygous loss of CDKN2A N=40	CDKN2A CN loss, LOH N=18	Euploid CDKN2A N=21
Age at diagnosis, median (IQR)	65.5 (61.2–74)	64.5 (61–70.5)	58 (52–67.6)
Sex, N (%)			
Male	35 (87.5)	16 (88.8)	16 (76.2)
Female	5 (12.5)	2 (11.2)	5 (23.8)
Histology, N (%)			
Epithelioid	33 (82.5)	18 (100%)	20 (95.2)
Biphasic	7 (17.5)	0 (0)	1 (4.8)
IMIG stage, N (%)			
I	0 (0)	0 (0)	1 (4.7)
II	6 (15)	2 (11.1)	3 (14.3)
III	27 (67.5)	11 (61.1)	14 (66.7)

IV	7 (17.5)	5 (27.8)	3 (14.3)
Neoadjuvant chemotherapy, N (%)	2 (5)	0 (0)	3 (14.3)
Survival status, N (%)			
Alive	1 (2.5)	0 (0)	0 (0)
Dead	39 (97.5)	18 (100)	21 (100)
Overall survival, median (95% CI)	10.98 (95% CI: 6.59-17.05)	8.52 (95% CI: 4.328-18.62)	45.8 (95% CI: 27.77-65.25)

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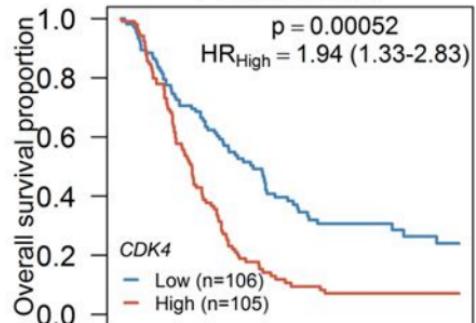
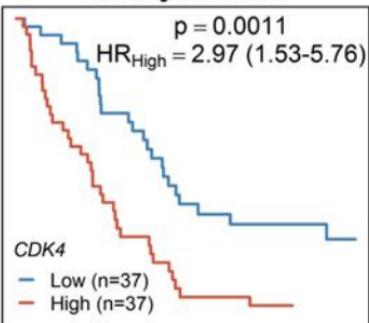
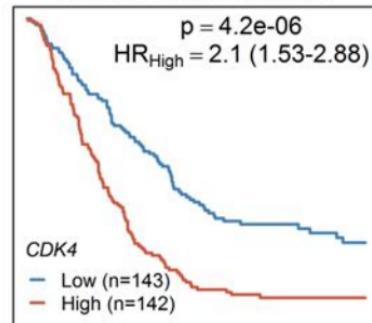
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803 **Table 2. Clinicopathological characteristics and main genomic and protein alterations found in primary cell lines were derived from**
 804 **patients with pleural malignant mesothelioma.** Additional predicted driver mutations have been identified using Cancer Genome Interpreter.
 805 (WES: whole exome sequencing; FISH: fluorescence in situ hybridization).

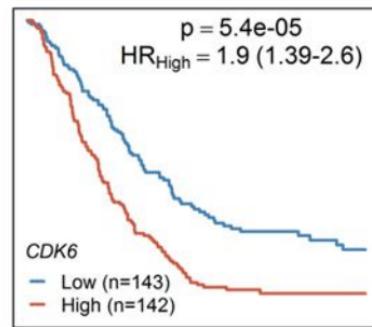
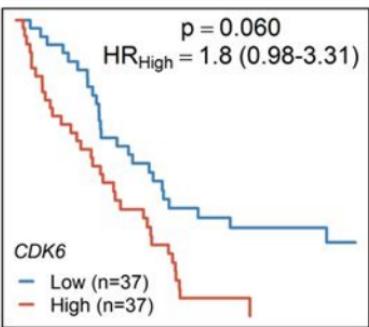
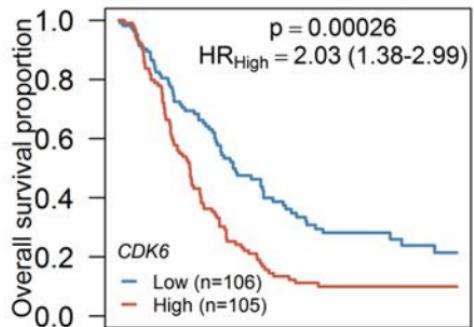
ID	Clinicopathological features						Molecular characterization by WES and FISH			
	Age	Sex	Asbestos	Histology	Prior	BAP1	TP53	NF2	CDKN2A	Additional predicted driver

