Deficiency of global genome nucleotide excision repair explains mutational signature observed in cancer

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ABSTRACT

Nucleotide excision repair (NER) is one of the main DNA repair pathways that protect cells against genomic damage. Deficiency in this pathway can contribute to the development of cancer and accelerate aging. In addition, NER-deficiency is an important determinant for cancer treatment outcome, as NER-deficient tumors are sensitive to cisplatin treatment. Non-silent mutations in the NER-gene *ERCC2* were previously associated with a specific mutational footprint (Signature 5), potentially providing a functional readout for NER-deficiency. However, not all NER-deficient tumors are characterized by a high Signature 5 contribution, illustrating the importance to further characterize the mutational consequences of NER-deficiency. Here, we analyzed the somatic mutational profiles of adult stem cells (ASCs) from NER-deficient progeroid *Ercc1*$^{-/\Delta}$ mice, using whole-genome sequencing analysis of clonally derived organoids. Our results indicate that NER-deficiency increases the point mutation load in liver, but not in small intestinal ASCs, which coincides with a tissue-specific aging-pathology observed in these mice. More specifically, this increase can be largely explained by Signature 8, a mutational footprint observed in human cancer with as yet unknown etiology. The genomic distribution of the acquired point mutations indicates that deficiency of global-genome NER (GG-NER), rather than transcription-coupled NER (TC-NER), is responsible for the accumulated mutations. We independently confirmed the link between Signature 8 and GG-NER-deficiency through mutational analysis of a human organoid culture that was deleted for *XPC* using CRISPR-Cas9 gene-editing. Elevated levels of Signature 8 may, therefore, serve as a novel biomarker for GG-NER-deficient tumors and could improve personalized cancer treatment strategies.

INTRODUCTION

The genome is continuously exposed to DNA-damaging agents, which ultimately can result in accumulation of mutations or, alternatively, the induction of senescence or cell death. To counteract mutagenic processes, cells exploit multiple DNA repair pathways that each repair specific lesions. Deficiency of these DNA repair pathways can contribute to cancer,

55 accelerate aging, or both (Hoeijmakers 2009). To increase insight into the cellular processes
56 that underlie mutation accumulation, including the activity of DNA repair pathways, mutation
57 loads and types can be characterized (Alexandrov et al. 2013; Nik-Zainal et al. 2016). To
58 date, systematic analyses of tumor genomes have revealed 30 signatures of point mutations
59 and 6 rearrangement signatures of mutational processes in cancer genomes (Alexandrov et
60 al. 2013; Nik-Zainal et al. 2016). These mutational signatures may have important diagnostic
61 value. For example, several signatures are associated with BRCA1/2 inactivity and can
62 consequently be predictive for a potentially beneficial response to PARP inhibition or
63 cisplatin treatment (Waddell et al. 2015; Davies et al. 2017).

64 Although for some signatures the underlying molecular process (Kim et al. 2016;
65 Alexandrov et al. 2013, 2016) and/or involved DNA repair pathway (Kim et al. 2016; Davies
66 et al. 2017; Alexandrov et al. 2013) is known, in-depth mechanistic insight is still lacking for
67 the majority of the mutational signatures. Efforts to link mutational processes to specific
68 signatures have mainly focused on associating mutation data from tumors to mutagen
69 exposure and DNA repair-deficiency. However, tumors are genomically highly unstable and
70 typically multiple mutational processes are active simultaneously and/or consecutively
71 (Alexandrov et al. 2013; Nik-Zainal et al. 2016), which hampers the identification of the
72 underlying processes that cause specific mutational signatures. Tissue-specific adult stem
73 cells (ASCs), on the other hand, maintain a highly stable genome during life (Blokzijl et al.
74 2016a). In addition, ASCs provide a relevant cell source to study mutational patterns, as
75 these cells are the cell-of-origin for specific types of cancer (Barker et al. 2009; Zhu et al.
76 2016; Adams et al. 2015). Moreover, DNA damage in the genomes of ASCs is suggested to
77 contribute to the depletion of ASCs in tissues, which is one of the hallmarks of aging (López-
78 Otín et al. 2013; Rossi et al. 2008; Hoeijmakers 2009). We recently developed a protocol for
79 studying the mutational consequences of mutagen exposure or inactivation of DNA repair
80 components in non-cancerous ASCs, by combining organoid culturing technology with
81 whole-genome sequencing (WGS) (M Jager, F Blokzijl, V Sasselli, S Boymans, R Janssen,
82 N Besselink, H Clevers, R van Boxtel and E Cuppen, in press).

83 Nucleotide excision repair (NER) is one of the main cellular DNA repair pathways
84 (Iyama and Wilson 2013). Within NER, two subpathways are recognized: global-genome
85 NER (GG-NER), which repairs bulky helix-distorting lesions throughout the genome, and
86 transcription-coupled NER (TC-NER), which resolves RNA polymerase blocking lesions
87 during transcription (Iyama and Wilson 2013; Marteijn et al. 2014; Hoeijmakers 2009).
88 Identification of NER-deficient tumors has great clinical potential, as these tumors show an
89 increased response to chemotherapeutic agents inducing bulky chemical adducts, distorting
90 helical structure and disrupting base-pairing, such as cisplatin treatment (Stubbert et al.
91 2010; Amable 2016; Van Allen et al. 2014; Olaussen et al. 2006; Li et al. 2000). Somatic
92 mutations in *ERCC2*, a key factor of NER, were recently associated with Signature 5 in
93 urothelial tumors (Kim et al. 2016). However, NER has been suggested to underlie multiple
94 mutational signatures, based on large-scale tumor mutation analyses (Alexandrov et al.
95 2013). Indeed, not all NER-deficient tumors are characterized by a high Signature 5
96 contribution (Kim et al. 2016). It is, therefore, important to determine which other mutational
97 signatures present in human cancer reflect NER-deficiency.

98 To determine the mutational consequences of NER-deficiency *in vivo*, we used
99 *Ercc1*$^{-/\Delta}$ mice. ERCC1, which forms a complex with XPF, plays an essential role in the core
100 NER-reaction involving both GG-NER and TC-NER (Kirschner and Melton 2010; Iyama and
101 Wilson 2013; Sijbers et al. 1996a; Aboussekhra et al. 1995), crosslink repair (Rahn et al.
102 2010) and single strand annealing (SSA) of double strand breaks (Al-Minawi et al. 2008).
103 *ERCC1* is mutated in ~4.5% of all human tumors, especially skin and liver cancer
104 (http://dcc.icgc.org), and single nucleotide polymorphisms in *ERCC1* have been linked to an
105 increased risk of developing colorectal cancer (Ni et al. 2014). Germline mutations in *ERCC1*
106 are extremely rare and have only been observed sporadically in humans. These patients
107 develop a severe form of Cockayne syndrome, a progeroid-like disease, called cerebro-
108 oculo-facial-skeletal syndrome (COFS) (Jaspers et al. 2007; Kashiyama et al. 2013).

109 Similar to patients with deleterious mutations in *ERCC1*, *Ercc1*$^{-/\Delta}$ mice have a
110 reduced lifespan as a result of progeroid-like symptoms. *Ercc1*$^{-/\Delta}$ mice can reach a maximum

111 age of approximately 26 weeks, which is approximately five times shorter than wild-type
112 (WT) littermates (Dollé et al. 2011; Vermeij et al. 2016). *Ercc1*$^{-/\Delta}$ mice are hemizygous for a
113 single truncated *Ercc1* allele, encoding a protein lacking the last seven amino acids at the C-
114 terminus, which largely corrupts protein function (Dollé et al. 2011; Weeda et al. 1997).
115 Disruption of this domain results in reduced NER-activity (Su et al. 2012). *Ercc1*$^{-/\Delta}$ livers
116 display various aging-like characteristics and pathology such as liver lipofuscin,
117 hepatocellular senescence and cell death, and steatosis (Dollé et al. 2011; Gregg et al.
118 2012; Niedernhofer et al. 2006; Weeda et al. 1997). In contrast, other organs, such as the
119 small intestine, do not show an obvious pathological phenotype, indicating that the
120 consequences of loss of ERCC1 differ considerably between tissues, although the reason
121 for this remains unclear.

122 Here, we exploited the organoid culture system to study the mutational
123 consequences of NER-deficiency in mouse and human ASCs. We first determined the
124 mutations that are acquired *in vivo* in the genomes of single ASCs in the liver and small
125 intestine of *Ercc1*$^{-/\Delta}$ mice and WT littermates. Our results indicated that mutation
126 accumulation in *Ercc1*$^{-/\Delta}$ ASCs is predominantly a result of dysfunctional GG-NER. Next, we
127 confirmed the observed mutational consequences of GG-NER-deficiency through targeted
128 deletion of the essential GG-NER component *XPC* (Iyama and Wilson 2013) in single human
129 ASCs using the CRISPR-Cas9 gene-editing technique in human organoids.

