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**Exploitation of the *Escherichia coli lac*-operon promoter for
controlled recombinant protein production**

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32 **Abstract**

33 The *Escherichia coli lac* operon promoter is widely used as a tool to control recombinant
34 protein production in bacteria. Here we give a brief review of how it functions, how it is
35 regulated, and how, based on this knowledge, a suite of *lac* promoter derivatives has been
36 developed to give controlled expression that is suitable for diverse biotechnology
37 applications.

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39 **Key words:** *Escherichia coli*, bacterial transcription initiation, *lac* promoter, *tac* promoter,
40 Lac repressor, recombinant protein production

41

42 **Abbreviations Used:** RPP, recombinant protein production; RNAP, RNA polymerase; bp,
43 base pairs; CRE, Core-recognition element; CRP, cyclic AMP receptor protein; LacI, lactose
44 operon repressor protein; IPTG, isopropyl β -D-1-thiogalactopyranoside; PAR, promoter
45 activity rating; GFP, green fluorescent protein; hGH, human growth hormone; Tat, twin
46 arginine translocon pathway; LB: lysogeny broth; ONPG, o-nitrophenyl- β -D-galactopyranose.

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49 **Introduction**

50 Most of the recombinant protein production (RPP) systems used for expressing proteins in
51 bacteria were constructed in the last century [1-4]. High level RPP provided by these
52 systems enables the synthesis and purification of large amounts of soluble recombinant
53 protein. However, the expression of difficult protein targets (e.g. membrane proteins or
54 proteins secreted out of the cytoplasm), using these RPP systems, may be too high for cells
55 to cope and adequately fold protein, resulting in substantial target degradation or the
56 production of insoluble aggregates (i.e. inclusion bodies) [5-8]. Many “tricks of the trade” can
57 be employed to slow down RPP expression and increase the level of soluble product, e.g.
58 lowering the growth temperature, decreasing the inducer concentration or using a weaker
59 promoter [6-9]. Although such tinkering can be very successful, determining the correct
60 combination of refinements can be time-consuming. This can also be very “hit-and-miss”,
61 being dependent on the particular target protein in question [6, 9], and for some induction
62 regimes, for example when using low inducer concentrations, only a proportion of the cells in
63 a culture may in fact express recombinant protein [10-12].

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65 The *E. coli lac* operon promoter was one of the first bacterial promoters to be adopted by
66 biotechnologists for RPP, and it is still used today, especially when *Escherichia coli* is used
67 as the host [6]. Here, we give a brief update of our current understanding of transcript
68 initiation in bacteria, emphasising special features of the *lac* promoter and its regulation. We
69 then review how, based on this information, many *lac* promoter derivatives have now been
70 engineered in order to facilitate controlled RPP expression and avoid the problems that are
71 concomitant with high level overexpression.

72

73 **Transcript initiation and regulation at the *E. coli lac* operon promoter**

74 Transcript initiation in bacteria takes place when the multisubunit DNA-dependent RNA
75 polymerase holoenzyme (RNAP) interacts with a DNA promoter sequence (Figure 1A). In
76 brief, the RNAP first interacts with double-stranded DNA to form a ‘closed complex’ in which
77 determinants in different RNAP subunits interact with different promoter sequence elements
78 (Figure 1B) [13]. Thus a determinant in the RNAP α subunit C-terminal domain interacts with
79 the promoter UP element, a determinant in Domain 4 of the RNAP σ subunit interacts with
80 the promoter -35 element, and a determinant in Domain 3 of the RNAP σ subunit interacts
81 with the extended -10 element (Figure 1B). Following this, Domain 2 of the RNAP σ subunit
82 drives the local unwinding of 13-15 base pairs (bp) of promoter DNA to form the ‘open
83 complex’, in which the single-stranded DNA template strand is positioned in the active site of
84 the RNAP, such that initiation of DNA-templated RNA synthesis can take place (Figure 1C)
85 [14]. Formation of the initiation-competent ‘open complex’ from the ‘closed complex’ is driven
86 by further specific interactions between other RNAP determinants and promoter sequences

87 [15-17]. Thus, determinants in Domain 2 of the RNAP σ subunit interact with single-stranded
88 bases of the promoter -10 element and with the promoter discriminator element. These
89 interactions involve only the non-template strand of the locally unwound segment of
90 promoter DNA, thereby permitting the single-stranded template strand to access the RNAP
91 active site. The exact position of the template strand in the active site, and the location of the
92 downstream junction between single-stranded and double stranded DNA, is set by other
93 contacts involving amino-acid side-chains of the RNAP β and β' subunits (which interact with
94 the promoter Core-recognition element, CRE) (Figure 1C) [16].

95
96 The activity of any bacterial promoter is set by the formation of the 'closed complex' and the
97 ensuing isomerisation to, and escape from, the 'open complex', as the RNAP copies the
98 template strand to elongate its transcript. In the case of the *E. coli lac* operon promoter,
99 defects in the UP element, -35 element and extended -10 element hinder 'closed complex'
100 formation but this is remedied by binding of an activatory factor, the cyclic AMP receptor
101 protein (CRP) to a target sequence centred between bp 61 and 62 (referred to as
102 position -61.5) upstream of the transcript start (denoted as +1; see Figure 1D) [18, 19]. A
103 second regulator protein, the lactose operon repressor protein (LacI) binds to a high affinity
104 target sequence, known as operator O1, centred at position +11 (Figure 1D) [19, 20]. LacI
105 binding to its target effectively shuts down *lac* promoter activity, but repression can be
106 broken by the presence of allolactose (a breakdown product of lactose) or by the sugar
107 analogue IPTG (isopropyl β -D-1-thiogalactopyranoside), which both bind to the LacI
108 repressor and cause it to release operator DNA [20]. LacI-dependent repression of the *lac*
109 promoter is supported by LacI binding to two secondary weaker operators, O3, located at
110 position -82 (Figure 1D), and far downstream, O2 [19-23]. Here, we review how the starting
111 *lac* promoter has been engineered to make it fit for different biotechnology purposes. We
112 focus on constructions that release the requirement for CRP, base changes in key promoter
113 elements, and the exploitation of the O3 operator.