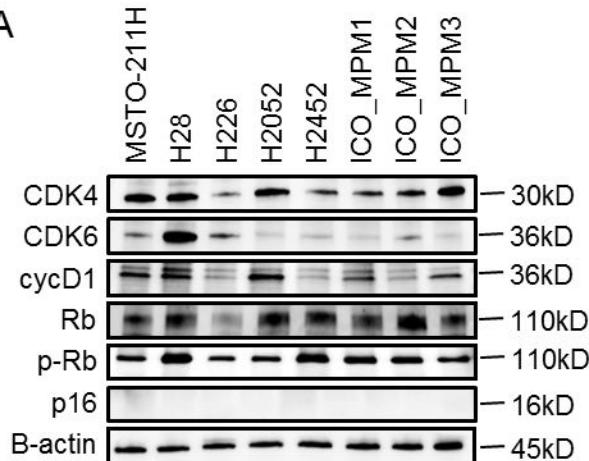
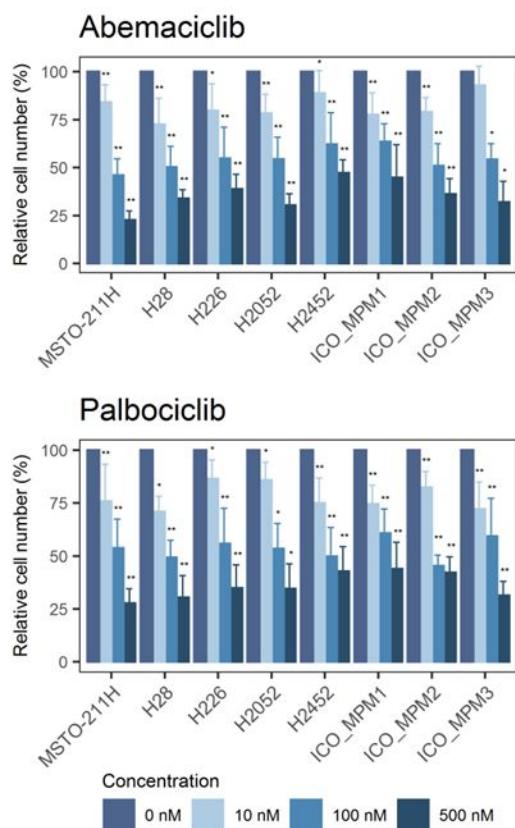
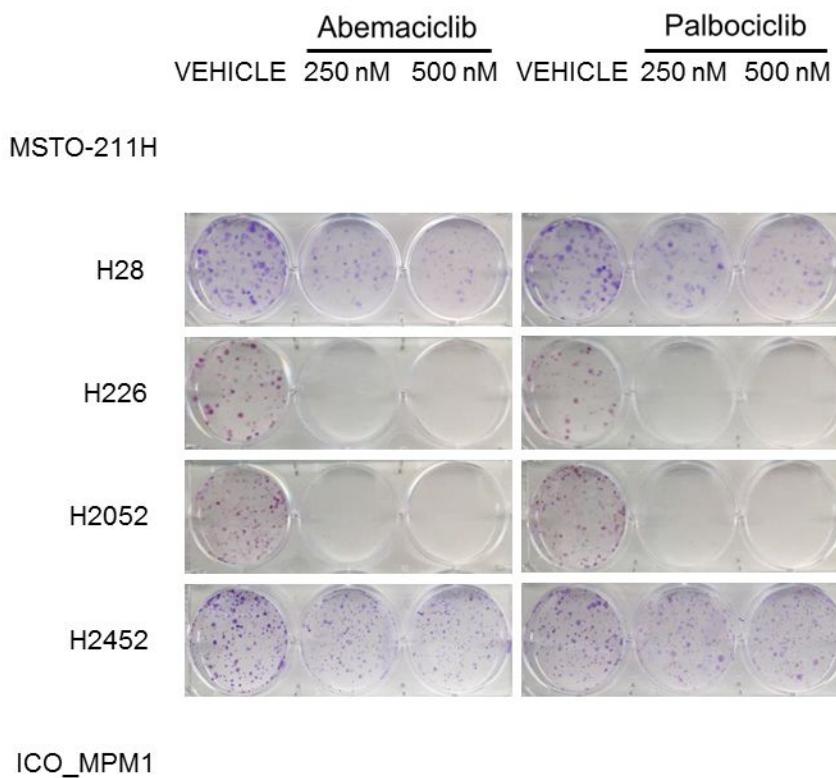
			exposure		chemotherapy	(WES)	(WES)	(WES)	(FISH)	mutations
ICO_MPM1	77	M	No	Epithelioid	Yes	p.(Lys651_Lys661del)	p.(Asn92Cys*26)	WT	Hemizygous deletion	<i>DHX15</i> p.(Pro478His) <i>SF3B1</i> p.(Tyr623Cys)
ICO_MPM2	73	F	Yes	Epithelioid	No	p.(Arg60*)	WT	WT	Hemizygous deletion	<i>CSNK2A1</i> p.(Asp210Tyr)
ICO_MPM3	70	M	No	Epithelioid	Yes	WT	WT	WT	Homozygous deletion	<i>ACO1</i> p.(Arg802His) <i>ABL1</i> p.(Gly1060Asp) <i>INPP4A</i> p.(Arg244Trp) <i>EP300</i> p.(Arg1356*) <i>SPEN</i> p.(Ser260Ile) <i>CREBBP</i> p.(Trp1718*)

