Identification of a Nervous System Gene Expression Signature in Colon Cancer Stem Cells Reveals a Role for Neural Crest Regulators *EGR2* and *SOX2* in Tumorigenesis

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31

32 **SUMMARY**

33 Recent data support a hierarchical model of colon cancer driven by a population of cancer
34 stem cells (CSCs). Greater understanding of the mechanisms that regulate CSCs may
35 therefore lead to more effective treatments. Serial limiting dilution xenotransplantation
36 assays of colon cancer patient-derived tumors demonstrated ALDH^{Positive} cells to be
37 enriched for tumorigenic self-renewing CSCs. In order to identify CSC modulators, we
38 performed RNA-sequencing analysis of ALDH^{Positive} CSCs from a panel of colon cancer
39 patient-derived organoids (PDOs) and xenografts (PDXs). These studies demonstrated
40 CSCs to be enriched for embryonic and neural development gene sets. Functional
41 analyses of genes differentially expressed in both ALDH^{Positive} PDO and PDX CSCs
42 demonstrated the neural crest stem cell (NCSC) regulator and wound response gene
43 *EGR2* to be required for CSC tumorigenicity and to control expression of homeobox
44 superfamily embryonic master transcriptional regulator *HOX* genes and the embryonic
45 and neural stem cell regulator *SOX2*. In addition, we identify *EGR2*, *HOXA2*, *HOXA4*,

46 *HOXA5*, *HOXA7*, *HOXB2*, *HOXB3* and the tumor suppressor *ATOH1* as new prognostic
47 biomarkers in colorectal cancer.
48
49 **INTRODUCTION**
50 Colorectal cancer (CRC), the third most common cancer and fourth most common cause
51 of cancer deaths worldwide[1], is a heterogeneous tumor driven by a subpopulation of
52 CSCs, that may also be the source of relapse following treatment[2–5]. Elucidation of the
53 mechanisms that regulate CSC survival and tumorgenicity may therefore lead to novel
54 treatments and improved patient outcomes.
55
56 CSCs are undifferentiated cancer cells that share many of the attributes of stem cells,
57 such as multipotency, self-renewal and the ability to produce daughter cells that
58 differentiate[2,6,7]. Stem cells are controlled by core gene networks that include the
59 embryonic master transcriptional regulator *HOX* genes[8,9] and *SOX2*[10], whose
60 misregulation can result in aberrant stem cell function, developmental defects and
61 cancer[11,12]. These genes are crucial for embryonic development and their expression is
62 maintained in adult tissue stem cells, where they regulate self-renewal and
63 differentiation[9,13–15]. *HOX* genes and *SOX2* are aberrantly expressed in several cancers,
64 including CRC, and emerging evidence demonstrates their involvement in the
65 transformation of tissue stem cells into CSCs[11,16–23]. Modulation of *HOX* genes and *SOX2*
66 could therefore provide novel therapeutic strategies to block tumorigenesis and overcome
67 therapy resistance in CRC and other CSC driven cancers.
68

69 During embryonic development of the neural crest, which gives rise to the peripheral
70 nervous system (PNS) and several non-neuronal cell types[24], *HOX* and *SOX* genes are
71 regulated by retinoic acid[25,26], a product of the normal tissue stem cell and CSC marker
72 aldehyde dehydrogenase (*ALDH1A1, ALDH1A2, ALDH1A3*)[8,26–29], and by the neural
73 crest stem cell (NCSC) zinc finger transcription factor and wound response gene *EGR2*
74 (*KROX20*)[30–41].
75
76 Here we carried out whole transcriptome analysis of functionally tested ALDH^{Positive} CSCs
77 from a panel of colon PDOs and PDX models and show that colon CSCs and Lgr5^{Positive}
78 intestinal stem cells (ISCs) are highly enriched for nervous system development and
79 neural crest genes. Furthermore, we demonstrate that the neural crest stem cell (NCSC)
80 gene *EGR*2 is a marker of poor prognosis in CRC and modulates expression of *HOX*
81 genes and *SOX2* in CSCs to regulate tumorigenicity and differentiation.
82

83 **RESULTS**

84 **Colon cancer PDOs are heterogeneous and enriched for ALDH^{Positive} self-renewing**
85 **CSCs**

86 Colon cancer PDO models were established from freshly isolated primary tumors and
87 metastases from colon cancer patients (Table S1) by embedding in growth-factor reduced
88 Matrigel and cultivating in serum free media, as previously described[42–44].
89 Immunostaining of PDOs for the structural proteins EZRIN and EPCAM demonstrated
90 that PDOs retain the apical-basal polarity and structural adhesion of the normal intestine
91 (Figure 1A). Immunostaining of PDOs and equivalent PDX models for stem cell regulator

92 Wnt signaling protein BETA-CATENIN demonstrated differences in nuclear localization
93 of BETA-CATENIN and confirmed previous data demonstrating heterogeneous Wnt
94 signaling activity within the tumors[43] (Figure 1B). Increased aldehyde dehydrogenase
95 (ALDH) activity, as measured using the Aldefluor™ assay, is a marker of CSCs in colon
96 cancer and many other cancer types[29]. We previously carried out limiting dilution serial
97 xenotransplantation of $ALDH^{Negative}$ and $ALDH^{Positive}$ cells and demonstrated that colon
98 CSCs are $ALDH^{Positive}$ and enriched for Wnt signaling activity[43]. However, $ALDH^{Negative}$
99 cells also gave rise to tumors when transplanted at higher cell numbers. In order to
100 determine if $ALDH^{Negative}$ and $ALDH^{Positive}$ cells maintained their self-renewal and
101 tumorigenic capacity, we performed additional rounds of limiting dilution serial
102 xenotransplantation of $ALDH^{Negative}$ and $ALDH^{Positive}$ cells (Figure 1E). These data
103 confirmed that PDOs are enriched for $ALDH^{Positive}$ cells compared to equivalent PDX
104 models (Figure 1C and D) and that $ALDH^{Positive}$ CSCs self-renew to maintain their
105 tumorigenic capacity over extended rounds of xenotransplantation, but that $ALDH^{Negative}$
106 cells do not (Figure 1E).
107

108 **Colon CSCs are enriched for embryonic and nervous system development gene**
109 **expression signatures**

110 In order to identify modulators of colon CSCs, $ALDH^{Negative}$ cells and $ALDH^{Positive}$ CSCs
111 were isolated from PDO and PDX models and subjected to whole transcriptome analysis
112 by RNA-sequencing. *ALDH1A1* is a marker of poor prognosis in several cancer
113 types[27,29,45–49] and has been reported to be responsible for the aldehyde dehydrogenase
114 activity that defines the $ALDH^{Positive}$ cell fraction in the Aldefluor™ assay[50]. However,

115 nineteen different isoforms of ALDH exist and several of these, including *ALDH1A2*,
116 *ALDH1A3* and *ALDH2* have also been reported to be involved in the Aldefluor™ assay[51–
117 53]. Here we show that *ALDH1A1* expression is enriched in ALDH^{Positive} CSCs compared
118 to ALDH^{Negative} cells (Figure 2A and S1). GSEA of ALDH^{Positive} and ALDH^{Negative} cells
119 isolated from PDO and PDX models demonstrated that ALDH^{Positive} CSCs are enriched
120 for nervous system development, TNFα via NFκB signaling, epithelial mesenchymal
121 transition (EMT), embryonic development and Wnt signaling transcripts (Figure 2B).
122
123 Differential gene expression analysis identified 218 genes upregulated in PDOs and 250
124 genes upregulated in PDX models compared to ALDH^{Negative} cells. Of these, 30 genes
125 were found to be differentially expressed in both ALDH^{Positive} PDO and PDX cells (Figure
126 2C). Interestingly, many of these differentially expressed and common PDO-PDX genes
127 are expressed during embryogenesis and have a role in neural crest cell (NCC) and
128 central nervous system (CNS) development. Of these 30 common genes (Figure S2) 10,
129 *ALDH1A1*[50], *EGR2*[31,38,41,54–60], *EGR3*[56,58,61–66], *HDGFRP3*[67–72], *OLFM2*[73–76],
130 *OLFML3*[75,77,78], *PCP4*[79–82], *PEG10*[83–91], *PRKACB*[92,93], and *THBS1*[94–99], were selected for
131 functional analysis based on their tissue expression and roles in development and cancer
132 (Figure 2D, S2 and S3).
133

134 **_EGR2_ is required for colon CSC survival in non-adherent cell culture**

135 The ability of CSCs to survive and form spheroids in non-adherent cell culture is the gold
136 standard assay for the assessment of normal stem cells and CSCs *in vitro*[100,101]. In order
137 to test 10 of the differentially expressed genes common to ALDH^{Positive} PDO-PDX models,

138 cells were transfected with siRNAs against *ALDH1A1, EGR2, EGR3, HDGFRP3, OLFM2,*
139 *OLFML3, PCP4, PEG10, PRKACB* and *THBS1* (Figure 3B), serially plated at limiting
140 dilution into low-attachment plates and assessed for spheroid formation. siRNA *EGR2*
141 caused a significant decrease in spheroid formation and proliferation in all models (Figure
142 3A, C and D). Immunostaining of PDO, PDX and clinical samples demonstrated *EGR2* to
143 be ubiquitously expressed, with increased cytoplasmic and nuclear expression in cancer
144 compared to normal mucosa (Figure S4).
145

146 **shRNA EGR2 cells are less tumorigenic, more differentiated and have decreased**
147 **expression of *HOX* genes and *SOX2***

148 Limiting dilution xenotransplantation of control virus transduced and shRNA EGR2
149 transduced 195-CB-P cells was carried out to determine if *EGR2* regulates tumorigenesis
150 *in vivo*. Control virus transduced cells generated xenografts at each cell dilution tested
151 but shRNA EGR2 transduced cells were significantly impaired in their ability to generate
152 tumors when transplanted at low cell number (Figure 3E). In addition, shRNA EGR2
153 tumors grew more slowly than control transduced cells (Figure 3F). These data
154 demonstrate that loss of *EGR2* in CSCs significantly decreased their tumorigenic
155 capacity. Quantitative RT-PCR analysis of three shRNA EGR2 tumors confirmed that the
156 shRNA EGR2 knockdown was present (Figure 3G). Significantly, expression of
157 proliferation (*MKI67, MYC*), intestinal stem cell genes (*ALCAM, ALDH1A1, BMI1, EPHA4,*
158 *EPHB2, LRIG1, OLFM4, PROM1*) and Wnt signaling genes (*AXIN2, CTNNB1, LGR5,*
159 *RUNX2*) were decreased, while the expression of differentiation markers, including the
160 tumor suppressor and Wnt signaling target *ATOH1*, were strongly increased (Figure 3G).