114 115 **Activator-independent *lac* promoter derivatives**

116 Figure 2A illustrates the organisation of the *E. coli lac* operon promoter, showing key
117 promoter elements, the DNA site for CRP, and the location of LacI-binding operators, O1
118 and O3. Figure 2B shows the base sequence of a typical DNA fragment carrying the *lac*
119 promoter that might be used in any biotechnology application. The fragment, which carries a
120 useful restriction site at each end, is denoted *lac* O3O1. Potentially, regulation by CRP might
121 be exploitable but, since CRP activity is difficult to control by external cues, many
122 biotechnology applications that use the *lac* promoter have sought to eliminate CRP effects
123 and focussed on regulation by LacI. One way to do this is by the use of the *lac* UV5 mutant
124 promoter. This mutant promoter carries a 2 bp change in the promoter -10 hexamer element
125 that creates a consensus -10 promoter element (Figure 2B) [19, 24]. The alternative is to
126 replace *lac* promoter upstream DNA sequences and this has been done in the *tac* promoter,
127 which is a chimeric fusion between the upstream elements of the *E. coli trp* promoter and the
128 downstream elements of the *lac*UV5 promoter [1, 2]. Figure 2A illustrates both the *lac*UV5
129 and *tac* promoters, and Figure 2B shows the base sequence of DNA fragments carrying
130 these promoters. Note that the *tac* promoter carries consensus -35 and -10 promoters
131 elements and a single operator for LacI, O1. For *E. coli* promoters that are dependent on the
132 housekeeping sigma factor σ^{70} the optimal spacing between the -35 and -10 promoter
133 elements is 17 bp and deviation from this leads to a reduction in promoter activity [25, 26].
134 Thus, it worth noting that both the *tac* and *lac* promoters are in fact suboptimal, having
135 spacers of 16 and 18 bp, respectively (Figure 2B).

136
137 Figure 3A-C illustrates the results of simple assays to compare the activities of the *tac*,
138 *lac*UV5 and *lac* promoters. To perform these assays, the *tac* O1 fragment, the *lac*UV5 O3O1
139 fragment and the *lac* O3O1 fragment were each cloned into a plasmid expression vector
140 (pRW50) such that the promoters controlled transcription of the gene (*lacZ*) encoding β -
141 galactosidase [27]. Recombinant plasmids were then transformed into a Δlac *E. coli* host

142 strain and β -galactosidase expression was measured. As expected the hierarchy of
143 promoter activity was *tac* > *lacUV5* > *lac* (Figure 3).

144

145 **Modulation of promoter activities using upstream *lac* operator sequences**

146 A key feature of LacI-dependent repression of the *E. coli lac* promoter is the contribution of
147 the auxiliary upstream operator, O₃, and this has been exploited to tailor promoter activity
148 levels. Data in Figure 3A illustrate how the introduction of certain *lac* operator sequences (*i.e.*
149 O₁ or the high affinity “ideal” *lac* operator O_{id}, see Figure 2A [21, 28, 29]) at position -82 of
150 the *tac* O₁ promoter fragment reduced the high activity of the *tac* promoter. Thus, expression
151 from the starting *tac* O₁ promoter fragment and each of the *tac* O₃O₁, *tac* O₁O₁ and *tac*
152 O_{id}O₁ derivatives was induced by IPTG but the introduction of the O₁ and O_{id} operator
153 sequences decreased IPTG-induced expression levels. Similarly, data in Figures 3B and 3C
154 illustrate how the introduction of higher affinity *lac* operators into the upstream region of the
155 *lacUV5* promoter (*i.e.* in the *lacUV5* O₁O₁ and *lacUV5* O_{id}O₁ promoter fragments) or the *lac*
156 promoter (*i.e.* in the *lac* O₁O₁ and *lac* O_{id}O₁ promoter fragments) decreased promoter
157 activity.

158

159 **The power of *lac*: combinations make anything possible**

160 In addition to controlling promoter activity by upstream-bound LacI, activity can be
161 modulated by point mutations in different promoter elements. Data in Figure 3D illustrate
162 how the p34G, p14G, p9A or p8A substitutions (at positions -34, -14, -9 or -8), which make
163 the -35 element, the extended -10 or the -10 element more similar to the respective
164 consensus, can be combined with different operator combinations to produce a suite of
165 IPTG-inducible promoters with a wide range of activities.

166

167 To illustrate the use of these promoters in RPP, we selected a subset of 8 promoters from
168 the above suite and gave each a promoter activity rating (PAR) value of PAR₁ to PAR₈
169 (Figure 4A). Our rationale for this is that, depending on the target protein being expressed,
170 specific IPTG-induced expression levels could be achieved. To examine this, some of the
171 promoter constructs were introduced into the low-copy-number vector pTorA-GFP [30] and
172 the high-copy-number vector pHAK1 [31], using standard techniques [32-34]. For pTorA-
173 GFP derivatives, each PAR promoter drives the expression of a *torA-GFP-6his* fusion (GFP,
174 green fluorescent protein), whilst, for pHAK1, each construct expresses a *torA-hGH-6his*
175 fusion (hGH, human growth hormone). Note that the *torA* signal sequence in each case will
176 direct the recombinant protein to the Tat (twin arginine translocon) system for periplasmic
177 targeting [7, 30, 31]. Plasmid constructs were transferred into *E. coli* BL21 cells and RPP
178 was induced in bacterial cultures by the addition of 1 mM IPTG for 3 hrs [7]. Normalised total
179 cellular protein from cells, expressing either TorA-GFP-6His or TorA-hGH-6His, were then
180 analysed by Western blotting. Results in Figures 4B and 4C show that both GFP and hGH
181 were expressed using the PAR promoter constructs. Note that, in some instances, two
182 product bands can be observed, in each case the species with the higher molecular weight
183 still carries the TorA signal sequence, whilst the smaller species has been processed and
184 lacks the TorA moiety [7, 30, 31, 35]. Importantly, using this expression system, inducible
185 expression of different target proteins can be set to specific levels when using both low- and
186 high-copy-number vectors.