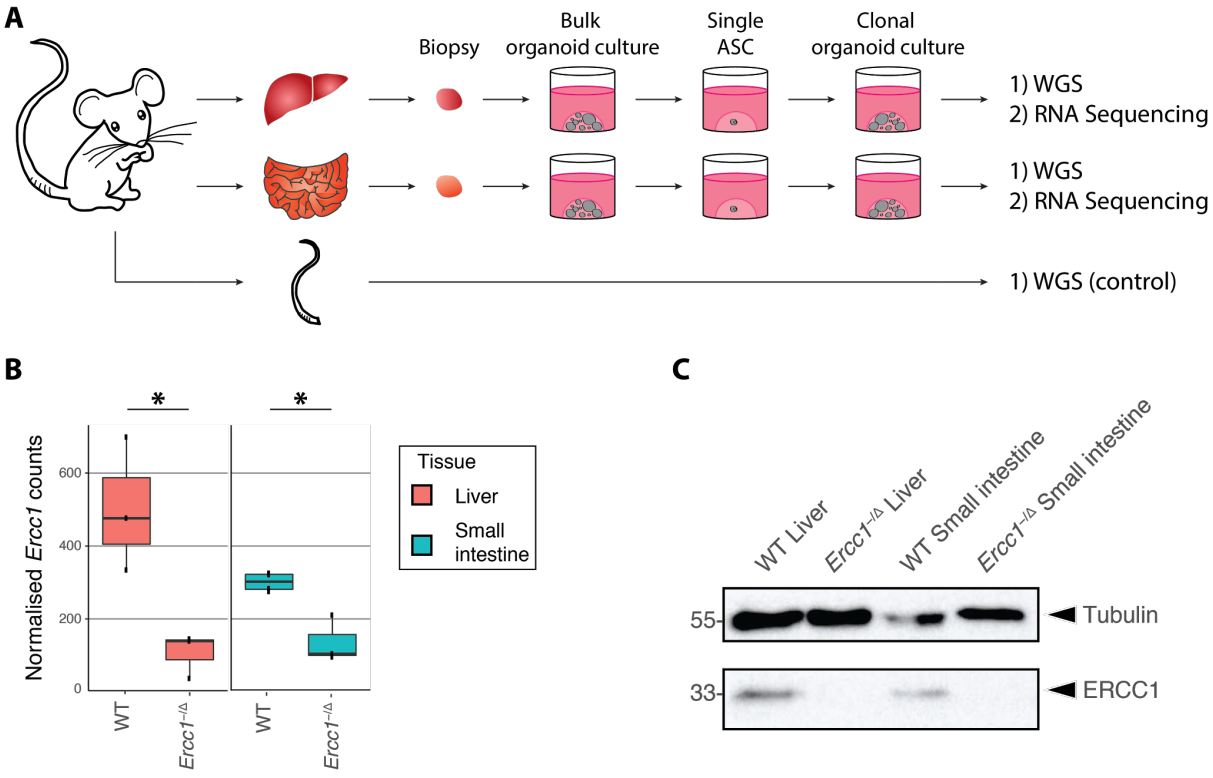
130

131 **RESULTS**

132 **Loss of NER protein ERCC1 increases point mutation load in liver, but not in small**
133 **intestinal mouse ASCs**

134 To characterize the mutational consequences of NER-deficiency, we generated clonal
135 organoid cultures from single liver and small intestinal ASCs of three 16-week-old female
136 *Ercc1*$^{-/\Delta}$ mice and three female WT littermates (Fig. 1A). The tissues were harvested at the
137 age of 16 weeks, which is the time point at which *Ercc1*$^{-/\Delta}$ mice generally start to die (Vermeij
138 et al. 2016). WGS analysis of DNA isolated from the clonal organoid cultures allows for

139 reliable determination of the somatic mutations that were present in the original ASCs and
140 accumulated during life, either in presence or absence of ERCC1 (Blokzijl et al. 2016a) (M
141 Jager, F Blokzijl, V Sasselli, S Boymans, R Janssen, N Besselink, H Clevers, R van Boxtel
142 and E Cuppen, in press). Subclonal mutations acquired after the single-cell-step will only be
143 present in a subpopulation of the cells and are filtered out based on a low allele frequency.
144 We also sequenced the genomes of polyclonal biopsies from the tail of each mouse, which
145 served as control samples to exclude germline variants.
146



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148 **Figure 1.** Experimental setup and tissue-specific expression of *Ercc1* in mouse ASCs. (A)
149 Schematic overview of the experimental setup used to determine the mutational patterns in
150 single ASCs from the liver and small intestine of mice. Biopsies from the liver and small
151 intestine of six 16-week-old female mice (three *Ercc1*$^{-/\Delta}$ mice and three WT littermates) were
152 cultured in bulk for ~1.5 week to enrich for ASCs. Subsequently, clonal organoids were
153 derived from these bulk organoid cultures and expanded for approximately 1 month, until
154 there were enough cells to perform both WGS and RNA sequencing. As a control sample for
155 filtering germline variants, a biopsy of the tail of each mouse was also subjected to WGS. (B)

156 Boxplots depicting normalized mRNA counts of *Ercc1* in ASC organoid cultures from liver
157 and small intestine of *Ercc1*$^{-/\Delta}$ mice (n = 3 and n = 3, respectively) and WT littermates (n = 3
158 and n = 4, respectively). Asterisks represent significant differences ($P < 0.05$, negative
159 binomial test). (C) Western blot analysis of ERCC1 in *Ercc1*$^{-/\Delta}$ and WT small intestinal and
160 liver mouse organoids.
161
162 To determine transcriptome profiles, we performed RNA sequencing on one clonal
163 organoid culture from each tissue of each mouse. *Ercc1* is significantly differentially
164 expressed ($P < 0.05$, negative binomial test) between WT and *Ercc1*$^{-/\Delta}$ in both liver and small
165 intestinal ASCs (Fig. 1B), confirming the anticipated effects of the *Ercc1* mutations at the
166 mRNA level. While there is some *Ercc1* expression in *Ercc1*$^{-/\Delta}$ ASCs, the C-terminal domain
167 of ERCC1 is essential in ERCC1-XPF complex formation and disruption of this interaction
168 reduces the stability of ERCC1 protein (Tripsianes et al. 2005; de Laat 1998; Sijbers et al.
169 1996b). Indeed, ERCC1 protein is not detectable by immunoblotting in *Ercc1*$^{-/\Delta}$ organoid
170 cultures of both tissues (Fig. 1C). No other DNA repair genes were differentially expressed
171 between WT and *Ercc1*$^{-/\Delta}$ ASCs (Supplemental File S1). Notably, the expression of 8 out of
172 9 core NER genes, including *Ercc1*, is higher in WT liver ASCs than WT small intestinal
173 ASCs (Supplemental Fig. S1, Supplemental Table S1).