161 Interestingly, *ATOH1* is also essential for neuronal differentiation during embryonic
162 development[102–109].
163
164 During embryogenesis *EGR2* has a conserved role in regulating embryonic master
165 transcriptional regulator HOX genes and the stem cell regulator *SOX2*[30–32,34–41]. In
166 addition, several HOX genes and *SOX2* have recently been shown to be enriched in and
167 to regulate colon CSCs[17–20,23]. We therefore investigated whether these genes were
168 similarly regulated by *EGR2* in colon PDX tumors. Notably, we found that *SOX2* and
169 several *HOX* genes, namely *HOXA2*, *HOXA4*, *HOXA5*, *HOXA7*, *HOXB2*, *HOXB3* and
170 *HOXD10*, were downregulated in shRNA EGR2 tumors (Figure 3G).
171
172 ***EGR2, ATOH1, HOXA2, HOXA4, HOXA5, HOXA7, HOXB2* and *HOXB3* are predictors**
173 **of patient outcome in colorectal cancer**
174 To characterize *EGR2, ATOH1, HOXA2, HOXA4, HOXA5, HOXA7, HOXB2, HOXB3*
175 *HOXD10* and *SOX2* expression in clinical samples, we analyzed expression across
176 different colorectal tumor stages (Figure 4A). These data demonstrated that *EGR2* (p-
177 value 0.027), *HOXA2* (p-value 0.026), *HOXA4* (p-value 0.000075) *HOXA5* (p-value
178 0.001), *HOXA7* (p-value 0.009), *HOXB3* (p-value 0.0016) and HOXD10 (p-value 0.043)
179 expression are more enhanced in late stage T4 clinical tumors. Of these, *HOXA4*,
180 *HOXA5*, *HOXA7*, and *HOXB3* are significant at FDR < 5%. Analysis of Kaplan-Meier
181 survival curves showed that patients with higher *EGR2, HOXA2, HOXA4, HOXA5,*
182 *HOXA7, HOXB2 and HOXB3* expression have a poorer clinical outcome (p-values
183 0.00017, 0.0028, 0.0006, 0.0043, 0.0022, 0.00025 and 0.019, respectively). Of these,

184 higher *EGR2*, *HOXA2*, *HOXA4*, *HOXA5* and *HOXA7* are significant at FDR < 5%.
185 Furthermore, these data demonstrated that high levels of *ATOH1* are predictive of good
186 prognosis (p-value 0.0013). These data support *ATOH1*, *EGR2* and its target genes
187 *HOXA2, HOXA4, HOXA5, HOXA7 and HOXB3* as potential new biomarkers for CRC
188 prognosis.
189

190 **DISCUSSION**

191 We previously demonstrated that colon cancer PDOs are enriched for CSCs and
192 preserve the functional and molecular heterogeneity found *in vivo*, thus making them
193 excellent models for the study of CSCs[43]. However, the defined conditions of the PDO
194 culture media results in reduced cell type diversity[42]. Conversely, the *in vivo* environment
195 promotes differentiation and reduces CSCs to a minority population. Therefore, in order
196 to identify genes that regulate CSC survival and differentiation we carried out whole
197 transcriptome analyses of functionally defined $ALDH^{Negative}$ cells and $ALDH^{Positive}$ CSCs
198 from colon cancer PDO and PDX models and performed functional analyses of genes
199 differentially expressed and common to $ALDH^{Positive}$ CSCs from both models.
200

201 Interestingly, these analyses revealed transcripts associated with nervous system
202 development and NCSCs to be highly enriched in both PDO and PDX CSCs. Recent
203 studies have demonstrated that solid tumors, including CRC, contain nerve fibers that
204 promote tumor growth and metastasis, indeed, neurogenesis in CRC is an independent
205 indicator of poor clinical outcome[110,111], but their origin and mechanism of innervation is
206 unknown[112–117].

207

208 A growing body of evidence has demonstrated a gut-neural axis[118–123] in which various
209 intestinal cells, including stem cells, interact with the autonomic nervous system (ANS),
210 either directly[124–130] or via the enteric nervous system (ENS)[131–133], a network of neurons
211 and glia within the bowel wall that regulates most aspects of intestinal function[134], to
212 control stem cell proliferation and differentiation[135,136]. For example, ISCs express ANS-
213 associated alpha2A adrenoreceptor (Adra2a) and acetylcholine (ACh) receptors
214 implicated in controlling intestinal epithelial proliferation[130,137–140]. In addition,
215 differentiated cell types, such as intestinal enterochromaffin (EC) cells have been found
216 to be electrically excitable and modulate serotonin-sensitive primary afferent nerve fibers
217 via synaptic connections, enabling them to detect and transduce environmental,
218 metabolic, and homeostatic information from the gut directly to the nervous system[141].
219 Recent studies have also demonstrated that enteroendocrine cells form neuroepithelial
220 circuits by directly synapsing with vagal neurons and called for a renaming of these cells
221 from enteroendocrine to neuropod cells[129,142]. Neuropod cells and EC cells, like all
222 differentiated intestinal cells (enteroendocrine, enterocyte, goblet, paneth) and CSCs,
223 derive from multipotent Lgr5^{Positive} crypt stem cells[143,144]. Significantly, colorectal CSCs
224 themselves have been shown to be capable of generating neurons when transplanted
225 intraperitoneally in nude mice[145]. Intestinal stem cells and CSCs should therefore possess
226 the capacity to express nervous system genes, since they are the progenitors of cells with
227 neural function. However, until now, no previous study had directly reported nervous
228 system gene enrichment in ISCs or CSCs.

229

230 We therefore carried out gene ontology analysis of Lgr5^{Positive} crypt stem cell
231 transcriptomes from earlier studies[146–148]. In agreement with our CSC data (Figure 2), this
232 analysis revealed normal ISCs to also be enriched for nervous system genes (Figure S5).
233 In addition, the PDOs showed ubiquitous staining for the epithelial cell marker EPCAM
234 (Figure 1A), demonstrating that they do not contain a separate non-epithelial neural cell
235 lineage that could be the origin of the nervous system gene expression. Overall, these
236 data suggest that CSCs may be a source of the neural connections that interact with the
237 ANS and peripheral nervous system (PNS) to drive tumor growth and metastasis[112–116].
238 Denervation of the ANS and PNS, which causes loss of autonomic neurotransmitters in
239 the gut, results in loss of crypt stem cell proliferation and suppression of tumorigenesis[124–
240 128,131,132,149–151]. The inhibition of nervous system gene transcription in CSCs and their
241 progeny may therefore provide a novel therapeutic strategy in colorectal cancer, with
242 results similar to denervation[149,150,152].
243
244 During embryonic development, the PNS, of which the ENS is a part, arises from NCSCs,
245 multipotent and highly migratory stem cells that move throughout the embryo to colonize
246 multiple organ primordia and differentiate into numerous cell types[24,153–155]. Recently, self-
247 renewing NCSCs have been discovered in post-natal tissue[156–160], including the adult
248 gut[161,162], although the degree to which these cells contribute to the adult tissue is not yet
249 known.
250
251 *EGR2* is a conserved regulator and marker of NCSCs that acts upstream of several *HOX*
252 genes and *SOX2* to control cell fate in embryonic and nervous system stem cells[30–41].

253 Interestingly, its expression is also rapidly activated after wounding in the embryonic and
254 adult mouse[33], suggesting a role in adult tissue stem cells, which contribute to tissue
255 regeneration and wound repair[163]. However, no previous study has identified a role for
256 *EGR2* in CRC. Here, we demonstrate that *EGR2* is enriched in colon CSCs and is
257 required for tumorigenicity and to maintain CSCs in an undifferentiated state by regulating
258 *HOX* genes and *SOX2*.
259
260 *SOX2* is one of the early genes activated in the developing neural crest and has a broad
261 role as a transcriptional regulator in embryonic and adult stem cells[15,164–169]. In embryonic
262 and adult neural stem cells, it is required for the maintenance of neural stem cell
263 properties, including proliferation, survival, self-renewal and neurogenesis[170–174]. In the
264 intestine, its expression results in cell fate conversion and redirects the intestinal
265 epithelium to a more undifferentiated phenotype[175–177]. In addition, *SOX2* has been
266 associated with a stem cell state in several cancer types[178–180] and is aberrantly
267 expressed in CRC[176,181,182]. Overall, these data, combined with our own, support a role
268 for *SOX2* in CRC tumor initiation and progression, possible by promoting neural
269 specification in CSCs and their descendants.
270
271 *HOX* genes have been reported to be enriched in and required for the maintenance of
272 normal stem cells and CSCs in various adult tissues[11,13,16,183–189]. Recently, *HOXA4,*
273 *HOXA9* and *HOXD10* were shown to be selectively expressed in ALDH^{Positive} intestinal
274 crypt stem cells and colon CSCs, to promote self-renewal and regulate expression of
275 stem cell markers[17,18]. Here, we demonstrate that the same *HOX* genes that are regulated

276 by *EGR2* in NCSCs are also regulated by *EGR2* in colon CSCs and that several of these,
277 *HOXA2*, *HOXA4*, *HOXA5*, *HOXA7*, *HOXB2*, *HOXB3*, along with *EGR2*, are indicators of
278 poor prognosis in CRC.
279
280 These data demonstrate that colon CSCs are enriched for neural crest and nervous
281 system development genes, including the NCSC regulator *EGR2*, which controls *SOX2*
282 and *HOX* genes to maintain CSCs in an undifferentiated state required for tumorigenesis.
283 Targeting *EGR2* to induce differentiation and block potential intestinal-neural cell
284 specification, e.g. by downregulating the neural stem cell regulator SOX2, may offer a
285 novel therapeutic strategy to eliminate colon CSCs and prevent nervous system driven
286 proliferation and metastasis.
287
288 **EXPERIMENTAL PROCEDURES**
289
290 **Human tissue samples and establishment of patient-derived cancer organoid cell**
291 **cultures**
292 Tumor material was obtained with informed consent from CRC patients under approval
293 from the local Institutional Review Board of Charité University Medicine (Charité Ethics
294 Cie: Charitéplatz 1, 10117 Berlin, Germany) (EA 1/069/11) and the ethics committee of
295 the Medical University of Graz and the ethics committee of the St John of God Hospital
296 Graz (23-015 ex 10/11). Tumor staging was carried out by experienced and board-
297 certified pathologists (Table S1). Cancer organoid cultures were established and
298 propagated as described[42,44].

299

300 **Limiting dilution xenotransplantation**

301 Housing and handling of animals followed European and German Guidelines for
302 Laboratory Animal Welfare. Animal experiments were conducted in accordance with
303 animal welfare law, approved by local authorities, and in accordance with the ethical
304 guidelines of Bayer AG. PDO derived PDX models were processed to single cells and
305 sorted by FACS (BD FACS Aria II) for ALDH activity (Aldefluor assay) and DAPI to
306 exclude dead cells. Cells were then re-transplanted at limiting dilutions by injected
307 subcutaneously in PBS and Matrigel (1:1 ratio) at limiting cell dilutions into female 8 – 10-
308 week-old nude$^{-/-}$ mice.

309

310 **Histology and immunohistochemistry**

311 Tumors were fixed in 4% paraformaldehyde overnight for routine histological analysis and
312 immunohistochemistry. Immunohistochemistry was carried out via standard techniques
313 with non-phospho (Active) β-Catenin (#8814, rabbit monoclonal, Cell Signaling
314 Technology; diluted 1:200) and EGR2 (ab43020, Abcam, rabbit IgG, polyclonal, diluted
315 1:1000) antibodies. Negative controls were performed using the same protocols with
316 substitution of the primary antibody with IgG-matched controls (ab172730, rabbit IgG,
317 monoclonal [EPR25A], Abcam). Colorectal cancer tissue microarrays from the
318 OncoTrack patient cohort[44] were obtained from The Institute of Pathology, Medical
319 University Graz, Austria and analyzed using Aperio TMALab and Image software (Leica
320 Biosystems).