187

188 **Perspectives**

189 The *lac* promoter and its derivatives have been widely used to express many recombinant
190 proteins to high levels in *E. coli* [1, 2, 7, 36] and many currently used vectors have been
191 designed to optimise expression. However, there are situations where expression must be
192 moderated. For example, the secretion of recombinant biopharmaceuticals out of the *E. coli*
193 cytoplasm into the periplasm is often a preferred industrial strategy, as this minimises
194 downstream processing costs, since the target protein can be purified from the periplasmic
195 contents, with minimal cellular and DNA contamination [37]. For this to be successful, RPP
196 needs to be slowed down so that product is not degraded before it is transported [7].

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In this review, we have sought to show how knowledge of the *E. coli lac* promoter can be exploited to produce a suite of derivative promoter fragments to cope with any situation. Previous promoter engineering had focused on altering the *lac* promoter -10 and -35 elements to change the basal promoter expression of constructs [1, 38]. Recent advances in our understanding of transcript initiation in bacteria and its regulation now allow *lac* promoters to be constructed with different operator sequences to alter the induced level of expression. This is possible because, even in the presence of inducer, LacI has some affinity for its operator sequence and, thus, in the induced state the LacI repressor can still remain bound to DNA, as has been observed in single molecule studies [39].

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Author contributions

D.F.B., S.J.W.B. and C.R. conceived and designed the research programme. D.F.B, R.E.G and K.L.R. performed the experiments. D.F.B. wrote the manuscript with input from all authors.

Competing Interests

The Authors declare that there are no competing interests associated with the manuscript.

221 **References**

- 222 1 de Boer, H.A., Comstock, L.J. and Vasser, M. (1983) The *tac* promoter: a functional hybrid
223 derived from the *trp* and *lac* promoters. *Proc Natl Acad Sci U S A.* **80**, 21-25
- 224 2 Amann, E., Brosius, J. and Ptashne, M. (1983) Vectors bearing a hybrid *trp-lac* promoter
225 useful for regulated expression of cloned genes in *Escherichia coli*. *Gene.* **25**, 167-178
- 226 3 Guzman, L.M., Belin, D., Carson, M.J. and Beckwith, J. (1995) Tight regulation, modulation,
227 and high-level expression by vectors containing the arabinose PBAD promoter. *J Bacteriol.* **177**,
228 4121-4130
- 229 4 Studier, F.W. and Moffatt, B.A. (1986) Use of bacteriophage T7 RNA polymerase to direct
230 selective high-level expression of cloned genes. *J Mol Biol.* **189**, 113-130
- 231 5 Wagner, S., Klepsch, M.M., Schlegel, S., Appel, A., Draheim, R., Tarry, M., Högbohm, M., van
232 Wijk, K.J., Slotboom, D.J., Persson, J.O. and de Gier, J.W. (2008) Tuning *Escherichia coli* for
233 membrane protein overexpression. *Proc Natl Acad Sci U S A.* **105**, 14371-14376
- 234 6 Overton, T.W. (2014) Recombinant protein production in bacterial hosts. *Drug Discov Today.*
235 **19**, 590-601
- 236 7 Browning, D.F., Richards, K.L., Peswani, A.R., Roobol, J., Busby, S.J.W. and Robinson, C. (2017)
237 *Escherichia coli* 'TatExpress' strains super-secrete human growth hormone into the bacterial
238 periplasm by the Tat pathway. *Biotechnol Bioeng.* **114**, 2828-2836
- 239 8 Quick, M. and Wright, E.M. (2002) Employing *Escherichia coli* to functionally express, purify,
240 and characterize a human transporter. *Proc Natl Acad Sci U S A.* **99**, 8597-8601
- 241 9 Gopal, G.J. and Kumar, A. (2013) Strategies for the production of recombinant protein in
242 *Escherichia coli*. *Protein J.* **32**, 419-425
- 243 10 Novick, A. and Weiner, M. (1957) ENZYME INDUCTION AS AN ALL-OR-NONE PHENOMENON.
244 *Proc Natl Acad Sci U S A.* **43**, 553-566
- 245 11 Maloney, P.C. and Rotman, B. (1973) Distribution of suboptimally induces -D-galactosidase in
246 *Escherichia coli*. The enzyme content of individual cells. *J Mol Biol.* **73**, 77-91
- 247 12 Khlebnikov, A., Risa, O., Skaug, T., Carrier, T.A. and Keasling, J.D. (2000) Regulatable
248 arabinose-inducible gene expression system with consistent control in all cells of a culture. *J*
249 *Bacteriol.* **182**, 7029-7034
- 250 13 Murakami, K.S. and Darst, S.A. (2003) Bacterial RNA polymerases: the whole story. *Curr Opin*
251 *Struct Biol.* **13**, 31-39
- 252 14 Feklistov, A., Sharon, B.D., Darst, S.A. and Gross, C.A. (2014) Bacterial sigma factors: a
253 historical, structural, and genomic perspective. *Annu Rev Microbiol.* **68**, 357-376
- 254 15 Bae, B., Feklistov, A., Lass-Napiorkowska, A., Landick, R. and Darst, S.A. (2015) Structure of a
255 bacterial RNA polymerase holoenzyme open promoter complex. *Elife.* **4**
- 256 16 Zhang, Y., Feng, Y., Chatterjee, S., Tuske, S., Ho, M.X., Arnold, E. and Ebright, R.H. (2012)
257 Structural basis of transcription initiation. *Science.* **338**, 1076-1080
- 258 17 Zuo, Y. and Steitz, T.A. (2015) Crystal structures of the *E. coli* transcription initiation
259 complexes with a complete bubble. *Mol Cell.* **58**, 534-540
- 260 18 Ebright, R.H. (1993) Transcription activation at Class I CAP-dependent promoters. *Mol*
261 *Microbiol.* **8**, 797-802
- 262 19 Müller-Hill, B. (1996) The *lac* Operon. A Short History of a Genetic Paradigm. Walter de
263 Gruyter, Berlin New York
- 264 20 Wilson, C.J., Zhan, H., Swint-Kruse, L. and Matthews, K.S. (2007) The lactose repressor
265 system: paradigms for regulation, allosteric behavior and protein folding. *Cell Mol Life Sci.* **64**, 3-16
- 266 21 Oehler, S., Eismann, E.R., Kramer, H. and Müller-Hill, B. (1990) The three operators of the *lac*
267 operon cooperate in repression. *Embo J.* **9**, 973-979
- 268 22 Kramer, H., Niemöller, M., Amouyal, M., Revet, B., von Wilcken-Bergmann, B. and Müller-Hill,
269 B. (1987) *lac* repressor forms loops with linear DNA carrying two suitably spaced *lac* operators. *Embo*
270 *j.* **6**, 1481-1491