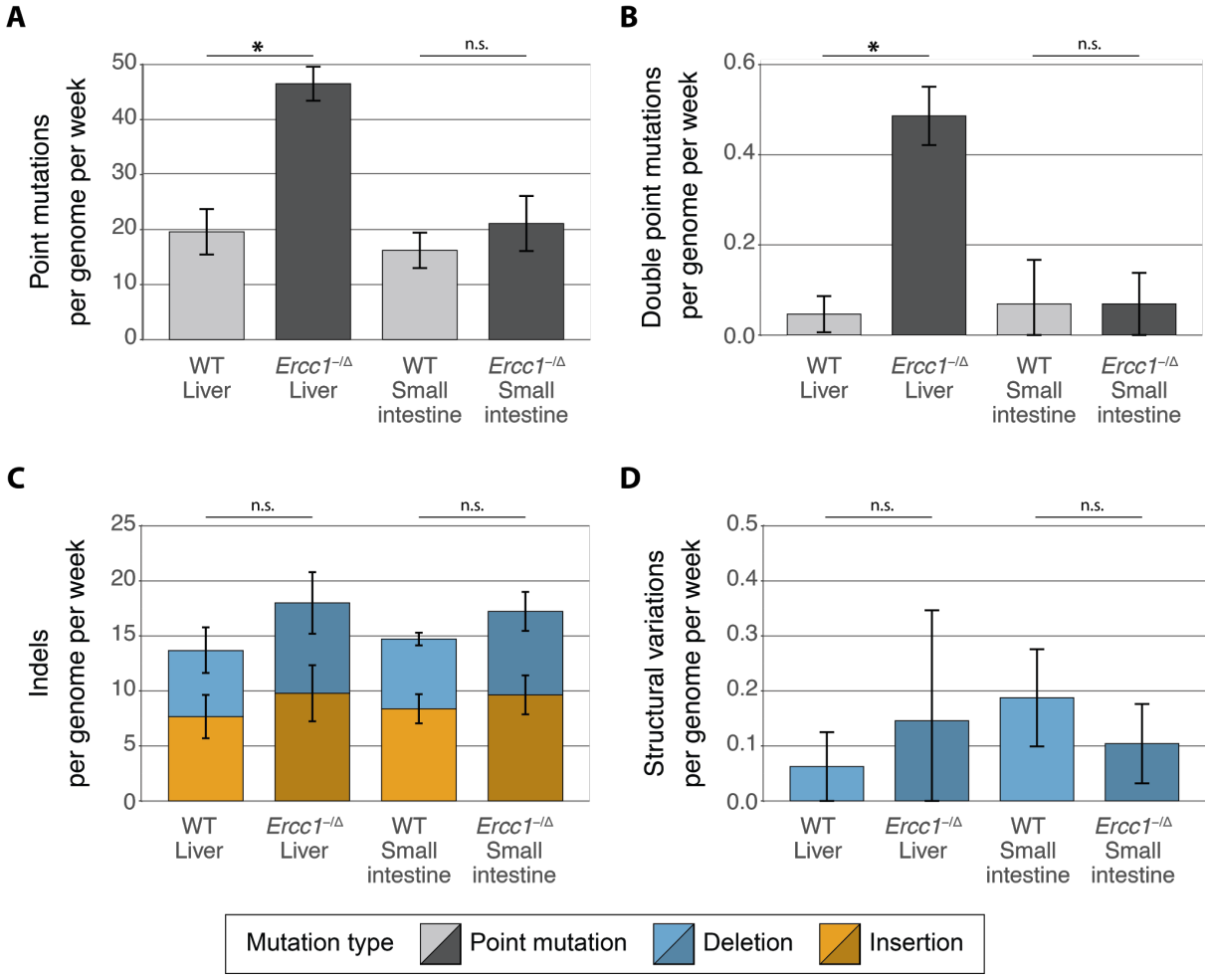


Figure 2. Somatic mutation rates in the genomes of ASCs from liver and small intestine of WT and *Ercc1*$^{-/\Delta}$ mice. (A) Point mutations, (B) double point mutations, (C) indels, and (D) SVs acquired per genome per week in ASCs of WT liver (n = 3), *Ercc1*$^{-/\Delta}$ liver (n = 3), WT small intestine (n = 2), and *Ercc1*$^{-/\Delta}$ small intestine (n = 3). Error bars represent standard deviations. Asterisks represent significant differences (q < 0.05, two-sided t-test, FDR correction). n.s. : non-significant ($q \geq 0.05$, two-sided t-test, FDR correction).

Next, we performed WGS analysis on the clonally-expanded organoid cultures (Fig. 1A). We identified 4,238 somatic point mutations in the autosomal genome of 11 clonal ASC samples. Liver ASCs of WT mice acquire 19.6 ± 4.1 (mean ± standard deviation) mutations per week. This rate is similar in ASCs of the small intestine, at 16.2 ± 3.2 mutations per week, and is in line with the observation that human liver and intestinal ASCs have similar

187 mutation accumulation rates *in vivo* (Blokzijl et al. 2016a). Loss of ERCC1 induces a twofold
188 increase (46.5 ± 3.1 point mutations per week) in the genome-wide number of point
189 mutations in ASCs in the liver (Fig. 2A, Supplemental Fig. S2A). However, we did not
190 observe a different mutation rate in small intestinal ASCs of *Ercc1*$^{-/\Delta}$ mice (21.1 ± 5.0 point
191 mutations per week) compared with WT small intestinal ASCs (Fig. 2A, Supplemental Fig.
192 S2A). We also observe a significant increase in the number of double point mutations in liver
193 ASCs lacking ERCC1 (q < 0.05, *t*-test, FDR correction; Fig. 2B, Supplemental Fig. S2B,
194 Supplemental Table S2). *Ercc1*$^{-/\Delta}$ liver ASCs acquire 0.49 ± 0.06 double point mutations per
195 week, while WT liver ASCs acquire only 0.05 ± 0.04 double point mutations per week. Again,
196 we did not observe this difference between WT and mutant ASCs of the small intestine (0.07
197 ± 0.10 and 0.07 ± 0.07 per week, respectively). The increased number of double point
198 mutations in the liver ASCs was still significant when we normalized for the total number of
199 point mutations (q < 0.05, *t*-test, FDR correction; Supplemental Fig. S2C), indicating a liver-
200 specific enrichment of double point mutations in *Ercc1*$^{-/\Delta}$ ASCs compared with WT.

201 In addition to the 4,238 point mutations, we identified 2,543 small insertions and
202 deletions (indels) and 21 larger deletions (≥100 bp) in the autosomal genome of the 11
203 clonal ASC samples. As opposed to the point mutations, we observed similar indel numbers
204 for WT and *Ercc1*$^{-/\Delta}$ ASCs of both tissues (Fig. 2C, Supplemental Fig. S2D). ASCs in the
205 small intestine and liver of the mice acquire approximately 13.7 - 18.0 indels per week,
206 independent of *Ercc1* mutation status. Likewise, loss of ERCC1 does not influence the
207 number or type of structural variations (SVs) in ASCs of the small intestine and the liver (Fig.
208 2D, Supplemental Fig. S2E, Supplemental Table S3). Each mouse ASCs carried 0 - 6
209 deletions (median length of 539 bp) after 16 weeks (Supplemental Table S3). Finally, a
210 genome-wide copy-number profile was generated to identify chromosomal gains and losses.
211 These profiles indicate that all WT and *Ercc1*$^{-/\Delta}$ ASCs were karyotypically stable during life
212 (Supplemental Fig. S3). Nevertheless, some subclonal aneuploidies were detected in a WT

213 as well as an *Ercc1*$^{-/\Delta}$ liver organoid sample, which are most likely culturing artefacts that
214 occurred *in vitro* after the clonal step irrespective of *Ercc1* mutation status.
215
216 **Loss of NER protein ERCC1 induces Signature 8 mutations in mouse ASCs**
217 To further dissect the mutational consequences of NER-deficiency, we characterized the
218 mutation spectra in the mouse ASCs. Irrespective of tissue-type, the mutation spectra of all
219 assessed ASCs are predominantly characterized by C:G > A:T mutations and C:G > T:A
220 mutations (Fig. 3A, Supplemental Fig. S4). Although the mutation spectra are highly similar
221 (Supplemental Fig. S5), we did observe some notable differences, such as an increased
222 contribution of T:A > A:T mutations in *Ercc1*$^{-/\Delta}$ ASCs compared with WT ASCs (Fig. 3A).
223 Furthermore, two subsequent nucleotides are more frequently substituted by TT or AA in
224 NER-deficient mouse ASCs (Supplemental Table S2). These results suggest that different
225 mutational processes are active in the *Ercc1*$^{-/\Delta}$ ASCs.