321

322 **Immunofluorescence staining of PDOs**

323 For immunofluorescence imaging, cancer organoid cultures were fixed in 4%
324 paraformaldehyde for 30 min at room temperature and permeabilized with 0.1% Triton X-
325 100 for 30 min and blocked in phosphate-buffered saline (PBS) with 10% bovine serum
326 albumin (BSA). Samples were incubated with primary antibodies overnight at 4°C.
327 Antibodies used were Non-phospho (Active) β-Catenin (#8814, rabbit monoclonal, Cell
328 Signaling Technology; diluted 1:200), EZRIN (ab40839, rabbit monoclonal, Abcam,
329 diluted 1:200), EPCAM (#2929, mouse monoclonal, Cell Signaling Technology, diluted
330 1:500) and EGR2 (ab43020, rabbit polyclonal, Abcam, diluted 1:1000). Samples were
331 stained with a conjugated secondary antibody overnight at 4°C. F-actin was stained with
332 Alexa Fluor® 647 Phalloidin (#A22287, Thermo Fisher; diluted 1:20) for 30 min at room
333 temperature. Nuclei were counterstained with DAPI. Negative controls were performed
334 using the same protocol with substitution of the primary antibody with IgG-matched
335 controls. Cancer organoids were then transferred to microscope slides for examination
336 using a Zeiss LSM 700 Laser Scanning Microscope.

337

338 **Aldefluor Assay**

339 Organoids and xenografts were processed to single cells and labelled using the Aldefluor
340 Assay according to manufacturer's (Stemcell Technologies) instructions. ALDH levels
341 were assessed by FACS on a BD LSR II analyzer.

342

343 **RNA Sequencing**

344 Cells were lysed in RLT buffer and processed for RNA using the RNeasy Mini Plus RNA
345 extraction kit (Qiagen). Samples were processed using Illumina's TrueSeq RNA protocol
346 and sequenced on an Illumina HiSeq 2500 machine as 2x125nt paired-end reads. The
347 raw data in Fastq format were checked for sample quality using our internal NGS QC
348 pipeline. Reads were mapped to the human reference genome (assembly hg19) using
349 the STAR aligner (version 2.4.2a). Total read counts per gene were computed using the
350 program "featureCounts" (version 1.4.6-p2) in the "subread" package, with the gene
351 annotation taken from Gencode (version 19). The "DESeq2" Bioconductor package was
352 used for the differential-expression analysis.
353

354 **siRNA transfection**

355 Cells were seeded in 100 µl volumes of Accell™ Delivery Media (Dharmacon™) at 1.0 x
356 10^5 cells per well in ultra-low attachment 96-well plates and transfected with 2 µM
357 concentrations of Accell™ siRNAs (Table S2) and control siRNA (Accell™ non-targeting
358 siRNA control) (Dharmacon™) by incubating for up to 72 h in Accell siRNA Delivery
359 Media.
360

361 **Viral transduction**

362 Cells were seeded in 100 µl volumes of antibiotic free culture media at 1.0 x10^5 cells per
363 well in ultra-low attachment 96-well plates. Control and shRNA lentiviruses were
364 purchased from Sigma-Aldrich (Table S3). Viral particles were added at a multiplicity of
365 infection of 1. Cells were transduced for up to 96 h or until GFP positive cells were

366 observed before being embedded in Matrigel for the establishment of lentiviral transduced
367 cancer organoid cultures. Puromycin (2 µg/ml) was used to keep the cells under selection.
368

369 **Limiting dilution spheroid assays**

370 For siRNA spheroid assays, transfected live ($DAPI^{Negative}$) cells were sorted at 10 cells per
371 well into 96-well ultra-low attachment plates. 20 days later wells containing spheroids
372 were counted and used to calculate CSC frequency using ELDA software. Proliferation
373 was measured using the CellTiter-Glo® Luminescent Cell Viability Assay.
374

375 **Gene expression analysis**

376 For quantitative real-time RT-PCR analysis RNA was isolated using the RNeasy Mini Plus
377 RNA extraction kit (Qiagen). cDNA synthesis was carried out using a Sensiscript RT kit
378 (Qiagen). RNA was transcribed into cDNA using an oligo dTn primer (Promega) per
379 reaction. Gene expression analysis was performed using TaqMan® Gene Expression
380 Assays (Applied Biosystems) (Table S4) on an ABI Prism 7900HT sequence detection
381 system (Applied Biosystems). GAPDH was used as an endogenous control and results
382 were calculated using the Δ-ΔCt method. Data were expressed as the mean fold gene
383 expression difference in three independently isolated cell preparations over a comparator
384 sample with 95% confidence intervals. Pairwise comparison of gene expression was
385 performed using R[190] together with package ggplot2[191] on log2 transformed RNAseq data
386 from 533 patients with clinical data (n=378 colon adenocarcinomas, n=155 rectal
387 carcinomas staged T1-T4) extracted from the cBioPortal for Cancer Genomics
388 (cbioportal.org)[192,193]. Survival curves were generated using the Kaplan-Meier Plotter

389 (www.kmplot.com/analysis)[194]. Gene ontology enrichment analysis was carried out using
390 the Gene Ontology Resource (www.geneontology.org)[195,196].
391

392 **Statistical analysis**

393 GraphPad Prism 6.0 was used for data analysis and imaging. All data are presented as
394 the means ± SD, followed by determining significant differences using the two-tailed t test.
395 Significance of RT-PCR data was determined by inspection of error bars as described by
396 Cumming *et al*. (2007)[197]. Limiting-dilution frequency and probability estimates were
397 analyzed by the single-hit Poisson model and pairwise tests for differences in stem cell
398 frequencies using the ELDA software (http://bioinf.wehi.edu.au/software/elda/index.html,
399 Hu and Smyth, 2009)[198]. Gene set enrichment analysis was carried out using pre-ranked
400 feature of the Broad Institute GSEA software version 2 using msigdb v5.1 gene sets[199,200].
401 The ranking list was derived from the fold changes (1.5fold upregulated) calculated from
402 the differential gene expression calculation and nominal p-values. P-values <0.05 were
403 considered as statistically significant. For the final list of significant genes, False
404 Discovery Rate was computed using the Benjamini-Hochberg method[201].
405

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Authors Contribution

Conceptualization, J.L.R.; Methodology, J.L.R. and M.L.; Investigation, J.L.R., D.S., S.S., A.S., R.L., J.T., T.J., J.H., N.G.-S., and M.L.; Writing, J.L.R.; Visualization, J.L.R; Data Curation, A.S., J.T.; Resources, J.H., U.K., C.R.A.R. and B.G.; Supervision, J.L.R., D.M., D.H., R.S., and M.L.

Accession Numbers

Array data are available in the ArrayExpress database (www.ebi.ac.uk/arrayexpress) under accession numbers E-MTAB-5209 and E-MTAB-8927.

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934

935 **FIGURE LEGENDS**

936

937 **Figure 1. Colon cancer PDOs are heterogeneous and enriched for self-renewing**
938 **ALDH^{Positive} CSCs**

939 (A) Immunofluorescence staining of colon cancer PDOs for EZRIN (green) and EPCAM
940 (red). Nuclei are stained blue with DAPI (Bars = 20 μm). (B) Immunofluorescence staining

941 of a PDO for BETA-CATENIN (green) and F-ACTIN (red) (left hand side) and
942 immunostaining of a PDX model for BETA-CATENIN (right hand side) (Bars = 20 μm).
943 (C) Representative Aldefluor Assay FACS plots of cells derived from PDO model 195-
944 CB-P (data from 10 independent experiments). DEAB (diethylaminobenzaldehyde) is a
945 specific inhibitor of ALDH and is used to control for background fluorescence. (D)
946 Frequency (±SD) of $ALDH^{Positive}$ cells in PDOs and corresponding PDX models (data from
947 10 independent experiments). (E) Tables show results of two rounds of limiting dilution
948 serial xenotransplantation of $ALDH^{Positive}$ and $ALDH^{Negative}$ cells from previously
949 established PDO derived xenograft models. The number of successfully established
950 tumors as a fraction of the number of animals transplanted is given. P-values for pairwise
951 tests of differences in CSC frequencies between $ALDH^{Positive}$ versus $ALDH^{Negative}$ cells in
952 151-ML-M, 278-ML-P, 302-CB-M and 195-CB-P in serial transplant round one tumors are
953 1.12×10^{-4}, 1.37×10^{-1}, 8.39×10^{-14} and 2.92×10^{-17} respectively and in 278-ML-P, 302-
954 CB-M and 195-CB-P serial transplant round two tumors are 3.82×10^{-7}. 3.67×10^{-22} and
955 3.78×10^{-15}, respectively. (See also Figure S1 and Table S1).
956

957 **Figure 2. PDO and PDX $ALDH^{Positive}$ CSCs are enriched for nervous system**
958 **development gene sets and neural crest stem cell genes**

959 (A) RNA sequencing generated FPKM values for ALDH1A1 (n = 3 separate cell
960 preparations). (B) Gene set enrichment analysis for nervous system development
961 (nominal p-values = <0.0005), TNFα signaling via NFkB (nominal p-value = <0.0005),
962 epithelial to mesenchymal transition (nominal p-values = <0.0005 and 0.002), embryonic
963 development (nominal p-value = <0.0005), and Wnt β-Catenin signaling (nominal p-