271 23 Oehler, S., Amouyal, M., Kolkhof, P., von Wilcken-Bergmann, B. and Muller-Hill, B. (1994)
272 Quality and position of the three *lac* operators of *E. coli* define efficiency of repression. *Embo J.* **13**,
273 3348-3355

274 24 Siebenlist, U., Simpson, R.B. and Gilbert, W. (1980) *E. coli* RNA polymerase interacts
275 homologously with two different promoters. *Cell.* **20**, 269-281

276 25 Hook-Barnard, I.G. and Hinton, D.M. (2007) Transcription initiation by mix and match
277 elements: flexibility for polymerase binding to bacterial promoters. *Gene Regul Syst Bio.* **1**, 275-293

278 26 Mitchell, J.E., Zheng, D., Busby, S.J. and Minchin, S.D. (2003) Identification and analysis of
279 'extended -10' promoters in *Escherichia coli*. *Nucleic Acids Res.* **31**, 4689-4695

280 27 Lodge, J., Fear, J., Busby, S., Gunasekaran, P. and Kamini, N.R. (1992) Broad host range
281 plasmids carrying the *Escherichia coli* lactose and galactose operons. *FEMS Microbiol Lett.* **74**, 271-
282 276

283 28 Sadler, J.R., Sasmor, H. and Betz, J.L. (1983) A perfectly symmetric *lac* operator binds the *lac*
284 repressor very tightly. *Proc Natl Acad Sci U S A.* **80**, 6785-6789

285 29 Simons, A., Tils, D., von Wilcken-Bergmann, B. and Muller-Hill, B. (1984) Possible ideal *lac*
286 operator: *Escherichia coli lac* operator-like sequences from eukaryotic genomes lack the central G X
287 C pair. *Proc Natl Acad Sci U S A.* **81**, 1624-1628

288 30 Albinia, A.M., Matos, C.F., Branston, S.D., Freedman, R.B., Keshavarz-Moore, E. and
289 Robinson, C. (2013) High-level secretion of a recombinant protein to the culture medium with a
290 *Bacillus subtilis* twin-arginine translocation system in *Escherichia coli*. *Febs j.* **280**, 3810-3821

291 31 Alanen, H.I., Walker, K.L., Lourdes Velez Suberbie, M., Matos, C.F., Bonisch, S., Freedman,
292 R.B., Keshavarz-Moore, E., Ruddock, L.W. and Robinson, C. (2015) Efficient export of human growth
293 hormone, interferon alpha2b and antibody fragments to the periplasm by the *Escherichia coli* Tat
294 pathway in the absence of prior disulfide bond formation. *Biochim Biophys Acta.* **1853**, 756-763

295 32 Bryksin, A.V. and Matsumura, I. (2010) Overlap extension PCR cloning: a simple and reliable
296 way to create recombinant plasmids. *Biotechniques.* **48**, 463-465

297 33 Sambrook, J. and Russell, D.W. (2001) Molecular cloning : a laboratory manual. Cold Spring
298 Harbor Laboratory Press, Cold Spring Harbor, N.Y.