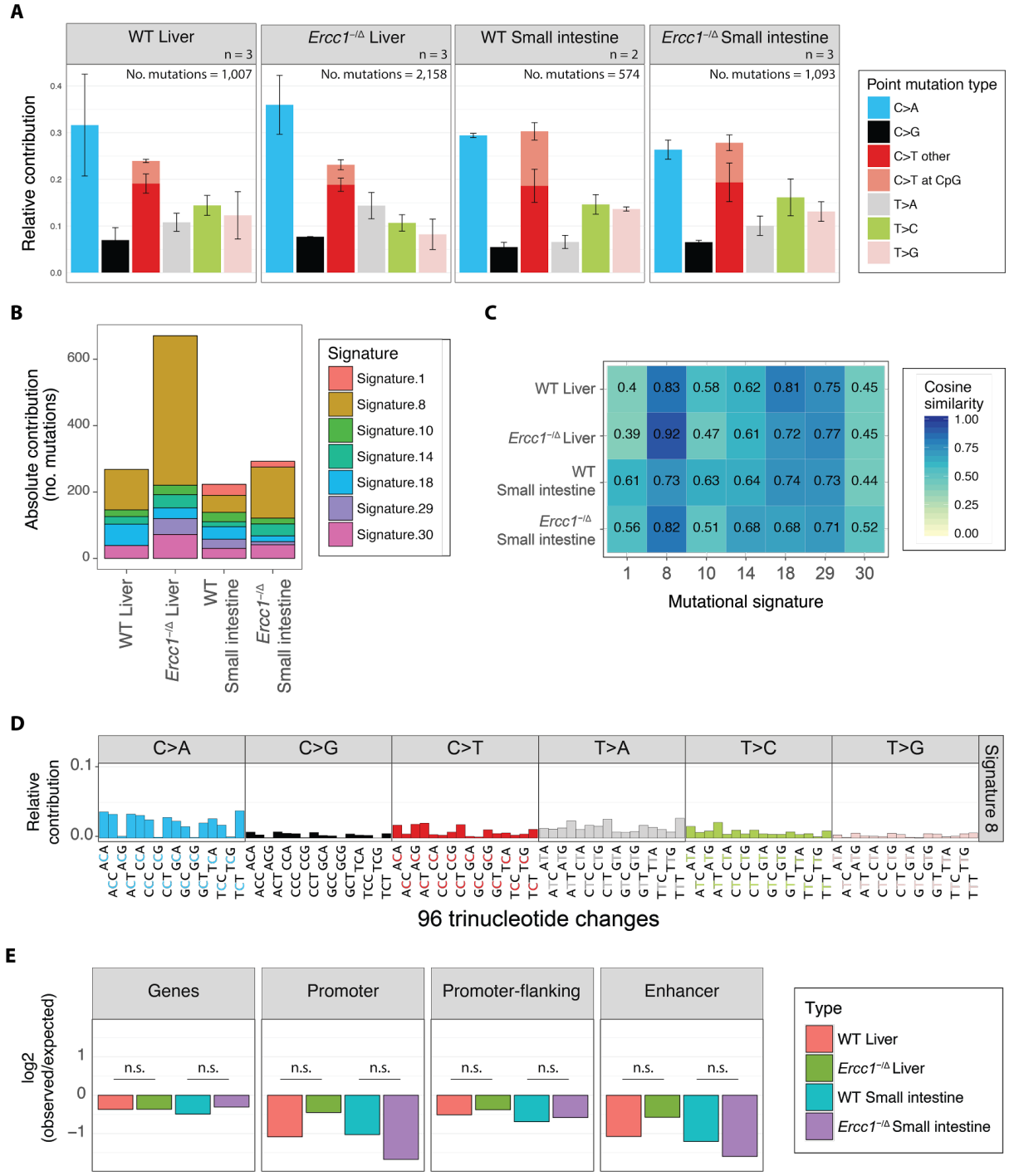
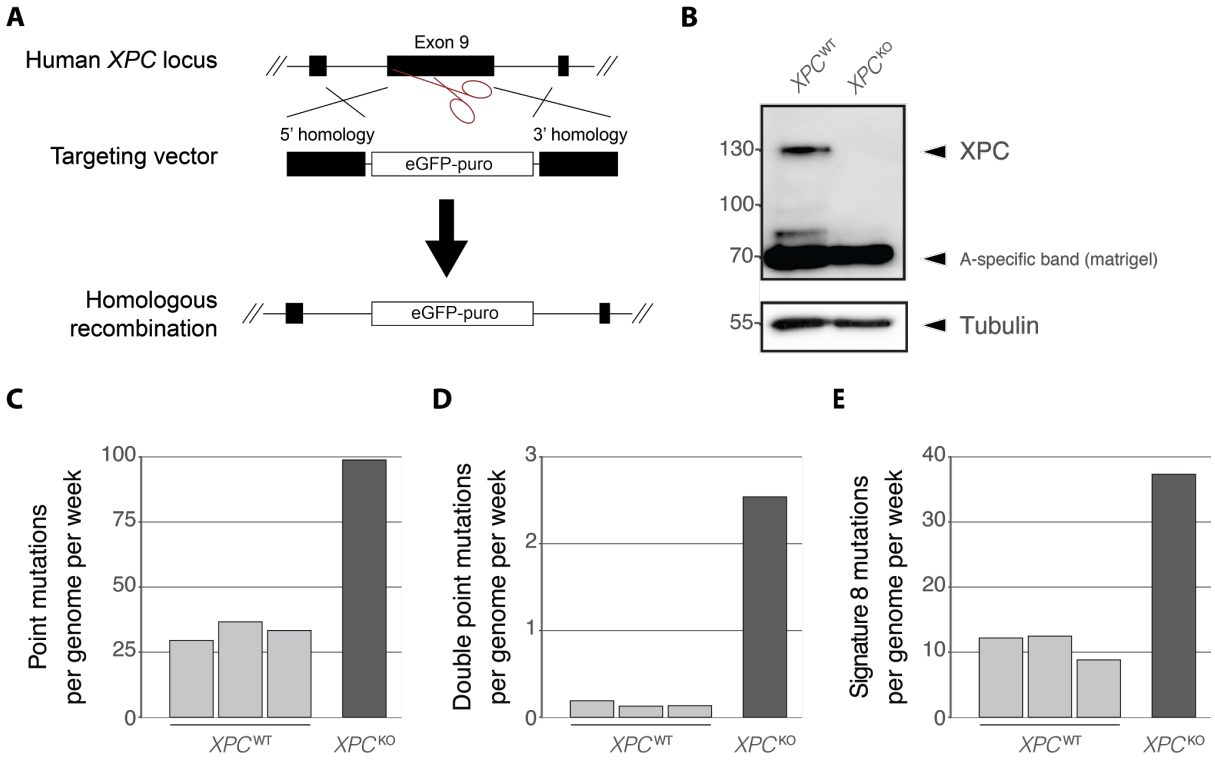


Figure 3. Mutational patterns of point mutations acquired in the genomes of ASCs from liver and small intestine of WT and *Ercc1*$^{-/\Delta}$ mice. (A) Mean relative contribution of the indicated mutation types to the mutational spectrum for each mouse ASC group. Error bars represent standard deviations. The total number of mutations, and total number of ASCs (n) per group is indicated. (B) Optimal absolute contribution of the indicated COSMIC mutational signatures per genome to reconstruct the mutational profile of each indicated mouse ASC

233 group. (C) Similarity of the mutational profiles to the COSMIC mutational signatures depicted
234 in (B). (D) Relative contribution of each indicated context-dependent point mutation type to
235 mutational Signature 8 (http://cancer.sanger.ac.uk/cosmic/signatures). (E) Depletion of
236 somatic point mutations in genes, promoters, promoter-flanking regions, and enhancers for
237 each indicated ASC group. The log2 ratio of the number of observed and expected point
238 mutations indicates the effect size of the depletion in each region.
239
240 To determine if any of the known mutational signatures is associated to NER-deficiency, we
241 assessed the contribution of each COSMIC mutational signature
242 (http://cancer.sanger.ac.uk/cosmic/signatures) to the mutational profiles of all ASCs. For this
243 analysis, we first inferred the contribution of each mutational signature and then selected
244 those with a contribution of at least 10% to the mutational profile of at least one of the four
245 ASC groups (*Ercc1*$^{-/\Delta}$ liver, *Ercc1*$^{-/\Delta}$ small intestine, WT liver, WT small intestine; Fig. 3B,
246 Supplemental Fig. S6). The mutational profiles of NER-deficient liver ASCs not only closely
247 resemble Signature 8 (cosine similarity of 0.92; Fig. 3C, Supplemental Fig. S7), but
248 Signature 8 can almost fully explain the increase in point mutations in NER-deficient liver
249 ASCs (Fig. 3B-D). The number of Signature 8 mutations is also increased in all small
250 intestinal ASCs of *Ercc1*$^{-/\Delta}$ mice compared with WT small intestinal ASCs. This result
251 suggests that NER-deficiency can cause Signature 8 mutations in ASCs, regardless of
252 tissue-type.
253 Mutations are distributed non-randomly throughout the genome in cancer cells and in
254 human ASCs (Blokzijl et al. 2016a; Schuster-Böckler and Lehner 2012). NER is one of the
255 pathways that is suggested to underlie this non-random distribution of mutations (Perera et
256 al. 2016; Zheng et al. 2014). Firstly, NER-activity has been linked to a local enrichment of
257 mutations at gene promoters (Perera et al. 2016). However, we do not observe any
258 significant differences in the depletion of mutations in promoters, promoter-flanking, and
259 enhancer regions between NER-proficient and -deficient ASCs (Fig. 3E, Supplemental Fig.
260 S8A). Secondly, TC-NER results in a depletion of mutations in expressed genes, as this