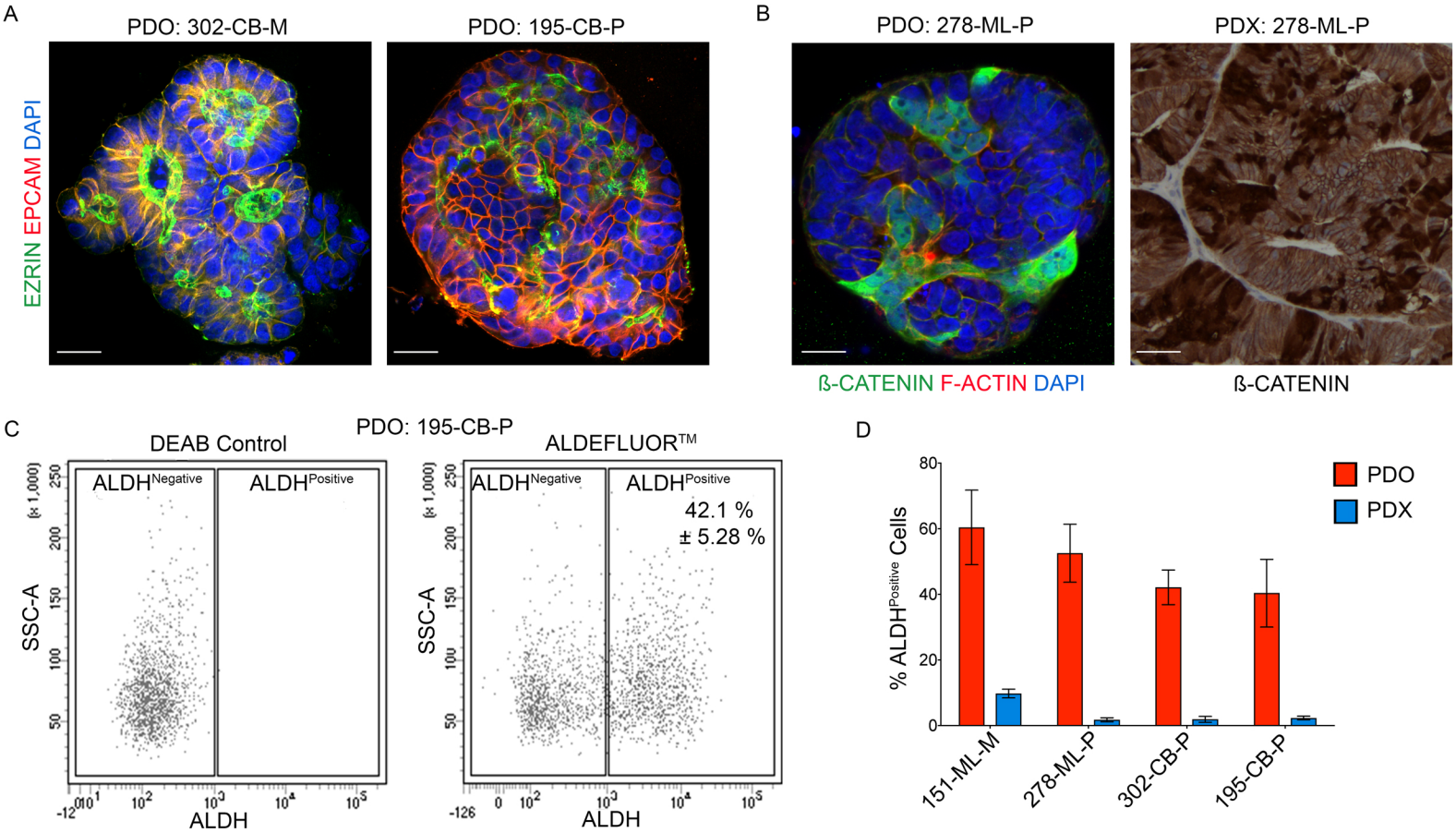
964 values= <0.0005) in ALDH^{Positive} cells (compared to ALDH^{Negative} cells) from PDO models
965 (top panels) and PDX models (bottom panels). (C) Venn diagram shows the number of
966 RNA-sequencing generated transcripts upregulated in PDO ALDH^{Positive} cells (218 genes)
967 and PDX ALDH^{Positive} cells (250 genes) and upregulated in both PDO ALDH^{Positive} cells
968 and PDX ALDH^{Positive} cells (30 genes) n = 4 separate cell preparations, basemean greater
969 than or equal to 100, log2 fold change = 1.5 fold upregulated, p-value <0.05). (D) Table
970 shows 10 genes upregulated in both PDO ALDH^{Positive} cells and PDX ALDH^{Positive} cells
971 selected for functional analysis by RNA-interference (relevant literature is cited in
972 brackets below gene names). (See also Figure S2 and S3).
973
974 **Figure 3. *EGR2* is required for CSC tumorigenicity and differentiation and regulates**
975 **expression of NCSC *HOX* genes and *SOX2***
976 (A) Proliferation of siRNA transfected patient-derived colon cancer cells in non-adherent
977 cell culture compared to control cells (mean ± SD; data from three independent
978 experiments). *p-value < 0.05; ***p-value < 0.001 (t test). (B) Fold expression of
979 *ALDH1A1, EGR2, EGR3, HDGFRP3 OLFML2, PCP4, PEG10, PRKACB* and *THBS1* RT-
980 PCR gene expression data (±95% confidence intervals) in siRNA transfected 278-ML-P
981 cells (n=3 independent cell preparations) over the comparator population (control siRNA
982 transfected 278-ML-P cells) (see also Table S2 and S4). (C) Frequency of siRNA EGR2
983 spheroid formation in non-adherent cell culture compared to control transfected cells
984 (mean ± SD; data from three independent experiments). ns = not significant; *p-value <
985 0.05; **p-value < 0.01 (t test). (D) Representative images of a 278-ML-P control spheroid
986 (LHS) and a siRNA EGR2 spheroid (RHS) in non-adherent cell culture (Bars = 100 μm).

987 (E) Table shows results of limiting dilution transplantation of control virus transduced and
988 shRNA EGR2 transduced 195-CB-P cells. The number of established tumors as a fraction
989 of the number of animals transplanted is given. P-values for pairwise tests of differences
990 in CSC frequencies between control virus versus shRNA EGR2 1, shRNA EGR2 2 and
991 shRNA EGR2 3 195-CB-P cells are 6.9 x10^{-9}, 4.9 x 10^{-6} and 6.92 x 10^{-8}, respectively. (F)
992 Growth curves for xenografts derived from control virus transduced cells and shRNA
993 EGR2 transduced cells. (G) Fold expression of *EGR2,* proliferation, differentiation, stem
994 cell genes, Wnt signaling and EGR2 NCSC target genes RT-PCR gene expression data
995 (±95% confidence intervals) in four separate 195-CB-P shRNA EGR2 tumors over the
996 comparator population (four control virus transduced 195-CB-P xenografts). Significant
997 differences are as follows: $*p < 0.05$, $**p < 0.01$. (see also Table S3).
998

999 **Figure 4. *EGR2, HOXA2, HOXA4, HOXA5, HOXA7* and *HOXB3* are increased in late**
1000 **stage tumors and are indicators of poor prognosis in clinical samples**
1001 (A) Expression *of EGR2, ATOH1, HOXA2, HOXA4, HOXA5, HOXA7, HOXB2, HOXB3,*
1002 *HOXD10* and *SOX2* in colorectal cancer patients across different tumor stages (T1 v T4,
1003 p-value = 0.027, 0.53, 0.026, 0.000075, 0.001, 0.009, 0.075, 0.0016, 0.043 and 0.1,
1004 respectively). Of these, *HOXA4*, *HOXA5*, *HOXA7*, and *HOXB3* are significant at FDR <
1005 5%. RNAseq and clinical data of 533 patients (n=378 colon adenocarcinoma, n=155
1006 rectal adenocarcinoma) was extracted from cBioPortal. (B) Kaplan-Meier survival curves
1007 for *EGR2, ATOH1, HOXA2, HOXA4, HOXA5, HOXA7, HOXB2, HOXB3, HOXD10* and
1008 *SOX2* in colorectal cancer patients comparing lower third percentile to upper third
1009 percentile (logrank p-values = 0.00017, 0.0013, 0.0028, 0.0006, 0.0043, 0.0022, 0.00025,

1010 0.019, 0.11 and 0.21, respectively. Of these, higher *EGR2*, *HOXA2*, *HOXA4*, *HOXA5* and
1011 *HOXA7* are significant at FDR < 5%. Results based upon data generated by the Kaplan-
1012 Meier Plotter (www.kmplot.com/analysis)[194].
1013

Figure 1



E

Serial PDX Transplant 1

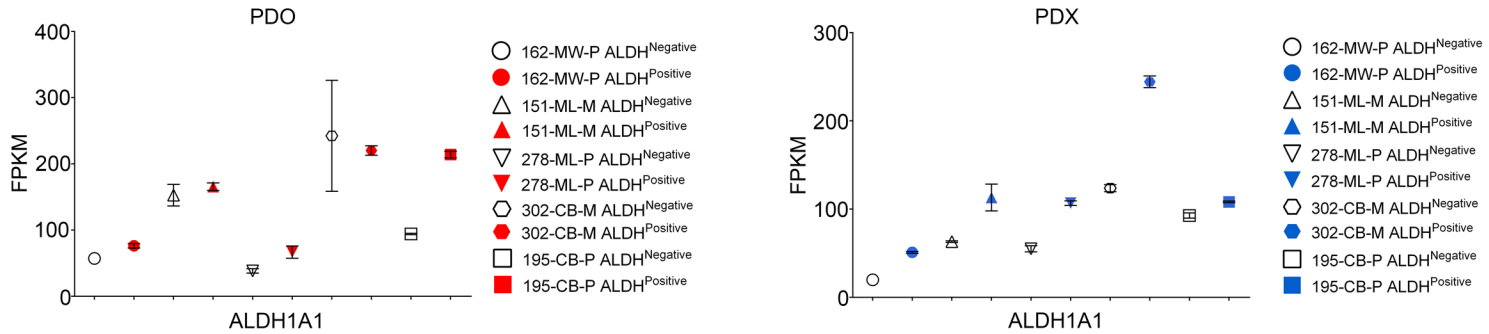
Cell dilution	151-ML-M		278-ML-P		302-CB-M		195-CB-P	
	ALDH^{Negative}	ALDH^{Positive}	ALDH^{Negative}	ALDH^{Positive}	ALDH^{Negative}	ALDH^{Positive}	ALDH^{Negative}	ALDH^{Positive}
100 cells	0/0	2/6	0/0	1/6	0/0	5/6	0/0	5/6
1000 cells	0/6	1/6	1/6	0/6	1/6	6/6	0/6	6/6
10000 cells	0/6	0/0	0/6	0/0	3/6	0/0	1/6	0/0
Frequency of Cancer Stem Cells	0	1 in 1,986	1 in 65,499	1 in 6,550	1 in 12,113	1 in 55.8	1 in 60,863	1 in 55.8
(95% confidence limits)	NA	(1 in 591 - 1 in 6,667)	(1 in 8,664 - 1 in 495,152)	(1 in 866 - 1 in 49,515)	(1 in 4,350 - 1 in 33,733)	(1 in 20.6 - 1 in 151)	(1 in 8,614 - 1 in 43,0042)	(1 in 20.6 - 1 in 151)

Serial PDX Transplant 2

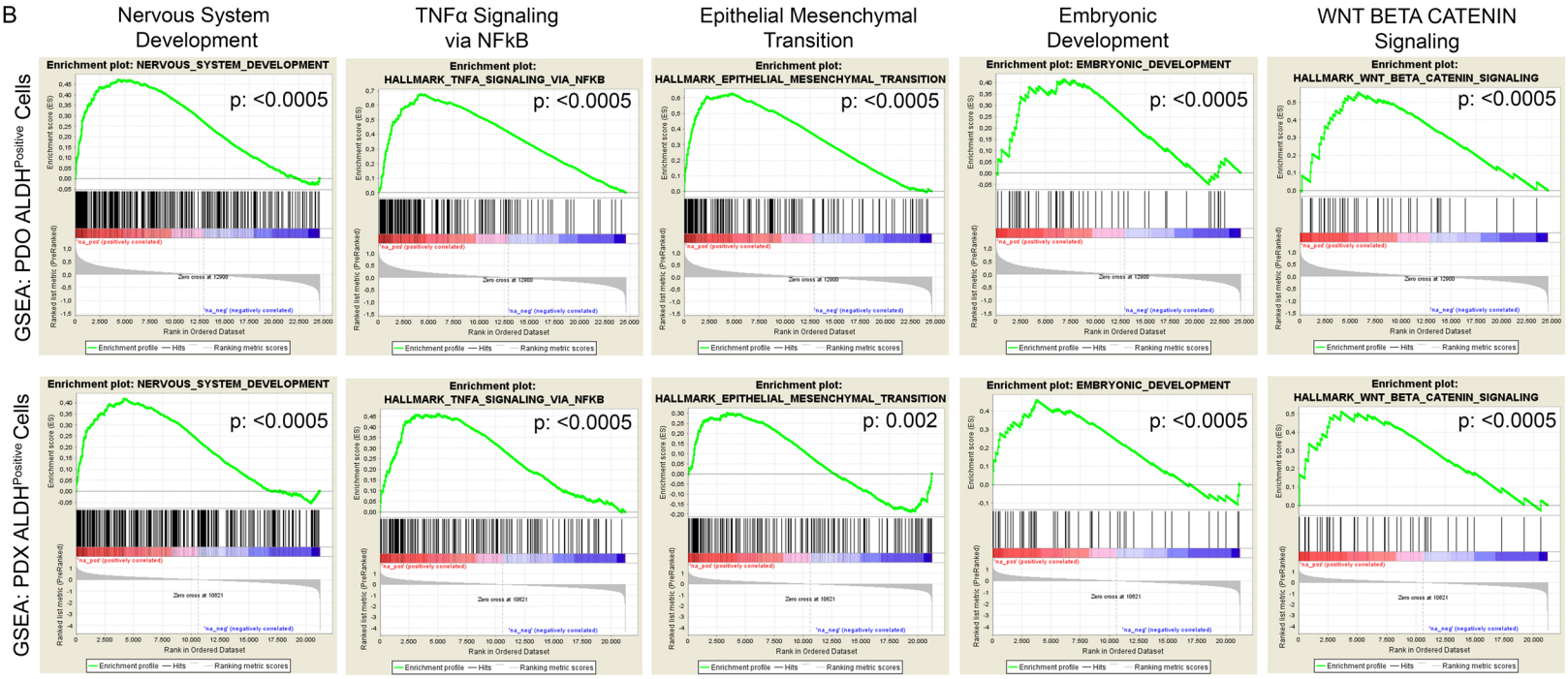
Cell dilution	278-ML-P		302-CB-M		195-CB-P	
	ALDH^{Negative}	ALDH^{Positive}	ALDH^{Negative}	ALDH^{Positive}	ALDH^{Negative}	ALDH^{Positive}
100 cells	0/0	3/6	0/0	6/6	0/0	5/6
1000 cells	1/6	3/6	0/6	6/6	0/6	5/6
10000 cells	0/6	0/0	0/6	0/0	0/6	0/0
Frequency of Cancer Stem Cells	1 in 65,499	1 in 772	0	1 in 1	0	1 in 247
(95% confidence limits)	(1 in 8,664 - 1 in 495,152)	(1 in 307 - 1 in 1,940)	NA	(1 in 1 - 1 in 107)	NA	(1 in 90 - 1 in 686)