299 34 Sarkar, G. and Sommer, S.S. (1990) The "megaprimer" method of site-directed mutagenesis.
300 *Biotechniques.* **8**, 404-407

301 35 Robinson, C., Matos, C.F., Beck, D., Ren, C., Lawrence, J., Vasisht, N. and Mendel, S. (2011)
302 Transport and proofreading of proteins by the twin-arginine translocation (Tat) system in bacteria.
303 *Biochim Biophys Acta.* **1808**, 876-884

304 36 Makoff, A.J. and Oxeer, M.D. (1991) High level heterologous expression in *E. coli* using mutant
305 forms of the *lac* promoter. *Nucleic Acids Res.* **19**, 2417-2421

306 37 Balasundaram, B., Harrison, S. and Bracewell, D.G. (2009) Advances in product release
307 strategies and impact on bioprocess design. *Trends Biotechnol.* **27**, 477-485

308 38 Weiss, D.S., Chen, J.C., Ghigo, J.M., Boyd, D. and Beckwith, J. (1999) Localization of FtsI (PBP3)
309 to the septal ring requires its membrane anchor, the Z ring, FtsA, FtsQ, and FtsL. *J Bacteriol.* **181**,
310 508-520

311 39 Garza de Leon, F., Sellars, L., Stracy, M., Busby, S.J.W. and Kapanidis, A.N. (2017) Tracking
312 Low-Copy Transcription Factors in Living Bacteria: The Case of the *lac* Repressor. *Biophys J.* **112**,
313 1316-1327

314 40 Browning, D.F. and Busby, S.J. (2016) Local and global regulation of transcription initiation in
315 bacteria. *Nat Rev Microbiol.* **14**, 638-650

316 41 Yanisch-Perron, C., Vieira, J. and Messing, J. (1985) Improved M13 phage cloning vectors and
317 host strains: nucleotide sequences of the M13mp18 and pUC19 vectors. *Gene.* **33**, 103-119

318 42 Browning, D.F. and Busby, S.J. (2004) The regulation of bacterial transcription initiation. *Nat*
319 *Rev Microbiol.* **2**, 57-65

320 43 Browning, D.F., Cole, J.A. and Busby, S.J. (2008) Regulation by nucleoid-associated proteins
321 at the *Escherichia coli nir* operon promoter. *J Bacteriol.* **190**, 7258-7267

322 44 Dykxhoorn, D.M., St Pierre, R. and Linn, T. (1996) A set of compatible tac promoter
323 expression vectors. *Gene*. **177**, 133-136
324 45 Browning, D.F., Matthews, S.A., Rossiter, A.E., Sevastyanovich, Y.R., Jeeves, M., Mason, J.L.,
325 Wells, T.J., Wardius, C.A., Knowles, T.J., Cunningham, A.F., Bavro, V.N., Overduin, M. and Henderson,
326 I.R. (2013) Mutational and topological analysis of the *Escherichia coli* BamA protein. *PLoS One*. **8**,
327 e84512

328

329 **FIGURE LEGENDS**

330

331 **Figure 1. Transcript initiation at bacterial promoters and regulation at the *lac* promoter**

332 **(A)** Bacterial promoter elements. A sketch showing the organization of different promoter
333 elements at a model bacterial promoter with respect to the transcript start site (+1). Elements
334 are denoted by coloured rectangles with their consensus sequence motifs indicated. Note
335 that bacterial promoters usually contain a selection of these elements but rarely contain all of
336 them [40].

337 **(B)** Sketch illustrating the key interactions between different domains of the RNAP sigma
338 and alpha subunits and different promoter elements in the initial “closed” complex at a
339 promoter. Note that the DNA duplex remains double-stranded and that the contacts result in
340 Sigma Domain 2 being positioned adjacent to the promoter -10 element.

341 **(C)** Sketch illustrating the key interactions between different RNAP determinants and
342 different promoter elements in the transcriptionally-competent “open” complex at a promoter.
343 Note that the DNA duplex around position +1 is unwound, with Sigma Domain 2 making
344 specific base contacts with the single-stranded non-template strand of the promoter -10
345 element, thereby permitting the single-stranded template strand to enter the RNAP active
346 site.

347 **(D)** A schematic representation of the *E. coli lac* operon promoter. The -35 and -10 promoter
348 elements are shown as green and yellow boxes, respectively, the *lac* operator sequences
349 (O1 and O3) are red boxes and the CRP binding site is shown by inverted arrows. The
350 position of each element is given with respect to the start site of transcription (+1). The LacI
351 tetramer binds to the O1 and O3 operators to form a repression loop, silencing *lac* operon
352 expression (-ve), whilst CRP activates transcription (+ve).

353

354

355 **Figure 2. Organisation of *lac*, *tac* and *lacUV5* promoter constructs**

356 **(A)** The panel shows schematic representations of the *lac* O3O1, *lacUV5* O3O1 and *tac* O1
357 promoters and the important elements involved in their regulation. All numbering is in
358 relation to the promoter transcription start (+1), which is indicated by a bent arrow. The O1
359 and O3 operator sequences, which bind the LacI repressor, are indicated by red boxes,
360 the -35 promoter elements by green boxes, and the CRP site, within the *lacUV5* and *lac*
361 promoters, is represented by inverted arrows. The *plac* -10 promoter element is shown as a
362 yellow box, whilst the *placUV5* and *ptac* consensus -10 elements are gold. The sequence of
363 the O3, O1 and Oid operators, and the site at which different operator sequences were
364 introduced into the *tac* O1, *lacUV5* O3O1 and *lac* O3O1 promoters is shown by an arrow.

365 **(B)** The panel shows the base sequence of DNA fragments carrying the *lac* O3O1, *lacUV5*
366 O3O1 and *tac* O1 promoters. All promoter fragments carry the relevant sequences from -92
367 to +38, in relation to the transcription start, and possess terminal EcoRI and HindIII sites for
368 cloning into the *lacZ* expression vector, pRW50 [27]. The O1 and O3 operator sequences
369 are highlighted in grey, CRP binding targets are underlined and the -35 and -10 promoter
370 elements are in bold and underlined, having also been aligned to the relevant consensus
371 sequence for each element [40]. Note that the *lacUV5* promoter only differs from the wild-
372 type *lac* promoter by carrying a consensus -10 element (*i.e.* the p8A and p9A substitutions)
373 [24].