261 pathway repairs lesions on the transcribed strand during transcription (Pleasance et al.
262 2010). Mutations are indeed depleted in genic regions of NER-proficient WT mouse ASCs,
263 but the depletion is not significantly different in NER-deficient ASCs (n.s., Poisson test, FDR
264 correction; Fig. 3E, Supplemental Fig. S8A). Moreover, the average expression levels of
265 genes in which the somatic mutations are located do not differ between *Ercc1*$^{-/\Delta}$ and WT
266 ASCs (n.s., *t*-test, FDR correction; Supplemental Fig. S8B), suggesting that *Ercc1*$^{-/\Delta}$ ASCs
267 do not accumulate more mutations in expressed genes. Finally, there are no obvious
268 changes in transcriptional strand bias, although the mutation numbers are too low to be
269 conclusive (Supplemental Fig. S8C). NER-deficiency thus influences both the mutation load
270 and mutation type, but not the genomic distribution of the observed point mutations in mouse
271 ASCs, suggesting that the contribution of TC-NER in the observed mutational consequences
272 is minimal.
273
274 **Loss of GG-NER protein XPC induces Signature 8 mutations in human ASCs**
275 To confirm the causal relationship between GG-NER-deficiency and Signature 8 and double
276 point mutations, we generated a human *XPC*-knockout (*XPC*^{KO}) using CRISPR-Cas9 gene-
277 editing in a small intestinal human organoid culture (Fig. 4A). After confirming absence of
278 XPC protein (Fig. 4B), we passaged the *XPC*^{KO} clones for ± 2 months to allow the ASCs to
279 accumulate sufficient mutations required for downstream analyses. Subsequently, we
280 derived subclonal cultures of single ASCs and expanded these until sufficient DNA could be
281 isolated for WGS. This approach allowed us to catalog the mutations that specifically
282 accumulated between the two clonal expansion steps in the absence of XPC (Supplemental
283 Fig. S9A) (Blokzijl et al. 2016a; Drost et al. 2017). As a control, WGS data of three
284 previously-established *XPC*^{WT} organoid cultures of the same human donor was used.
285 Similar to the *Ercc1*$^{-/\Delta}$ mouse ASCs, loss of XPC in human ASCs induced an
286 increase in the genome-wide number of point mutations acquired per week (3-fold increase;
287 Fig. 4C, Supplemental Fig. S9B). In addition, the number of double point mutations acquired
288 per week was also increased (12-fold increase; Fig. 4D). Similar as for the *Ercc1*$^{-/\Delta}$ ASCs,

289 we did not observe a significant change in the genomic distribution of acquired mutations as
290 a result of *XPC* deletion in human ASC, nor a change in transcriptional strand bias
291 (Supplemental Fig. S9C-D). Importantly, ~39% of the increase in point mutations in the
292 XPC^{KO} ASCs can be explained by Signature 8 on average (Fig. 4E, Supplemental Fig. S9B),
293 underscoring that NER-deficiency causes Signature 8, independent of tissue-type or
294 species.
295



296

297 **Figure 4.** Mutational consequences of XPC^{KO} in human intestinal organoid cultures *in vitro*.
298 (A) Targeting strategy for the generation of XPC^{KO} organoid cultures using CRISPR-Cas9
299 gene-editing. (B) Western blot analysis of XPC in human XPC^{WT} and XPC^{KO} organoids. (C)
300 Number of point mutations, (D) double point mutations, and (E) Signature 8 mutations
301 acquired per genome per week in human XPC^{WT} ASCs (n = 3) and an XPC^{KO} ASC (n = 1) *in*
302 *vitro*.
303

304 **DISCUSSION**

305 We exploited the organoid culturing system, CRISPR-Cas9, WGS, and mutational signature
306 analyses to study the genome-wide mutational consequences of NER-deficiency in
307 individual ASCs of human and mice. Our results show that loss of ERCC1 induces a
308 significant increase in the number of both single and double point mutations in mouse liver
309 ASCs, but not in mouse small intestinal ASCs. Similarly, a LacZ reporter assay showed
310 increased point mutation frequency in livers of *Ercc1*$^{-/\Delta}$ mice (Dollé et al. 2006). Interestingly,
311 this tissue-specific mutational effect coincides with the tissue-specific pathological aging
312 phenotype observed in *Ercc1*$^{-/\Delta}$ mice (Dollé et al. 2011; Gregg et al. 2012). A possible
313 explanation for this tissue-specific effect is that liver ASCs might be more dependent on DNA
314 repair facilitated by ERCC1 compared with small intestinal ASCs, e.g. as a result of tissue-
315 specific mutagen exposure. In line with this, WT liver ASCs show a higher basal expression
316 of *Ercc1* and other NER genes than WT small intestinal ASCs. However, the transcription
317 levels of DNA repair components do not necessarily reflect DNA repair-activity, due to post-
318 transcriptional regulation (Naipal et al. 2015). Alternatively, liver and small intestinal ASCs
319 might use different mechanisms to cope with unrepaired DNA damage as a result of the loss
320 of ERCC1, such as the utilization of alternative DNA repair mechanisms, like translesion
321 synthesis (TLS) polymerases to bypass polymerase-blocking lesions, or differential induction
322 of apoptosis or senescence.

323 ERCC1 is involved in multiple DNA repair pathways, including TC-NER, GG-NER,
324 SSA, and crosslink repair. Previously, it has been shown that SSA- and crosslink repair-
325 deficiencies result in increased number of indels and SVs in mice, whereas NER-deficiency
326 introduces point mutations (Dollé et al. 2006). Since we only observe an increase in point
327 mutations, NER-deficiency is likely responsible for the mutational consequences of loss of
328 ERCC1 in mouse liver ASCs. If TC-NER-deficiency underlies the mutation accumulation, this
329 would be reflected by an increase in mutations in expressed genes in *Ercc1*$^{-/\Delta}$ mice.
330 However, in both WT and *Ercc1*$^{-/\Delta}$ cells a depletion of mutations is observed in genes, and
331 the expression levels of genes in which the somatic mutations are located do not differ
332 between NER-proficient and -deficient ASCs, suggesting that the observed mutational

333 consequences of impaired ERCC1 is rather an effect of defective GG-NER. We
334 independently confirmed that GG-NER-deficiency induces an increase in both single and
335 double point mutations, by cataloguing mutations that are acquired in a human small
336 intestinal organoid culture that is deleted for GG-NER component *XPC* by CRISPR-Cas9
337 gene-editing. More specifically, the majority of the increase in point mutations can be
338 explained by an increase in Signature 8 in both systems, suggesting that perturbations of
339 GG-NER result in the accumulation of Signature 8 in both mouse and human ASCs.

340 Until now, the etiology of Signature 8 was unknown
341 (http://cancer.sanger.ac.uk/cosmic/signatures). Signature 8 is characterized by C:G > A:T
342 point mutations and is associated with double point mutations (Alexandrov et al. 2013; Nik-
343 Zainal et al. 2016). C:G > A:T mutations have been linked to several processes, including
344 oxidative stress (Kamiya et al. 1995; Degtyareva et al. 2013). Interestingly, NER has been
345 suggested to play a role in the repair of tandem DNA lesions that result from oxidative stress
346 (Bergeron et al. 2010; Cadet et al. 2012). If left unrepaired, these lesions can block regular
347 DNA polymerases, but can be bypassed by error-prone TLS polymerases, resulting in
348 increased mutation incorporation (Cadet et al. 2012). Moreover, it has been shown that
349 oxidative stress results in increased induction of double point mutations in NER-deficient
350 human fibroblasts (Lee 2002). Similarly, UV- and smoking-induced tandem DNA lesions
351 have been linked to NER and double point mutation rates, but these mutagens are unlikely
352 to affect the genomes of ASCs in liver and small intestine (Helleday et al. 2014). Taken
353 together, an increase in double point and Signature 8 mutations could thus reflect mutation
354 incorporation as a result of oxidative damage in NER-deficient cells.

355 In human urothelial cancer, somatic mutations in *ERCC2*, a key factor in both TC-
356 NER and GG-NER, have been associated with a high contribution of mutational Signature 5
357 (Kim et al. 2016; Iyama and Wilson 2013). However, we did not observe an increase
358 Signature 5 contribution in ASCs without ERCC1 or XPC. This difference in mutational
359 consequences could reflect various differences between these systems, such as different
360 effects of the mutations on protein function, distinct roles of the proteins, or tumor- and/or

361 tissue-specific activity of mutagenic damage and/or DNA repair processes. In our study, we
362 deleted specific NER components in an otherwise normal genetic background, providing us
363 with the unique opportunity to characterize the direct mutational consequences of NER-
364 deficiency.