Figure 2

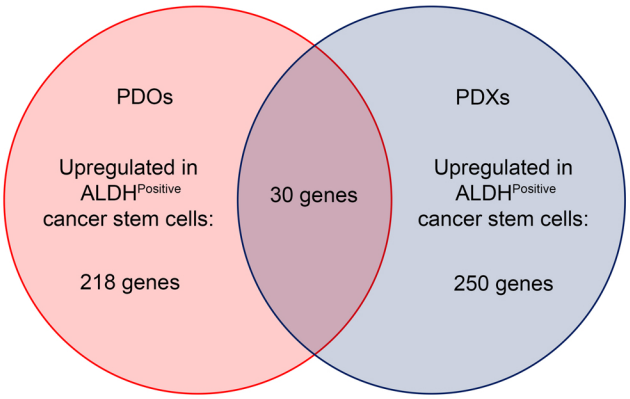
A



B



C

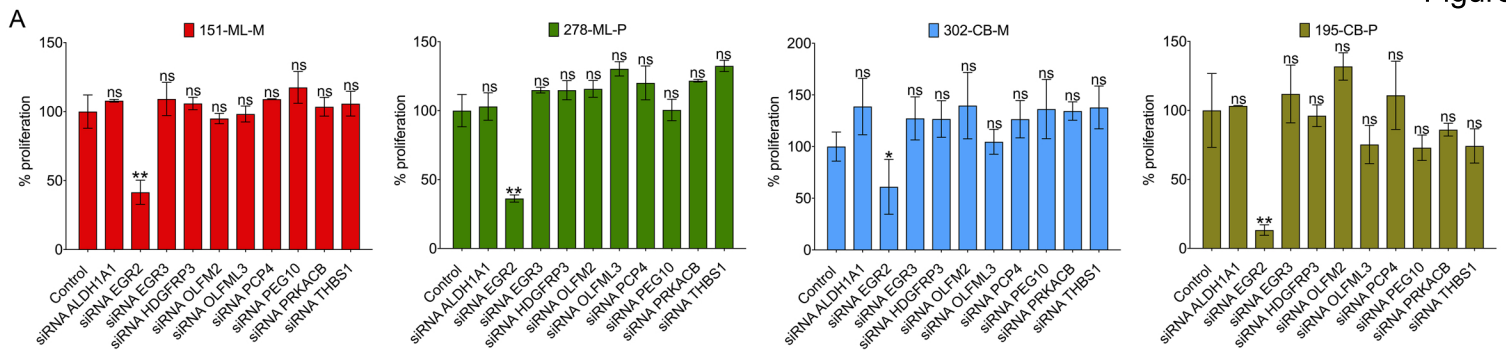


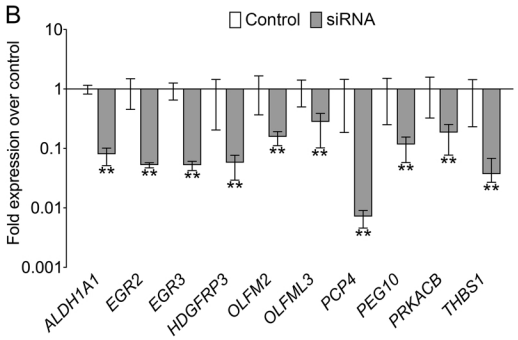
baseMean ≥ 100
log2 Fold Change ≥ 0.586 (1.5fold upregulated)
p-value ≤ 0.05

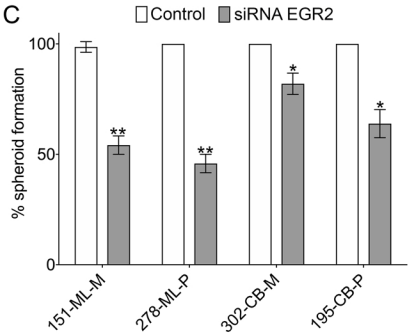
D

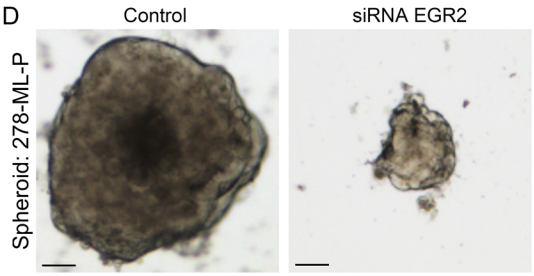
Gene Name	Expression	Development	Cancer
ALDH1A1 (52)	Liver, Kidney, Stomach, Colon, Lung, Breast, Nervous system, Pancreas, Testis, Prostate, Ovary	Embryogenesis, Hematopoiesis, CNS, NCC	Liver, Lung, Colorectal, Breast, Stomach, Ovarian
EGR2 (31,38,41,56–62)	Thyroid, Testis, Uterine, Prostate, Nervous system	Embryogenesis, CNS, NCC	Breast, Leukemia, Gastric, Uterine, Glioblastoma, Prostate
EGR3 (58,60,63–68)	Nervous system, Adrenal gland, Gall bladder	Embryogenesis, CNS, NCC	Renal cell, Colorectal, Breast, Prostate
HDGFRP3 (69–74)	Testis, Nervous system, Endometrium, Adrenal gland, Colon	Embryogenesis, CNS, Muscle	Lung, Hepatocellular
OLFM2 (75–78)	Nervous system, Skin, Smooth muscle	Embryogenesis, CNS, NCC	Unknown
OLFML3 (77,79,80)	Uterine, Endometrium, Placental, Smooth muscle	Embryogenesis, CNS, NCC	Numerous
PCP4 (81–84)	Nervous system	CNS, NCC	Breast
PEG10 (85–93)	Placenta, Nervous system, Testis, Ovary, Adrenal gland	Placenta	Hepatocellular, Pancreatic, Breast, Prostate, Leukemia, Colorectal
PRKACB (94,95)	Nervous system, Colon, Adrenal gland	CNS, NCC	Prostate, Colorectal, Gastric, Adrenal
THBS1 (96–101)	Appendix, Gall bladder, Placenta, Endometrium, Smooth muscle	Embryogenesis, CNS	Numerous

Figure 3





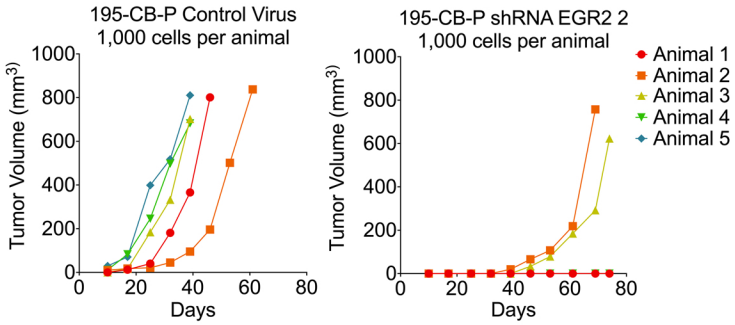


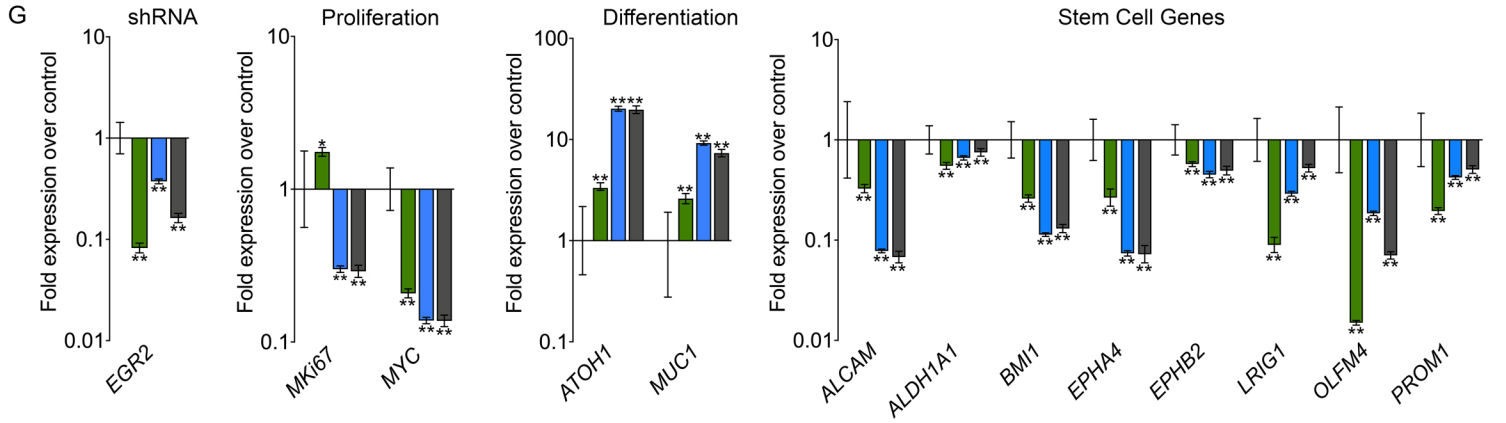


E

195-CB-P

Cell Dilution	Control Virus	shRNA EGR2 1	shRNA EGR2 2	shRNA EGR2 3
100 cells	3/5	0/5	2/5	1/5
1,000 cells	5/5	1/5	2/5	2/5
10,000 cells	5/5	3/5	4/5	3/5
Frequency of Tumor Initiating Cells (95% confidence limits)	1 in 106 (1 in 34.1 - 1 in 348)	1 in 9,341 (1 in 3,301 - 1 in 26,436)	1 in 3,150 (1 in 1,137 - 1 in 8,722)	1 in 4,947 (1 in 1,886 - 1 in 12,974)