374

375 **Figure 3. Expression levels of engineered *ptac* and *plac* promoter derivatives**

376 The figure illustrates measured β -galactosidase activities of *E. coli* K-12 strain JM109 (Δlac ,
377 *lac^f*) cells carrying pRW50 [27, 41] containing different promoter fragments. Promoter
378 fragments were generated using PCR and cloned into pRW50 to create *lacZ* transcriptional
379 fusions, using standard techniques [27, 33]. Panels **(A)**, **(B)** and **(C)** show the effect of
380 introducing the O3, O1 and Oid operator sequences into the upstream region of the *tac* O1,
381 *lacUV5* O3O1 and *lac* O3O1 promoter fragments, respectively, as displayed in Figure 2. **(D)**
382 The panel details the effect of introducing point mutations into the -10 and -35 elements of
383 various *lac* promoter derivatives (*i.e.* *lac* O3O1, *lac* O1O1, *lacUV5* O3O1, *lacUV5* O1O1) to

384 improve these regions in relation to the extended -10 and -35 consensus sequences (see
385 Figure 2) [42]. By convention, locations are labelled in relation to the *plac* transcript start
386 point (+1). Note that the *lac* O1O1 D19 promoter carries a base pair deletion at position -19.
387 The fold increase in expression, in comparison to the weakest promoter (*lac* O1O1) is
388 indicated for each promoter in the presence of IPTG. In all panels, JM109 cells were grown
389 in LB medium until mid-exponential phase, in the presence or absence of 1 mM IPTG. β -
390 galactosidase activities were determined using o-nitrophenyl- β -D-galactopyranose (ONPG)
391 and a Miller protocol, as in our previous work [43], and are expressed as nmol of ONPG
392 hydrolysed $\text{min}^{-1} \text{mg}^{-1}$ dry cell mass. Each activity is the average of three independent
393 determinations and the error bars represent the standard deviation of values.

394
395

396 **Figure 4. The expression of TorA-protein fusions can be set to different levels with**
397 **PAR promoter constructs**

398 **(A)** Expression from the PAR promoter constructs. The panel shows the β -galactosidase
399 activities measured in the *E. coli* K-12 strain JM109 (Δlac , *lacI^q*) containing the *lacZ*
400 expression vector pRW50 carrying various PAR promoters. PAR promoters (PAR1 to PAR8)
401 were selected from the various *tac* and *lac* promoters detailed in Figure 3. β -galactosidase
402 activities are expressed as nmol of ONPG hydrolysed $\text{min}^{-1} \text{mg}^{-1}$ dry cell mass. Each activity
403 is the average of three independent determinations and standard deviations are shown for
404 all data points. **(B)** Expression of a TorA-GFP-6His protein fusion in BL21 cells (Novagen),
405 using pGFP-TorA based vectors [30]. PAR promoters, PAR4 to PAR6 and PAR8 were
406 introduced into the low-copy-number vector pGFP-TorA, such that each promoter drives the
407 expression of a *torA-gfp-6his* fusion. Note that pGFP-TorA is a derivative of expression
408 vector pEXT22 [44], which has been included as an empty vector control. **(C)** Expression of
409 a TorA-hGH-6His protein fusion in BL21 cells, using pHAK1 based vectors [31]. PAR
410 promoters, PAR5 to PAR8 were introduced into the high-copy-number vector pHAK1 such
411 that each promoter drives the expression of a *torA-hGH-6his* fusion. Note that the *torA* signal
412 sequence directs the GFP-6His and hGH-6His moieties to the Tat translocon for periplasmic
413 targeting [7, 30, 31]. Cells were grown in LB medium until an OD_{600} of ~ 0.4 when RPP was
414 induced by the addition of 1 mM IPTG for 3 hrs. In **(B)** and **(C)** expression of TorA-GFP-6His
415 and TorA-hGH-6His was analysed by Western blotting (upper panel), using either anti-GFP
416 antibody (Sigma) or polyclonal anti-hGH antibody, respectively, and a Coomassie blue
417 stained SDS-PAGE gel (lower panel), using normalised total cell protein from BL21 cells, as
418 detailed in [45]. Samples were calibrated by loading Page Ruler Plus prestained markers
419 (Thermo Scientific). Note that, in the Western blot in panel **(B)**, all lanes were from the same
420 blot and have only been separated to aid presentation of the data.