365 Determination of the NER-capacity of tumors can be important for precision
366 medicine, as it has been shown that tumors with mutations in NER genes (Stubbert et al.
367 2010; Van Allen et al. 2014; Amable 2016; Zhang et al. 2017), and tumors with low
368 expression of *ERCC1* (Olaussen et al. 2006; Li et al. 2000; Amable 2016) are sensitive to
369 cisplatin treatment. However, translation of these findings into the clinical setting has been
370 challenging, because connecting tumor biopsy mRNA levels and immunohistochemistry
371 measurements to NER-activity remains an unresolved issue (Bowden 2014), and
372 interpreting the effects of mutations in DNA repair genes on NER-capacity is challenging.
373 Rather than looking for the presence of causal events, mutational catalogs can be used as a
374 functional readout of NER-capacity in tumors. Here, we show that GG-NER-deficiency
375 specifically induces Signature 8 and double point mutations in both mouse and human
376 ASCs. Signature 8 has an overall prevalence of 2% in sequenced human tumors, is found in
377 medulloblastoma (Alexandrov et al. 2013) and contributes to the mutational profile of the
378 majority of, but not all, breast cancer tumors (Nik-Zainal et al. 2016; Alexandrov et al. 2013).
379 We propose that an elevated contribution of Signature 8 in combination with double point
380 mutations might serve as a novel biomarker for GG-NER-deficiency and has the potential to
381 guide treatment decision. Additional studies are required to demonstrate the predictive value
382 of these mutations for treatment response.

383

384 **METHODS**

385 **Mouse tissue material**

386 *Ercc1*$^{-/\Delta}$ mice were generated and maintained as previously described (Vermeij et al., 2016).
387 Briefly, by crossing *Ercc1*$^{\Delta/+}$ (C57BL6J or FVB background) with *Ercc1*$^{+/-}$ mice (FVB or

388 C57BL6J background), *Ercc1*$^{-/\Delta}$ mice were generated in a uniform F1 C57BL6J/FVB hybrid
389 background. Wild type F1 littermates were used as controls. Animals were housed in
390 individual ventilated cages under specific pathogen-free conditions in a controlled
391 environment (20–22 °C, 12 h light : 12 h dark cycle). Experiments were performed in
392 accordance with the Principles of Laboratory Animal Care and with the guidelines approved
393 by the Dutch Ethical Committee in full accordance with European legislation.
394 We used three 16-week old female *Ercc1*$^{-/\Delta}$ mice and three female WT littermates for
395 our experiments. Tails were harvested and stored at -20°C. Livers and small intestines were
396 harvested and kept on ice in Adv+++ medium (Advanced DMEM/F-12 with 1% GlutaMAX,
397 HEPES 10 mM and 1% penicillin/streptomycin) for a few hours until further processing.
398
399 **Human tissue material**
400 Endoscopic biopsies were performed at the University Medical Center Utrecht and the
401 Wilhelmina Children's Hospital. The patients' informed consent was obtained and this study
402 was approved by the ethical committee of University Medical Center Utrecht.
403
404 **Generation of clonal *Ercc1*$^{-/\Delta}$ and WT mouse organoid cultures**
405 Single liver ASCs were isolated from livers as described previously (Kuijk et al. 2016). Liver
406 organoid cultures were initiated by culturing the liver ASCs in BME overlaid with mouse liver
407 culture initiation medium (50% Adv+++ medium, 35% WNT3A conditioned medium
408 (produced in house), 5% NOGGIN conditioned medium (produced in house), 5% RSPOI
409 conditioned medium (produced in house), 1x B27 without retinoic acid, 1x N2, 1x Primocin,
410 10mM Nicotinamide, 0.625mM N-acetylcysteine, 100ng/ml FGF-10, 10μM ROCKi, 50 ng/ml
411 HGF, 10nM Gastrin, and 50ng/ml hEGF). 1.5 week after culture initiation, clonal organoid
412 liver cultures were generated and expanded according to protocol (M Jager, F Blokzijl, V
413 Sasselli, S Boymans, R Janssen, N Besselink, H Clevers, R van Boxtel and E Cuppen, in
414 press) in mouse liver expansion medium (90% Adv+++ medium, 5% RSPOI conditioned
415 medium (produced in house), 1x B27 without retinoic acid, 1x N2, 1x Primocin, 10mM

416 Nicotinamide, 0.625mM N-acetylcysteine, 100ng/ml FGF-10, 50 ng/ml HGF, 10nM Gastrin,
417 and 50ng/ml hEGF).
418 Crypts were isolated from small intestines as described previously (Sato et al. 2009).
419 Small intestinal organoid cultures were initiated by culturing the small intestinal ASCs in
420 matrigel overlaid with mouse small intestine medium (50% WNT3A conditioned medium
421 (produced in house), 30% Adv+++ medium, 10% NOGGIN conditioned medium (produced in
422 house), 10% RSPOI conditioned medium (produced in house), 1x B27, 1x hES Cell Cloning
423 & Recovery Supplement, 1x Primocin, 10µM ROCKi, 1.25mM N-acetylcysteine, and 50ng/ml
424 hEGF). Clonal small intestinal organoid cultures were generated by picking single organoids
425 manually and clonally expanding these organoid cultures according to protocol in mouse
426 small intestine medium (M Jager, F Blokzijl, V Sasselli, S Boymans, R Janssen, N Besselink,
427 H Clevers, R van Boxtel and E Cuppen, in press). Culture expansion failed for the small
428 intestine of mouse WT1.
429
430 **Generation of a clonal and subclonal *XPC*^{KO} organoid culture**
431 Clonal *XPC*^{KO} organoid cultures were generated froma small intestinal bulk organoid culture
432 derived previously (Blokzijl et al. 2016a) using the CRISPR-Cas9 gene-editing technique as
433 described in (Drost et al. 2017). One clonal human *XPC*^{KO} organoid culture was obtained
434 and cultured for 72 days in human small intestinal organoid medium (50% WNT3A
435 conditioned medium (produced in house), 30% Adv+++ medium, 20% RSPOI conditioned
436 medium (produced in house), 1x B27, 1x Primocin, 1.25mM N-acetylcysteine, 0.5µM A83-
437 01, 10µM SB202190, 100ng/ml recombinant Noggin, and 50ng/ml hEGF). Subsequently, a
438 subclonal culture was derived according to protocol (M Jager, F Blokzijl, V Sasselli, S
439 Boymans, R Janssen, N Besselink, H Clevers, R van Boxtel and E Cuppen, in press).
440
441 **Western blot**
442 Protein samples from mouse organoid cultures were collected in Laemmli buffer and
443 measured using the Qubit^{tm} 3.0 Fluorometer (Thermo Fisher Scientific) with the Qubit^{tm}

444 Protein Assay Kit (Thermo Fisher Scientific, Q33211). Protein samples from human organoid
445 cultures were collected in Laemmli buffer and measured using a Lowry protein assay. 30µg
446 of protein per sample was run on a 10% SDS page gel. Subsequently, the proteins were
447 transferred to a nitrocellulose membrane. After transfer, the membrane was blocked for 1
448 hour using 5% ELK (Campina) at room temperature and subsequently incubated overnight
449 with the primary antibody (ERCC1: Abcam, ab129267; XPC: Cell Signaling Technology;
450 #12701). Secondary antibody was incubated 1 hour at room temperature, and subsequently
451 proteins were visualized using the Amersham ECL Western blotting analysis system (GE
452 Healthcare, RPN2109) and the Amersham Imager 600 system (GE Healthcare).
453
454 **RNA sequencing and differential expression analysis of *Ercc1*$^{-/\Delta}$ and WT mouse**
455 **organoid cultures**
456 For each mouse (three *Ercc1*$^{-/\Delta}$ mice and three WT littermates), we performed RNA
457 sequencing on one clonal organoid culture from the liver and the small intestine. An
458 additional small intestinal organoid clone was sequenced of mice WT2 and WT3 to increase
459 the amount of replicates for differential expression analysis, as culture expansion failed for
460 the small intestine of WT1. Total RNA was collected in TRIzol and purified from all organoid
461 cultures using the Qiasymphony (Qiagen). RNA libraries for Illumina sequencing were
462 generated from 50 ng of poly-A selected mRNA using the Neoprep (Illumina) and sequenced
463 2 x 75 bp paired-end to approximately 3300 Million base pairs per sample with the Illumina
464 NextSeq 500 at the Utrecht Sequencing Facility.
465 RNA sequencing reads were mapped with STAR v.2.4.2a to the mouse reference
466 genome GRCm38. The BAM files were sorted with Sambamba v0.5.8 and reads were
467 counted with HTSeq-count version 0.6.1p1 (default settings) to exons as defined in
468 GRCm38v70.gtf (Ensembl). Non-uniquely mapped reads were not counted. Subsequently,
469 DESeq v1.28.0 was used to normalize counts. DESeq nbinomTest was used to test for
470 differential expression (1) of *Ercc1* between *Ercc1*$^{-/\Delta}$ and WT liver ASCs, (2) of *Ercc1*
471 between *Ercc1*$^{-/\Delta}$ and WT small intestinal ASCs, (3) of 83 other DNA repair genes (Casorelli