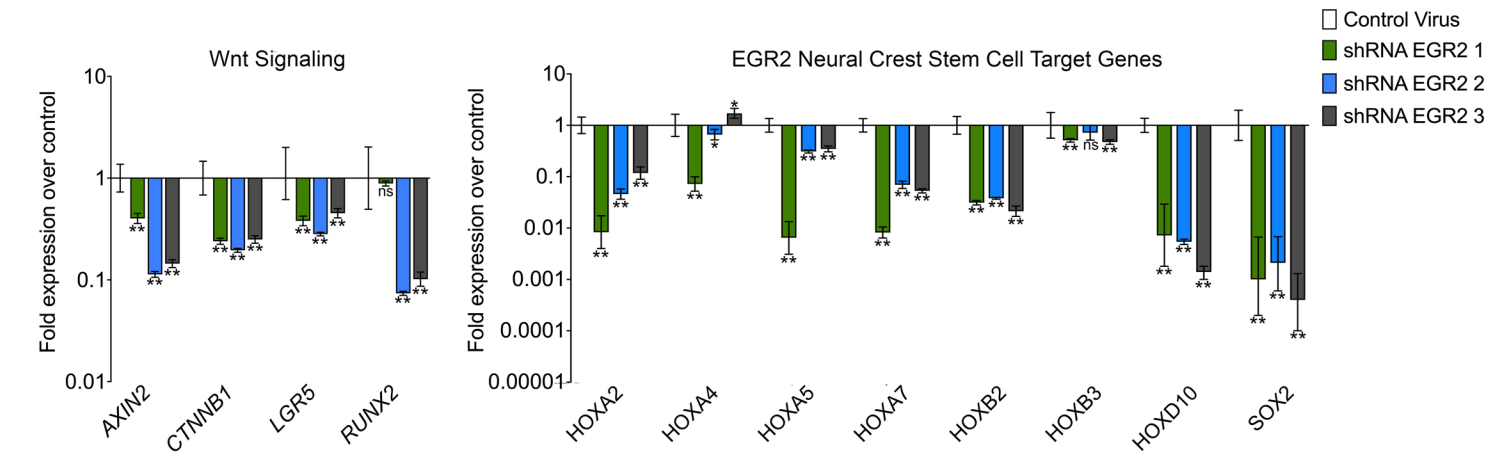
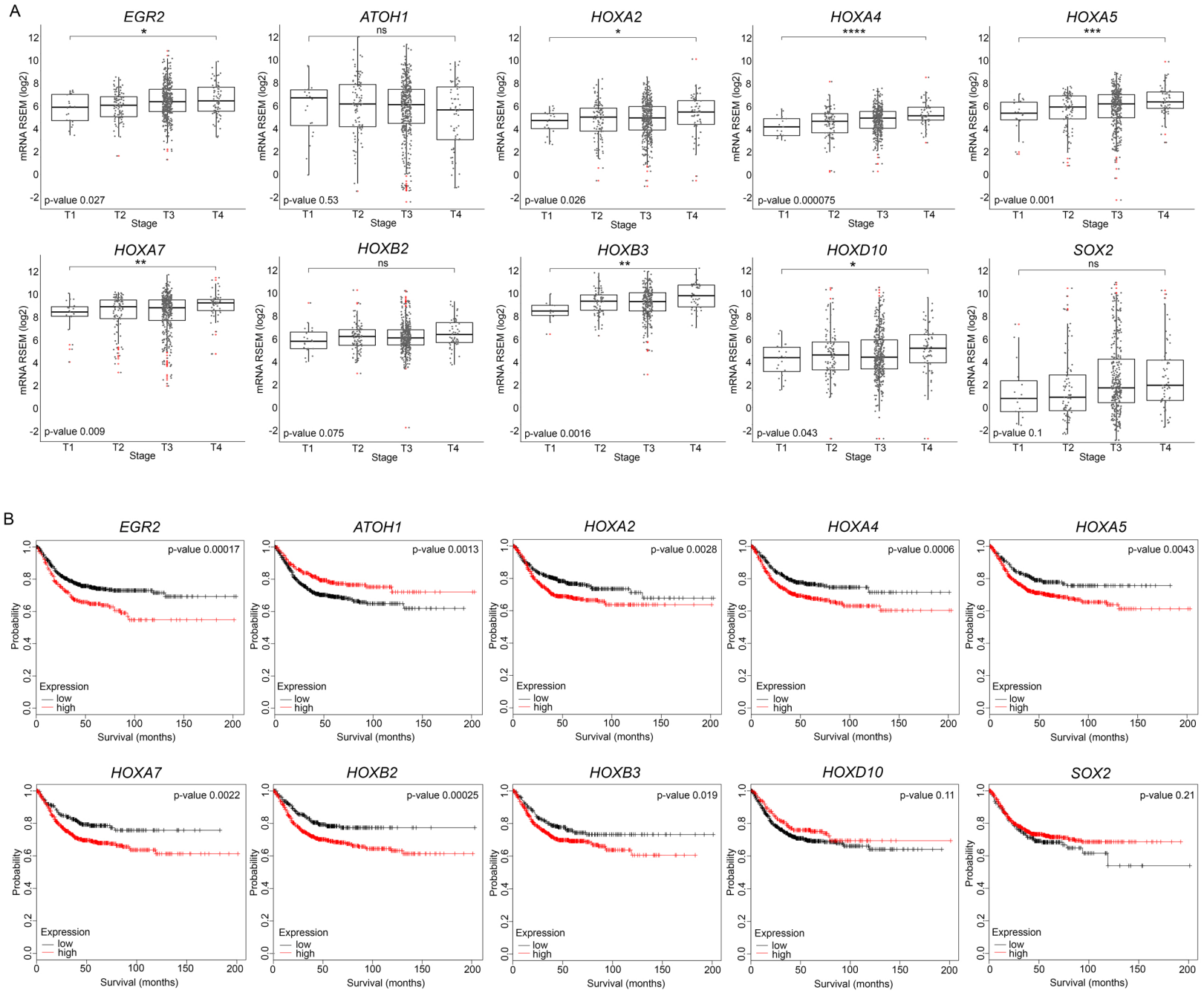


Figure 4


A
EGR2
*
p-value 0.027
ATOH1
ns
p-value 0.53
HOXA2
*
p-value 0.026
HOXA4
****
p-value 0.000075
HOXA5
***
p-value 0.001
HOXA7
**
p-value 0.009
HOXB2
ns
p-value 0.075
HOXB3
**
p-value 0.0016
HOXD10
*
p-value 0.043
SOX2
ns
p-value 0.1
mRNA RSEM (log2)
Stage
T1
T2
T3
T4
B
EGR2
p-value 0.00017
ATOH1
p-value 0.0013
HOXA2
p-value 0.0028
HOXA4
p-value 0.0006
HOXA5
p-value 0.0043
HOXA7
p-value 0.0022
HOXB2
p-value 0.00025
HOXB3
p-value 0.019
HOXD10
p-value 0.11
SOX2
p-value 0.21
Probability
Survival (months)
Expression
low
high

Supplementary Information

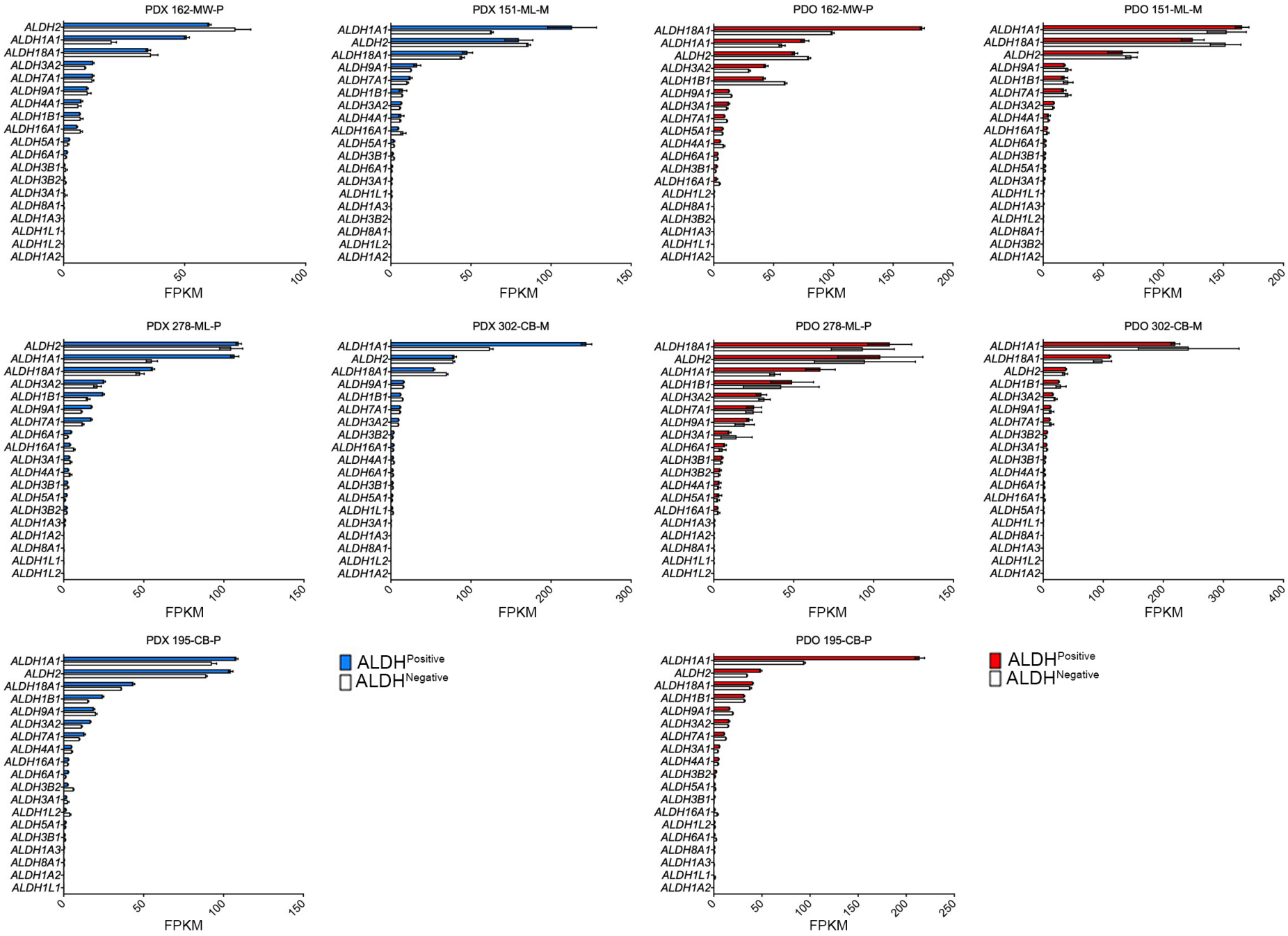


Figure S1: ALDH isoform expression in ALDH^{Positive} PDO (LHS) and PDX (RHS)cells. Related to Figure 1 and 2.