Figure 1

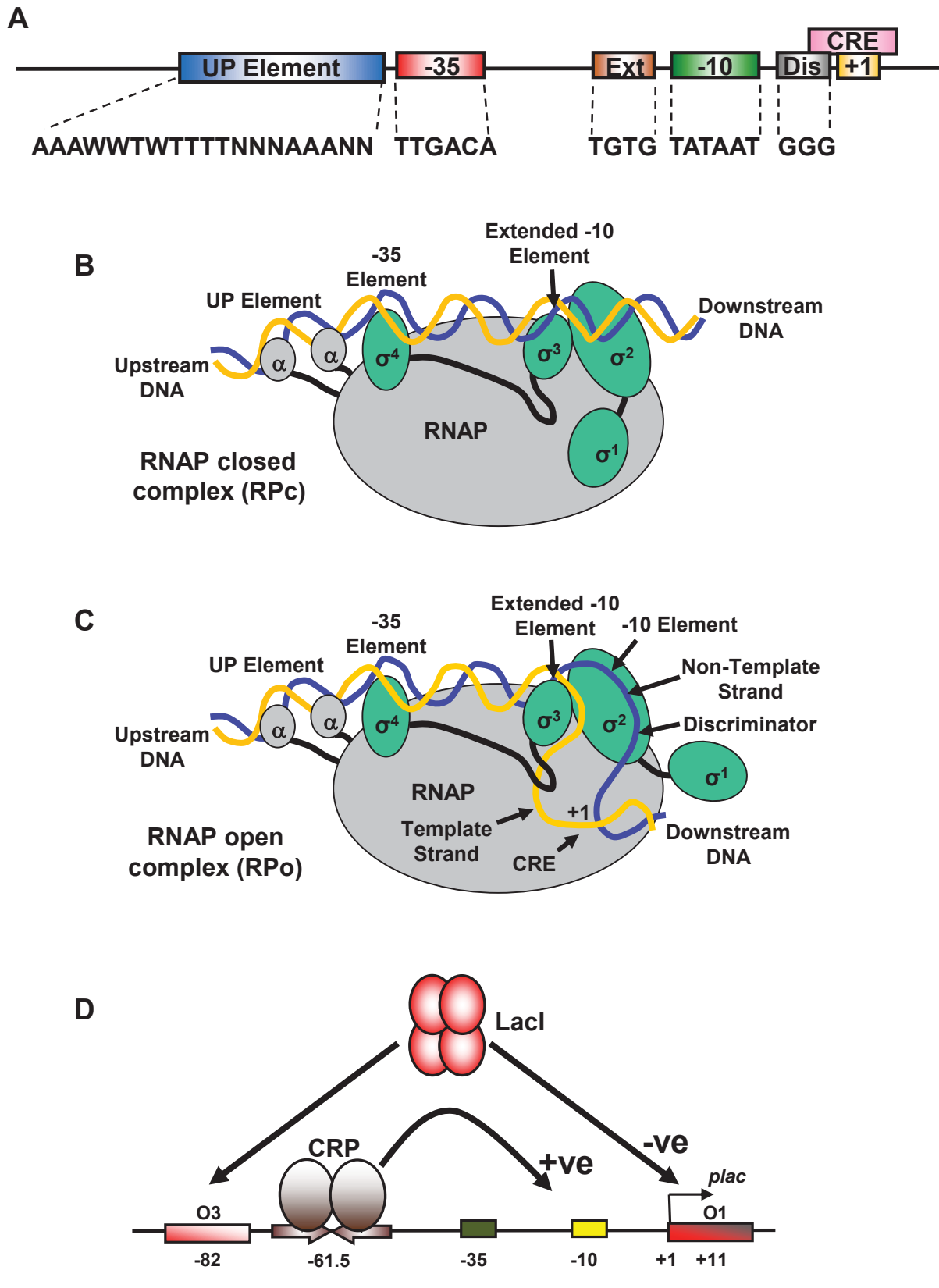


Figure 2

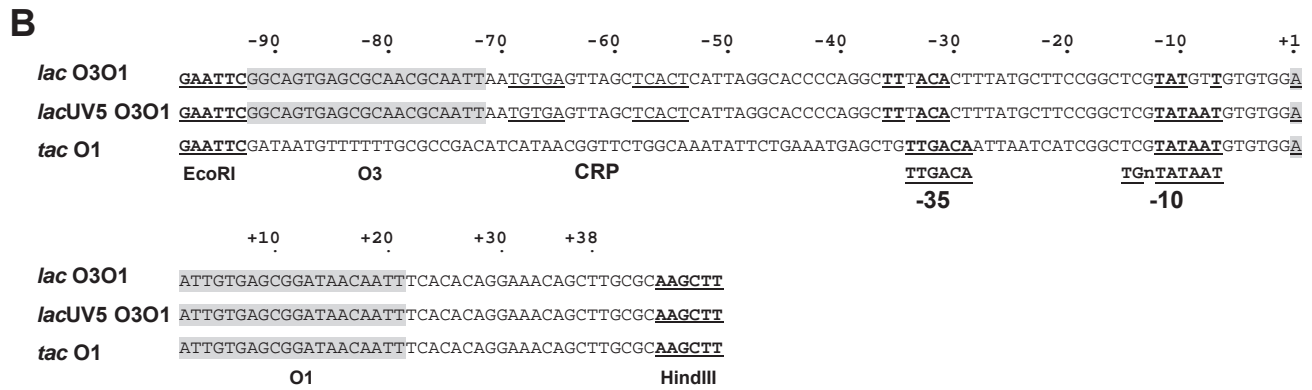
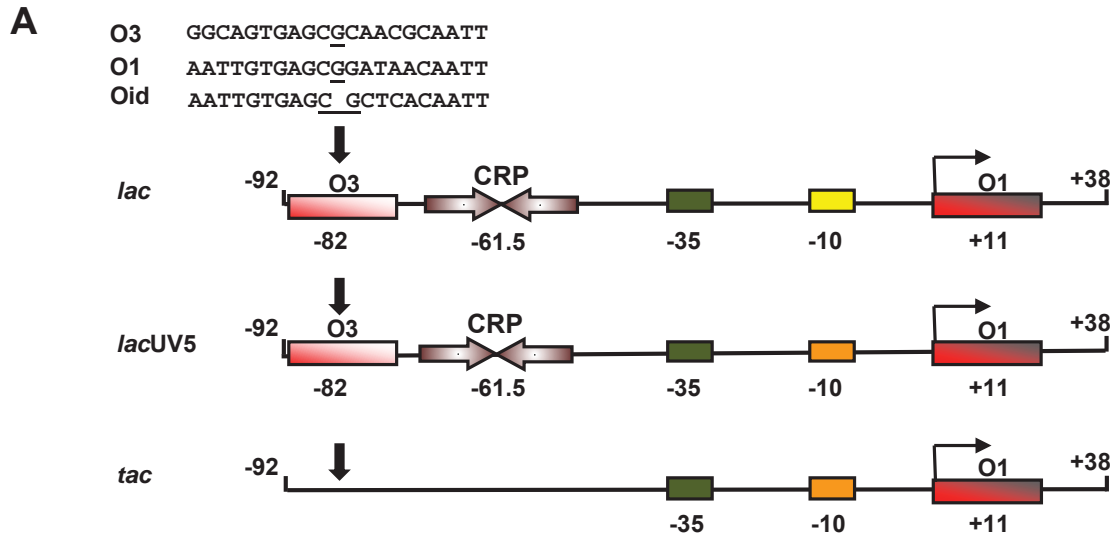