472 et al. 2006) between *Ercc1*$^{-/\Delta}$ and WT liver ASCs, and (4) between *Ercc1*$^{-/\Delta}$ and WT small
473 intestinal ASCs, and (5) of 9 NER genes between the WT liver and WT small intestinal
474 ASCs. Differentially expressed genes with an adjusted P-value $q < 0.05$ (Benjamini-
475 Hochberg FDR multiple-testing correction) were considered significant.
476
477 **WGS and read alignment**
478 DNA was isolated from mouse liver organoid cultures and mouse control (tail) samples using
479 the genomic tip 20-G kit (Qiagen) and from mouse small intestinal organoid samples and the
480 human *XPC*^{KO} sample using the Qiasymphony (Qiagen). DNA libraries for Illumina
481 sequencing were generated from 200 ng genomic DNA using standard protocols (Illumina)
482 and sequenced 2 x 100 bp paired-end to 30X base coverage with the Illumina HiSeq Xten at
483 the Hartwig Medical Foundation. The sequence reads of *XPC*^{KO} were mapped to the
484 GRCh37 human reference genome using using the Burrows–Wheeler Aligner (BWA) v0.7.5a
485 (Li and Durbin 2009), with settings '-t 4 -c 100 -M'. The mapped data of clonal *XPC*^{WT}
486 organoids was previously generated in the study ('donor_id' 6) (Blokzijl et al. 2016a). The
487 sequence reads of the mouse ASCs were mapped to the GRCm38 mouse reference
488 genome using using the Burrows–Wheeler Aligner (BWA) v0.7.5a (Li and Durbin 2009), with
489 settings '-t 4 -c 100 -M'. The WGS data of the tails confirmed that the *Ercc1*$^{-/\Delta}$mice have
490 compound heterozygous mutations in *Ercc1* and the WT littermates do not (Supplemental
491 Fig. S10).
492
493 **Callable genome**
494 The callable genome was defined for all sequenced samples using the GATK CallableLoci
495 tool v3.4.46 (Van der Auwera et al. 2013) with default settings and additional optional
496 parameters 'minBaseQuality 10', 'minMappingQuality 10',
497 'maxFractionOfReadsWithLowMAPQ 20', and 'minDepth 20'. 'CALLABLE' regions were
498 extracted from every output file. Subsequently, genomic regions that were callable (1) in the
499 mouse organoid clone and the control (tail) sample, and (2) in the human organoid clone,

500 subclone, and control (blood) were intersected to define a genomic region that is surveyed in
501 all samples that were compared. Approximately 90 ± 1% of the autosomal genome was
502 surveyed in every mouse clone, and 73 - 88% of the autosomal genome was surveyed in
503 each human subclone (Supplemental Table S4).
504
505 **Point mutation and indel calling**
506 For both human and mouse samples, point mutations and indels were multi-sample called
507 with GATK HaplotypeCaller v3.4.46 with default settings and additional options '-
508 stand_call_conf 30 -stand_emit_conf 15' and GATK Queue v3.4.46. For mouse samples the
509 quality of the calls was assessed using GATK VariantFiltration v3.4.46 with options 'QD <
510 2.0, MQ < 40.0, FS > 60.0, HaplotypeScore > 13.0, MQRankSum < -12.5,
511 ReadPosRankSum < -8.0' for point mutations and 'QD < 2.0, FS > 200.0,
512 ReadPosRankSum < -20.0' for indels, with additional options 'clusterSize 3' and
513 'clusterWindowSize 35'. For human samples the quality of the calls was assessed using
514 GATK VariantFiltration v3.4.46 with options 'QD < 2.0, MQ < 40.0, FS > 60.0,
515 HaplotypeScore > 13.0, MQRankSum < -12.5, ReadPosRankSum < -8.0, MQ0 >= 4 &&
516 ((MQ0 / (1.0 * DP)) > 0.1), DP < 5, QUAL < 30, QUAL >= 30.0 && QUAL < 50.0, SOR > 4.0'
517 for point mutations and 'QD < 2.0, FS > 200.0, ReadPosRankSum < -20.0, MQ0 >= 4 &&
518 ((MQ0 / (1.0 * DP)) > 0.1), DP < 5, QUAL < 30.0, QUAL >= 30.0 && QUAL < 50.0, SOR >
519 10.0' for indels, with additional options 'clusterSize 3' and 'clusterWindowSize 10.
520
521 **Point mutation filtering**
522 To obtain high-quality catalogs of somatic point mutations, we applied a comprehensive
523 filtering procedure. For the mouse samples, we only considered positions on the autosomal
524 genome that were callable (see "Callable genome") in both the organoid and control (tail)
525 sample. We excluded positions at which indels were called, as these positions likely
526 represent false-positive point mutation calls. Furthermore, we only included positions with a

527 'PASS' flag by GATK VariantFiltration, a GATK phred-scaled quality score ≥ 100, a sample-
528 level genotype quality of 99 in the organoid culture and ≥ 10 in the control (tail) sample, and
529 a coverage of ≥ 20X in the organoid and the tail sample. We subsequently excluded variants
530 with any evidence in another organoid sample or control (tail) sample of the same mouse to
531 remove germline variants. To exclude potentially missed germline events, we also removed
532 positions that have any evidence in the organoid and/or control samples of the other mice.
533 Finally, we excluded positions with a variant allele frequency (VAF) < 0.3 in the organoid
534 sample to exclude mutations that were induced after the clonal step.

535 For the human samples, we only considered positions on the autosomal genome that
536 were callable (see "Callable genome") in the control (blood) sample, clonal organoid and
537 subclonal organoid culture. We considered mutations with a 'PASS' flag by GATK
538 VariantFiltration and a GATK phred-scaled quality score ≥ 100. For both the clonal and
539 subclonal organoid cultures, all variants with evidence in the control (blood) sample were
540 excluded, to remove germline variants. To exclude potentially missed germline events, we
541 removed positions that are in the Single Nucleotide Polymorphism Database v137.b3730, or
542 in a blacklist with positions that are recurrent in unmatched individuals (BED-file available
543 upon request). Subsequently, for both the clonal and subclonal cultures, all variants with a
544 VAF < 0.3 were excluded. Finally, the resulting somatic point mutation catalogs of the clonal
545 and subclonal cultures were compared and all events unique to the subclonal organoid were
546 considered to be accumulated after the *XPC* deletion, that is: between the two sequential
547 clonal expansion steps.

548

549 **Clonality of organoid cultures**

550 We validated whether the organoid samples were clonal based on the VAF of somatic point
551 mutations, before the final filter step (VAF < 0.3). Each cell acquires its own set of somatic

552 mutations and the reads supporting a mutation will be diluted in the WGS data of non-clonal
553 samples, resulting in a low VAF. After extensive filtering of somatic point mutations, liver
554 organoid samples from WT1, WT2, and *Ercc1*$^{-/\Delta}$2 showed a shift in the VAK-peak away from
555 0.5 and therefore these samples were excluded from further analyses (Supplemental Fig.
556 S11). An additional liver organoid culture from these mice was sequenced and these
557 samples were confirmed to be clonal (Supplemental Fig. S11).
558
559 **Double point mutations**
560 We selected point mutations from the filtered variant call format (VCF) files that were called
561 on consecutive bases in the mouse or human reference genome. The double point
562 mutations were subsequently manually checked in the Integrative Genomics Viewer (IGV) to
563 exclude double point mutations present in the control sample, and/or with many point
564 mutations or indels in the region, as these are (likely) false positives.
565
566 **Indel filtration of *Ercc1*$^{-/\Delta}$ and WT mouse organoid cultures**
567 We only considered positions on the autosomal genome that were callable (see "Callable
568 genome") and had a sequencing depth of ≥ 20X in both the organoid sample and the control
569 (tail) sample. We excluded positions that overlap with a point mutation. Furthermore, we only
570 considered positions with a filter 'PASS' from VariantFiltration, a GATK phred-scaled quality
571 score > 250 and a sample-level genotype quality of 99 in both the organoid sample and the
572 control (tail) sample. We subsequently excluded Indels that are located within 50 base pairs
573 of an indel called in another organoid sample and indels with any evidence in another
574 organoid sample or a control (tail) sample. Finally, we excluded positions with a VAF < 0.3 in
575 the organoid sample.
576
577 **SV calling and filtration of *Ercc1*$^{-/\Delta}$ and WT mouse organoid cultures**