Gene Name	Description	Expression	Function
LINGO1	Leucine rich repeat and Immunoglobin domain-containing protein 1	nervous system, placenta, testis	regulates myelination, oligodendrocyte differentiation, axon regeneration, and neuronal survival
EGR2	Early growth response 2	thyroid, nervous system, placenta, testis	early myelination of the peripheral nervous system
RASL11B	RAS like family 11 member B	ovary, heart, kidney, nervous system, placenta	member of the small GTPase protein family with a high degree of similarity to RAS
DEFA6	defensin alpha 6	intestine, colon	antimicrobial and cytotoxic peptide thought to be involved in host defense
PRKACB	protein kinase cAMP-activated catalytic subunit beta	nervous system, placenta, testis	mediates cAMP-dependent signaling; regulates diverse cellular processes including cell proliferaton and differentiation
THBS1	thrombospondin 1	placenta, endometrium, smooth muscle	mediates cell-to-cell and cell-to-matrix interactions, roles in platelet aggregation, angiogenesis, and tumorigenesis
PCP4	Purkinje cell protein 4	nervous system	development of the central nervous system, may play a role in neuronal differentiation through activation of calmodulin-dependent kinase signaling pathways
EGR3	early growth response 3	nervous system, adrenal gland, gall bladder	early growth response gene induced by mitogenic stimulation; regulates biological rhythm, endothelial cell growth and migration, and neuronal development
FBLN1	fibulin 1	placenta, uterine,	mediates platelet adhesion via binding fibrinogen
CFI	complement factor I	liver, kidney, gallbladder	encodes a serine proteinase that is essential for regulating the complement cascade
ADAMTSL2	ADAMTS like 2	adenal gland, kidney, nervous system	a secreted glycoprotein that binds the cell surface and extracellular matrix
PHYHIPL	phytanoyl-CoA 2-hydroxylase interacting protein like	nervous system, adrenal gland, intestine, placenta, testis	May play a role in the development of the central system
OSBPL6	oxysterol binding protein like 6	nervous system, skeletal muscle, intestine	intracellular lipid receptor
HDGFRP3	Hepatoma-Derived Growth Factor 2	testis, nervous system, endometrium, placenta	nnhances DNA synthesis and may play a role in cell proliferation
OLFML3	olfactomedin like 3	uterine, endometrium, placental, smooth muscle	facilitates protein-protein interactions, cell adhesion, and intercellular interactions, scaffold protein and pro-angiogenic vascular tissue remodeler
FRMPD1	FERM and PDZ domain containing 1	testis, skin, nervous system	a regulatory binding partner for AGS3, which stabilizes GDP-bound inhibitory G proteins. FRMPD1 binds to and secures AGS3 localization at cell membranes
LMCD1	LIM and cysteine rich domains 1	skeletal ann smooth muscle, adipose tissue, placenta	protein-protein interactions, may act as a co-regulator of transcription
DACT1	dishevelled binding antagonist of beta catenin 1	nervous system, ovary, testis, placenta, colon	regulates dishevelled-mediated signaling pathways during development; may play role in the regulation of Wnt signaling via degradation of CTNNB1
PEG10	paternally expressed 10	placenta, nervous tissue, testis, ovary, adrenal	cell proliferation, differentiation and apoptosis; Overexpression of this gene has been associated with several malignancies
TENT5C	Terminal Nucleotidyltransferase 5C	bone marrow, colon, testis, stomach	Probable nucleotidyltransferase that may act as a non-canonical poly(A) RNA polymerase; Seems to enhance replication of some viruses
ERVMER34-1	endogenous retrovirus group MER34 member 1, envelope	Placenta, kidney, heart	retroviral envelope proteins, which mediate receptor recognition and membrane fusion during early infection.
SULT1B1	sulfotransferase family 1B member 1	intestine, liver, spleen	catalyze the sulfate conjugation of many hormones, neurotransmitters, drugs, and xenobiotic compounds
OLFM2	olfactomedin 2	nervous system, skin	involved in early eye development and function; plays a role in TGFB-mediated differentiation of smooth muscle cells from mesenchymal stem cells
MAP1B	microtubule associated protein 1B	nervous system	microtubule assembly, required for neurogenesis
PCDHB16	protocadherin beta 16	parathyroid gland, nervous system	specific functions are unknown; likely plays a critical role in the establishment and function of specific cell-cell neural connections
ALDH1A1	aldehyde dehydrogenase 1 family member A1	liver, stomach, intestine, testis, ovary, adrenal	conversion/oxidization of retinaldehyde to retinoic acid
SLC2A12	solute carrier family 2 member 12	protate, endometrium, intestine, nervous system	Facilitative glucose transporter
UGT2A3	UDP glucuronosyltransferase family 2 member A3	Instestine, kidney	important in the conjugation and subsequent elimination of potentially toxic xenobiotics and endogenous compounds
PCSK5	proprotein convertase subtilisin/kexin type 5	Intestine, adipose, placenta, uterine, ovary, testis	likely functions in the secretory pathways; essential role in pregnancy establishment by proteolytic activation factors such as BMP2, CALD1 and alpha-integrins
RAB30	RAB30, member RAS oncogene family	nervous system, ovary, breast, placenta	regulator of intracellular membrane trafficking; required for maintaining the structural integrity of the Golgi apparatus,

Figure S2: List of genes differentially expressed and common in ALDH^{Positive} PDO and ALDH^{Positive} PDX CSCs. Related to Figure 2.

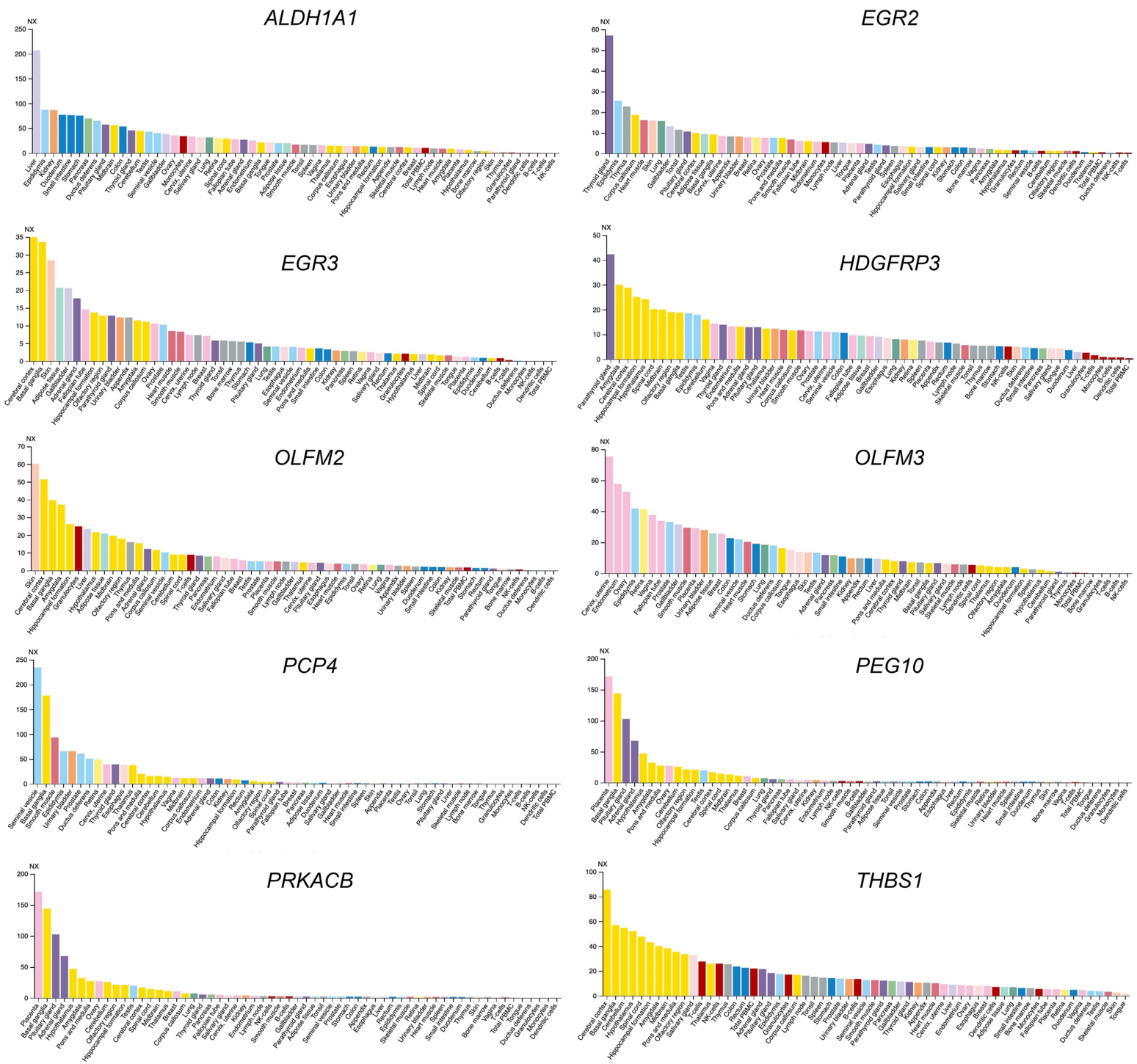


Figure S3: RNA tissue expression of differentially expressed and common ALDH^{Positive} PDO and ALDH^{Positive} PDX cells. Related to Figure 2.

Consensus RNA-seq dataset from the Human Protein Atlas (HPA) the Genotype-Tissue Expression (GTEx) project and CAGE data from FANTOM5 project. Color-coding is based on tissue groups, each consisting of tissues with functional features in common.