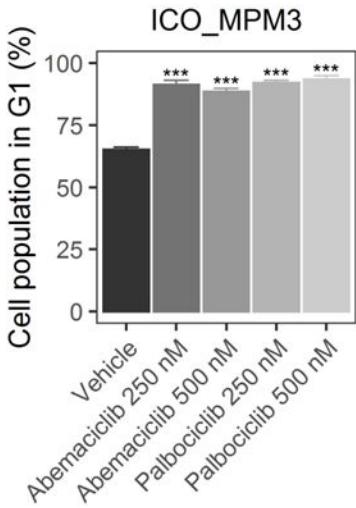
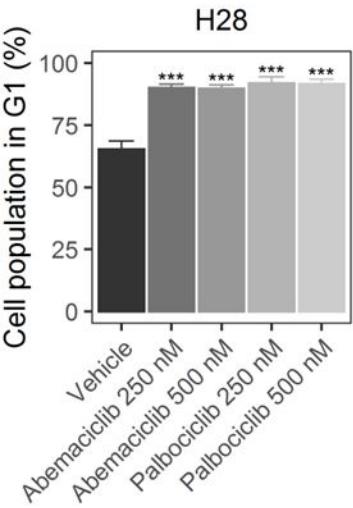
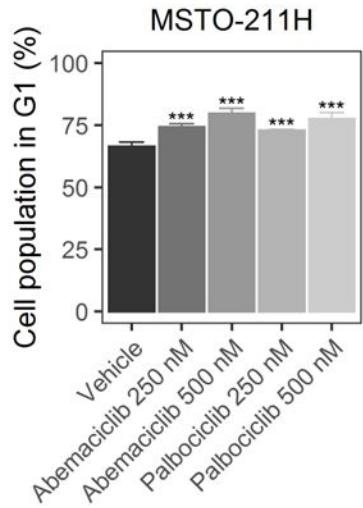
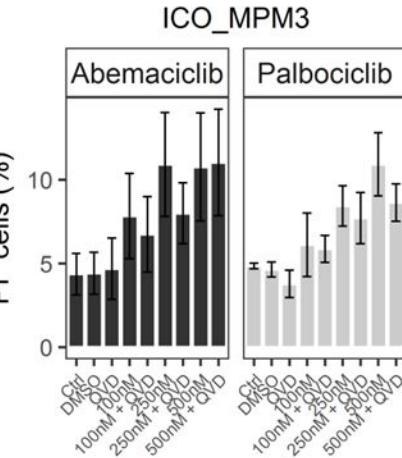
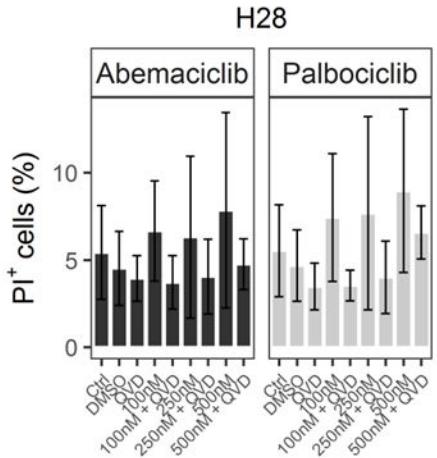
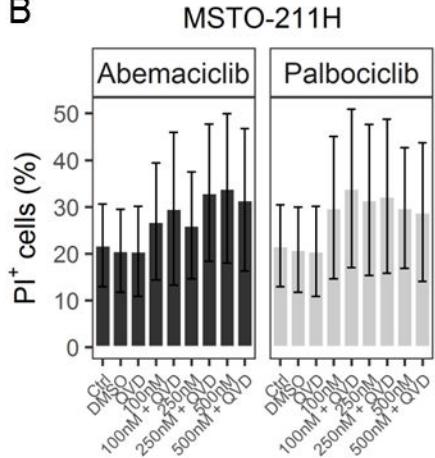
A

Bueno et al.**Hmeljak et al.****Combined cohorts**

B



A**B****C**

A**B****C**