578 SVs were called with DELLY v0.7.2 with settings 'type DEL DUP INV TRA INS', 'map-qual
579 1', 'mad-cutoff 9', 'min-flank 13', and 'geno-qual 5' (Rausch et al. 2012). We only considered
580 SVs of at least 100 bp on the autosomal chromosomes that were called with a filter 'PASS',
581 and a sample-specific genotype quality of at least 90 in the organoid culture and the control
582 sample. We subsequently excluded positions with any evidence in the control (tail) sample.
583 The filtered SVs were finally checked manually in IGV to reduce false-positives and we
584 excluded SVs present in the tail sample, with no visible change in the read-depth (for
585 duplications and deletions), and/or with many point mutations in the region.
586
587 **Genome-wide copy number profiles of *Ercc1*$^{-/\Delta}$ and WT mouse organoid cultures**
588 To generate a virtual karyotype, genome-wide copy number states were determined using
589 FreeC v7.2 with settings 'ploidy 2', 'window 1000' and 'telocentromeric 50000' (Boeva et al.
590 2012). Subsequently, the average copy number across bins of 500,000 bp was calculated
591 and plotted to assess genome stability.
592
593 **Quantification of the contribution of COSMIC mutational signatures to the mutational**
594 **profiles**
595 We retrieved the point mutation types from all the filtered VCF files, converted them to the 6
596 types of point mutations that are distinguished by convention and generated a mutational
597 spectrum for four ASC groups (*Ercc1*$^{-/\Delta}$ liver, *Ercc1*$^{-/\Delta}$ small intestine, WT liver, and WT small
598 intestine), as well as *XPC*^{KO}, *XPC*^{WT}1, *XPC*^{WT}2, and *XPC*^{WT}3 ASCs. We retrieved the
599 sequence context for all point mutations to generate the mutational profiles with 96 point
600 mutation types. Subsequently, we estimated the contribution of the 30 COSMIC mutational
601 signatures (http://cancer.sanger.ac.uk/cosmic/signatures) to the retrieved mutational profiles.
602 This function determines the non-negative linear combination of signatures that best
603 reconstructs each mutational profile, by minimizing the Euclidean norm of the residual. Next,
604 we selected signatures with a contribution of at least 10% to the mutational profile of at least
605 one of the four ASC groups (Supplemental Fig. S6), and re-estimated the contribution of

606 these 7 signatures to the mutational profiles of the four ASC groups (Fig. 3B). Furthermore,
607 we calculated the cosine similarity of the 7 signatures to the mutational profiles of each of
608 the four ASC groups (Fig 3C). All mutational pattern analyses were performed with
609 MutationalPatterns (Blokzijl et al. 2016b).
610
611 **Enrichment or depletion of point mutations in genomic regions**
612 To test whether the point mutations appear more or less frequently than expected in genes,
613 promoters, promoter-flanking, and enhancer regions, we loaded the UCSC Known Genes
614 tables as TxDb objects for Mm10 (Team BC and Maintainer 2016) and Hg19 (Carlson and
615 Maintainer 2015), and the regulatory features for Mm10 and Hg19 from Ensembl using
616 biomaRt (Durinck et al. 2005, 2009). We tested for enrichment or depletion of point
617 mutations in the genomic regions per ASC group (*Ercc1*$^{-/\Delta}$ liver, *Ercc1*$^{-/\Delta}$ small intestine, WT
618 liver, WT small intestine, *XPC*^{KO} and *XPC*^{WT}) using a one-sided Binomial test with
619 MutationalPatterns (Blokzijl et al. 2016b), which corrects for the surveyed genomic areas
620 (Supplemental Fig. S8A, Supplemental Fig. S9C). Two-sided Poisson tests were performed
621 to test for significant differences in the ratio of point mutations within a genomic region
622 divided by the total number of point mutations between (1) mouse WT and *Ercc1*$^{-/\Delta}$ liver
623 ASCs, (2) mouse WT and *Ercc1*$^{-/\Delta}$ small intestinal ASCs, and (3) human *XPC*^{KO} and human
624 *XPC*^{WT} ASCs (Fig. 3E, Supplemental Fig. S8A, Supplemental Fig. S9C). Within species,
625 differences in mutation rates with an adjusted P-value $q < 0.05$ (Benjamini-Hochberg FDR
626 multiple-testing correction) were considered significant.
627 To test whether point mutations occur more frequently in more highly expressed
628 genes in the NER-deficient mouse ASCs, we first selected point mutations that occurred
629 within genes in the mouse ASCs. Per ASC group, we next determined the average Reads
630 Per Kilobase per Million mapped reads (RPKM) of these genes. Two-sided *t*-tests were
631 performed to test for significant difference in the average expression of genes that carry a
632 somatic mutation between (1) mouse WT and *Ercc1*$^{-/\Delta}$ liver ASCs, and (2) mouse WT and
633 *Ercc1*$^{-/\Delta}$ small intestinal ASCs (Supplemental Fig. S8B). Differences in gene expression

634 distributions with an adjusted P-value $q < 0.05$ (Benjamini-Hochberg FDR multiple-testing
635 correction) were considered significant.
636
637 **Transcriptional strand bias of point mutations**
638 For the point mutations within genes we determined whether the mutations are located on
639 the transcribed or the non-transcribed strand. To this end, we determined whether the
640 mutated "C" or "T" base is on the same strand as the gene definition, which is untranscribed,
641 or the opposite strand, which is transcribed. We generated a mutational profile per ASC
642 group with the relative contribution of each mutation type with separate bars for the
643 mutations on the transcribed and untranscribed strand, and calculated the significance of the
644 strand bias using a two-sided Poisson test with MutationalPatterns (Supplemental Fig. S8C,
645 Supplemental Fig. S9D) (Blokzijl et al. 2016b). Furthermore, we performed two-sided
646 Poisson tests to test whether there is a significant difference in strand bias per mutation type
647 between (1) mouse WT and *Ercc1*$^{-/\Delta}$ liver ASCs, (2) mouse WT and *Ercc1*$^{-/\Delta}$ small intestinal
648 ASCs, and (3) human *XPC*^{KO} and human *XPC*^{WT} ASCs (Supplemental Fig. S8C,
649 Supplemental Fig. S9D). Within species, differences in strand bias with an adjusted P-value
650 $q < 0.05$ (Benjamini-Hochberg FDR multiple-testing correction) were considered significant.
651
652 **Calculation and comparison of mutation rates**
653 To calculate the mutation rates per genome per week, we quantified the number of somatic
654 point mutations, double nucleotide mutations, indels, and SVs for each mouse ASC.
655 Moreover, we quantified the number of point mutations, double nucleotide mutations, and
656 Signature 8 mutations for the human ASCs. All event counts were extrapolated to the entire
657 autosomal genome using the callable genome length (see" Callable genome") for both
658 mouse and human ASCs to correct for differences in the surveyed genome (Supplemental
659 Table S4). Subsequently, the mutation rates were calculated by dividing the extrapolated
660 number of mutations by the number of weeks in which the mutations were accumulated (WT
661 and *Ercc1*$^{-/\Delta}$ mouse organoids: 16 weeks; *XPC*^{WT} human organoids: 20.6 weeks; *XPC*^{KO}

662 human organoids 10.3 weeks). Two-tailed *t*-tests were performed to determine whether the
663 mutation rates differ significantly between (1) mouse WT and *Ercc1*$^{-/\Delta}$ liver ASCs, and (2)
664 mouse WT and *Ercc1*$^{-/\Delta}$ small intestinal ASCs. Differences in mutation rates between *Ercc1*$^{-}$
665 $^{/\Delta}$ and WT mouse ASCs with an adjusted P-value $q < 0.05$ (Benjamini-Hochberg FDR
666 multiple-testing correction) were considered significant. To determine the proportion of
667 additionally accumulated mutations in the *XPC*^{KO} culture that can be attributed to Signature 8
668 in human ASCs, we first calculated the increase in point mutations and the increase in
669 Signature 8 mutations of *XPC*^{KO} compared to *XPC*^{WT}1, *XPC*^{WT}2, and *XPC*^{WT}3 separately. We
670 then divided the increase in Signature 8 mutations by the total increase in point mutations.
671

672 **DATA ACCESS**

673 The sequencing data of the mouse samples have been deposited at the European
674 Nucleotide Archive under accession number ERP021379. The sequencing data of the
675 human samples have been deposited at the European Genome-Phenome archive under
676 accession numbers EGAS00001001682 and EGAS00001002681.
677

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684

685 **AUTHOR CONTRIBUTIONS**

686 M.J., E.K., M.V., N.B., and R.B. performed organoid culture. N.B. and R.B. generated
687 western blots and sequenced the organoid cultures. M.J., F.B., R.J., S.B., J.L., and R.B.
688 performed bioinformatic analyses. M.J., F.B., E.K., J.H., J.P., R.B., and E.C. were involved in
689 the conceptual design of this study. M.J., F.B., R.B., and E.C. wrote the manuscript.

690

691 **DISCLOSURE DECLARATION**

692 The authors have nothing to disclose.

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