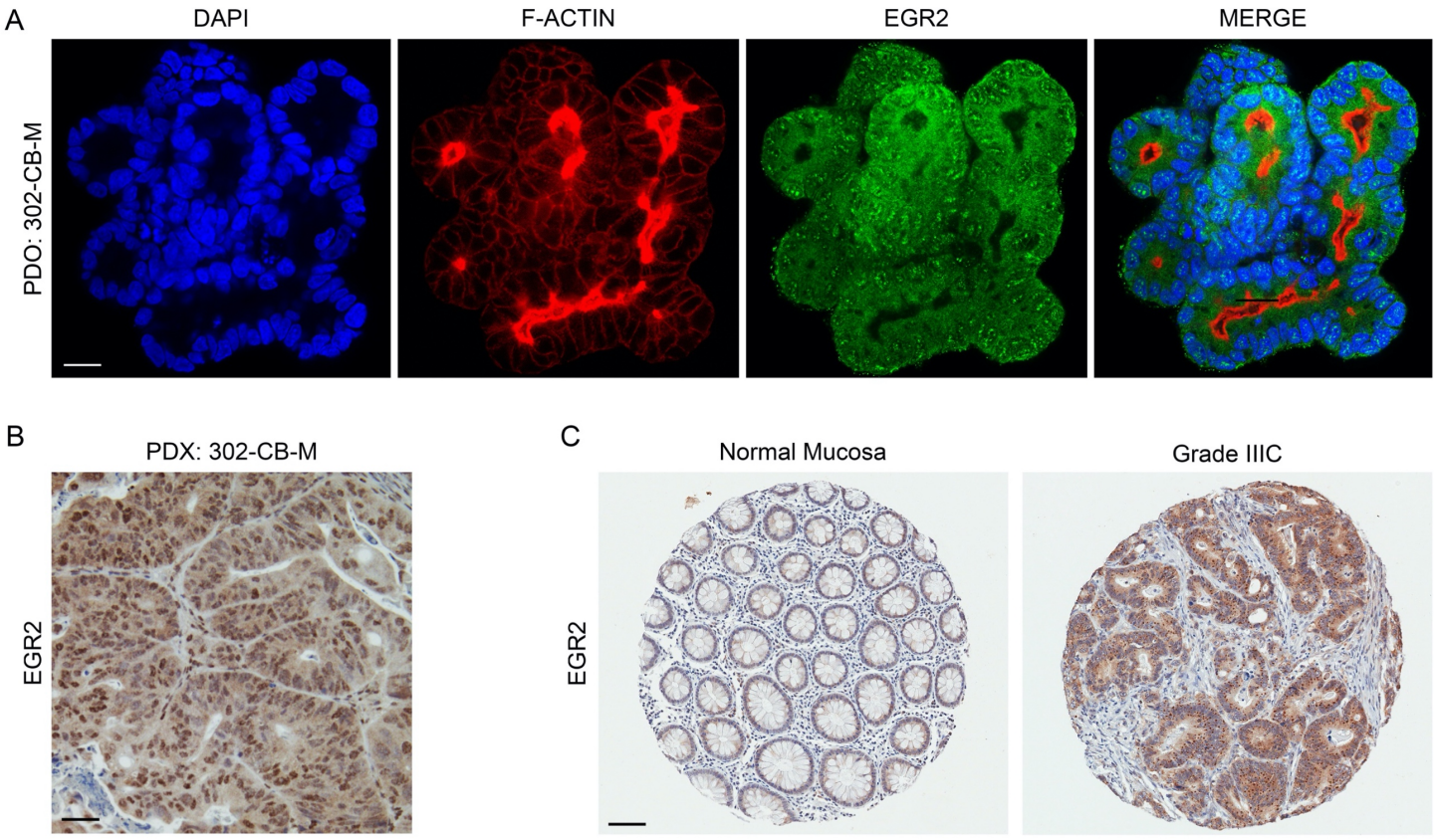


Figure S4: EGR2 immunostaining in PDO, PDX and clinical samples.

(A) Immunofluorescence staining of PDO for EGR2 (green) and F-ACTIN (red). Nuclei are stained blue with DAPI (Bars = 20 μm). Immunostaining of PDX tissue (B) and tissue microarrays of normal intestinal mucosa and colorectal cancer patient tissue (C) for EGR2. (Bars = 200 μm). Related to Figure 3.

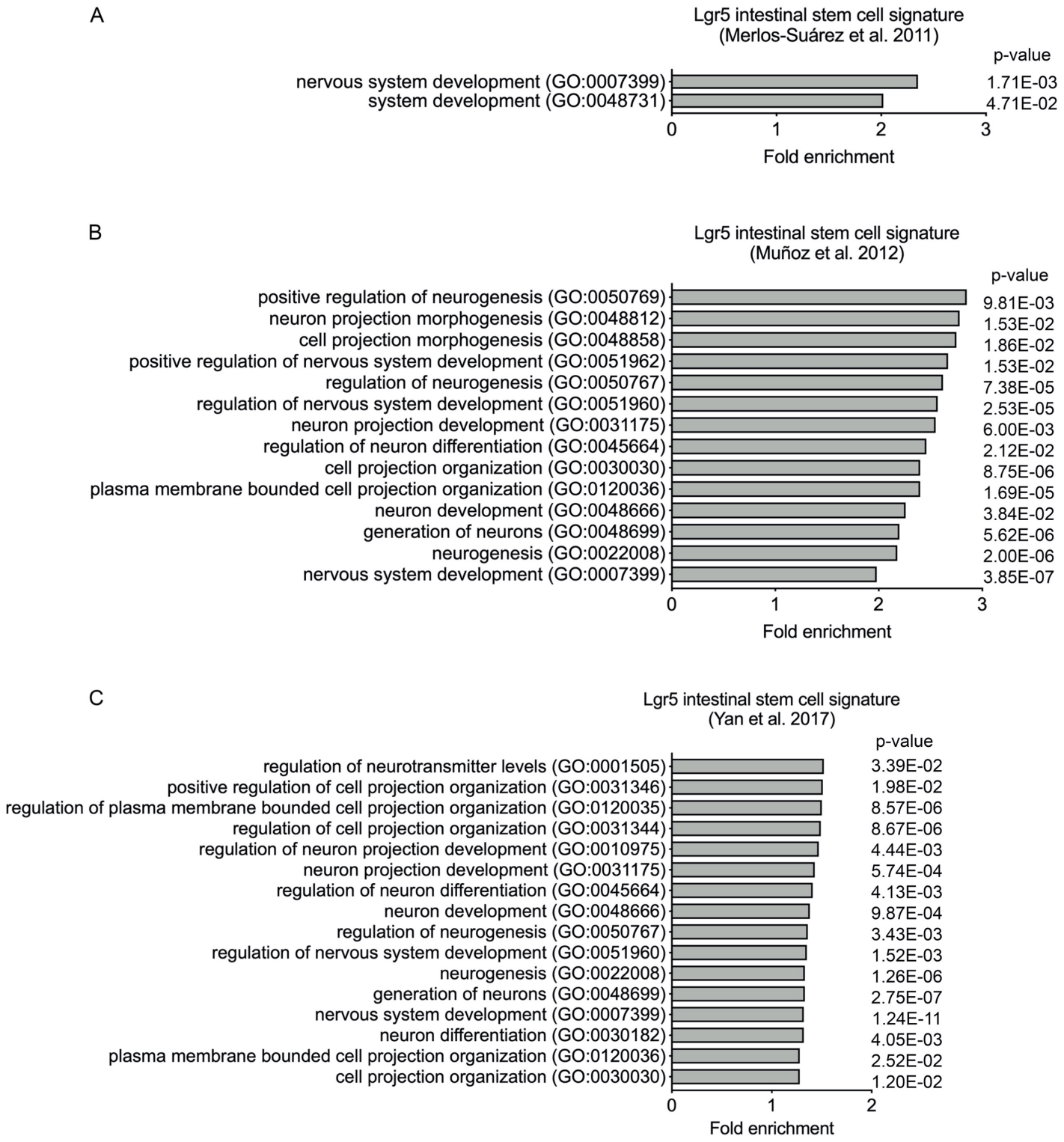


Figure S5: Lgr5 intestinal crypt-base stem cells are enriched for nervous system genes.

Gene ontology analysis of Lgr5 intestinal stem cell gene signatures from (A) Merlos-Suarez, *et al*., 2011), (B) Munoz, *et al*., (2012) and (C) Yan, *et al*., (2017). Related to Figure 2.

Patient Model	Origin	TNM stage	Stage
162-MW-P	Sigmoid colon & descending colon	T3 N0 M0	IIA
151-ML-M	Liver	T2 N0 M0 , M1a	IVA
278-ML-P	Sigmoid colon & descending colon	T4a N0 M0	IIB
302-CB-M	Liver	T3 N1a M1a	IVA
195-CB-P	Sigmoid colon	T4a N2b M1a	IVA

Table S1 Tissue Origin and TNM Classification of Malignant Tumors (TNM). Related to Figure 1.

T: primary tumor size, N: regional lymph nodes involved, M: distant metastasis.

siRNA	Dharmacon™ Product	Product Number
ALDH1A1	Accell Human (216) siRNA - SMARTpool	E-008722-00-5
EGR2	Accell Human (1959) siRNA - SMARTpool	E-006527-01-5
EGR3	Accell Human (1960) siRNA - SMARTpool	E-006528-00-5
HDGFRP3	Accell Human (50810) siRNA - SMARTpool	E-017093-00-5
OLFM2	Accell Human (93145) siRNA - SMARTpool	E-015212-00-5
OLFML3	Accell Human (56944) siRNA - SMARTpool	E-020325-00-5
PCP4	Accell Human (5121) siRNA - SMARTpool	E-020122-00-5
PEG10	Accell Human (23089) siRNA - SMARTpool	E-032579-00-5
PRKACB	Accell Human (5567) siRNA - SMARTpool	E-004650-00-5
THBS1	Accell Human (7057) siRNA - SMARTpool	E-019743-00-5

Table S2: Dharmacon™ Smartpool siRNAs. Related to Figure 3.

LENTIVIRUS	SIGMA PRODUCT	PRODUCT NAME	VECTOR	TRC NUMBER
Control	SHC003V	MISSION® tGFP™ Positive Control Transduction Particles	–pLKO.1-puro-CMV-tGFP	NA
shEGR2 1	SHCLNV-NM_000399	EGR2 MISSION shRNA Lentiviral Transduction Particles	–hPGK-Puro-CMV-tGFP	TRCN0000013839
shEGR2 2	SHCLNV-NM_000399	EGR2 MISSION shRNA Lentiviral Transduction Particles	–hPGK-Puro-CMV-tGFP	TRCN0000013840
shEGR2 3	SHCLNV-NM_000399	EGR2 MISSION shRNA Lentiviral Transduction Particles	–hPGK-Puro-CMV-tGFP	TRCN0000013841

Table S3. Lentiviral Transduction Particles. Related to Figure 3.

Symbol	Gene Name	UniGene ID	TaqMan® Gene Expression Assay
ATOH1	atonal BHLH transcription factor 1	Hs.532680	Hs00245453_s1
AXIN2	axin 2	Hs.156527	Hs00610344_m1
BMI1	BMI1 proto-oncogene, polycomb ring finger	Hs.380403	Hs00180411_m1
CTNNB1	catenin beta 1	Hs.476018	Hs00355049_m1
EGR2	early growth response 2	Hs.1395	Hs00166165_m1
EPHA4	EPH receptor A4	Hs.371218	Hs00953178_m1
EPHB2	EPH receptor B2	Hs.523329	Hs00362096_m1
GAPDH	glyceraldehyde-3-phosphate dehydrogenase	Hs.544577	Hs02758991_g1
HOXA2	homeobox A2	Hs.445239	Hs00534579_m1
HOXA5	homeobox A5	Hs.655218	Hs00430330_m1
HOXA7	homeobox A7	Hs.610216	Hs00600844_m1
HOXB2	homeobox B2	Hs.514289	Hs01911167_s1
HOXB3	homeobox B3	Hs.654560	Hs05048382_s1
HOXD10	homeobox D10	Hs.123070	Hs00157974_m1
LGR5	leucine rich repeat containing G protein-coupled receptor 5	Hs.658889	Hs00969422_m1
MKI67	MKI67	Hs.689823	Hs04260396_g1
MUC1	mucin 1, cell surface associated	Hs.89603	Hs00159357_m1
MYC	v-myc avian myelocytomatosis viral oncogene homolog	Hs.202453	Hs00153408_m1
RUNX2	runt related transcription factor 2	Hs.535845	Hs01047973_m1
SOX2	SRY-box 2	Hs.518438	Hs01053049_s1
HDGFRP3	hepatoma-derived growth factor, related protein 3	Hs.513954	Hs00274988_m1
OLFM2	olfactomedin 2	Hs.169743	Hs01017934_m1
OLFML3	olfactomed like 3	Hs.9315	Hs01113293_g1
PCP4	Purkinje cell protein 4	Hs.80296	Hs01113638_m1
PEG10	paternally expressed 10	Hs.147492	Hs00248288_s1
PRKACB	protein kinase cAMP-activated catalytic subunit beta	Hs.487325	Hs01086757_m1
THBS1	thrombospondin 1	Hs.164226	Hs00962908_m1

Table S4. Taqman Gene Expression Assays. Related to Figure 3.