Figure 3

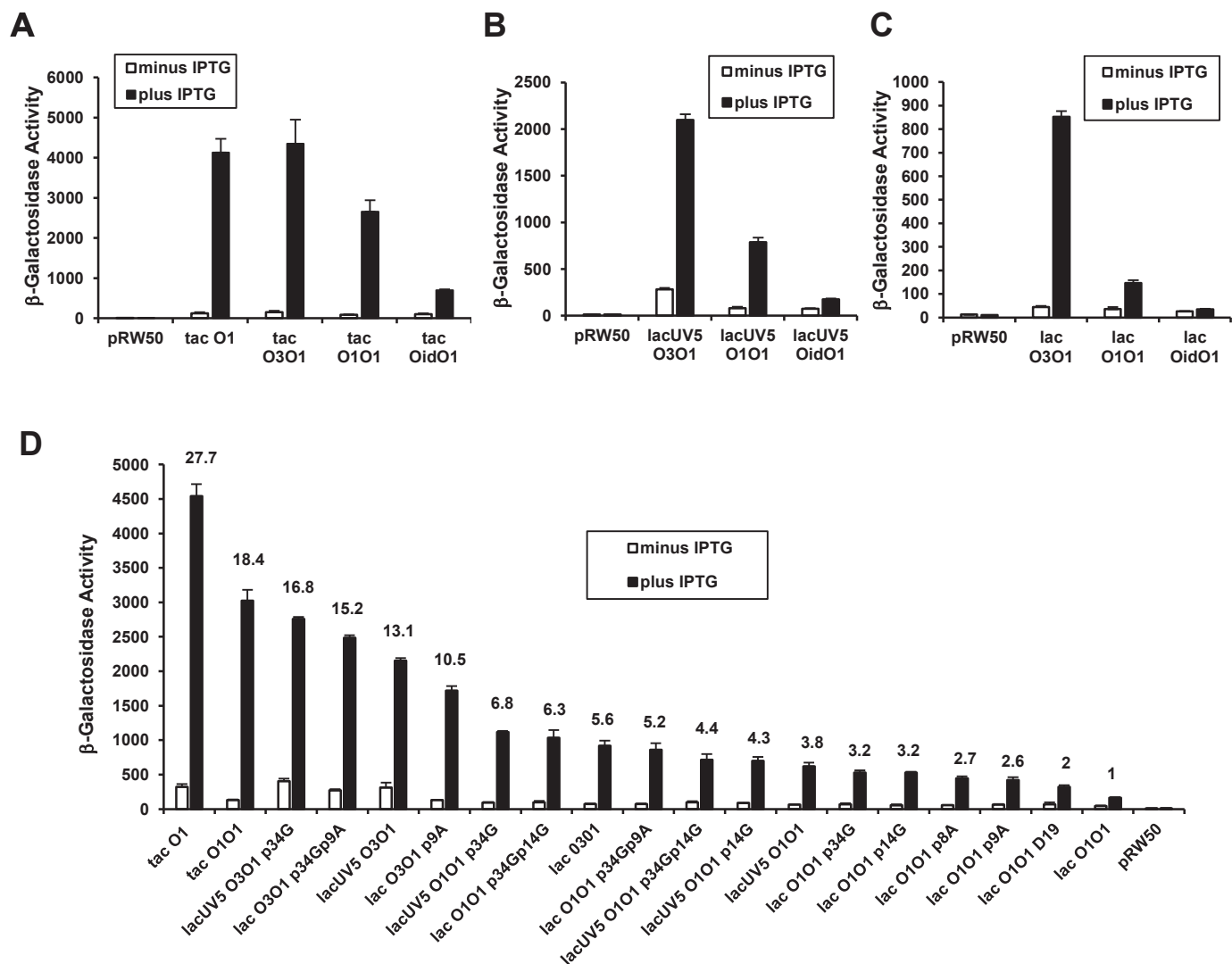
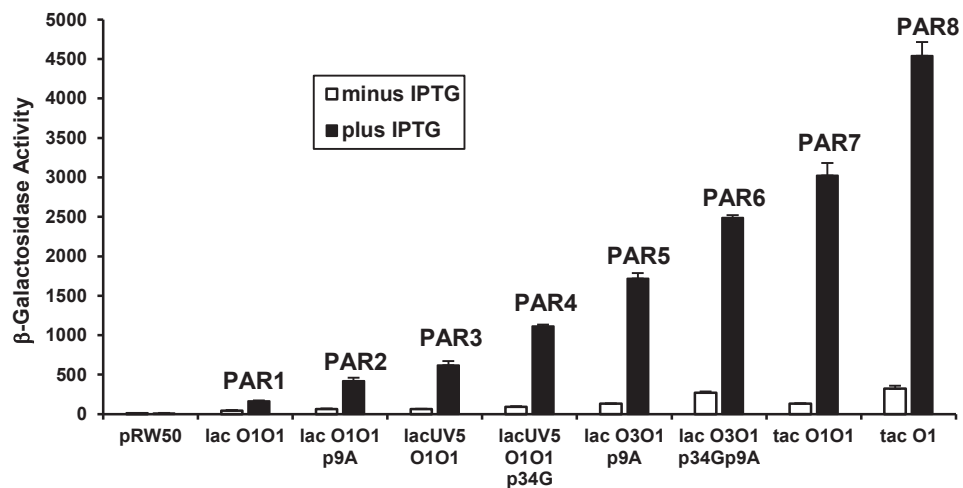
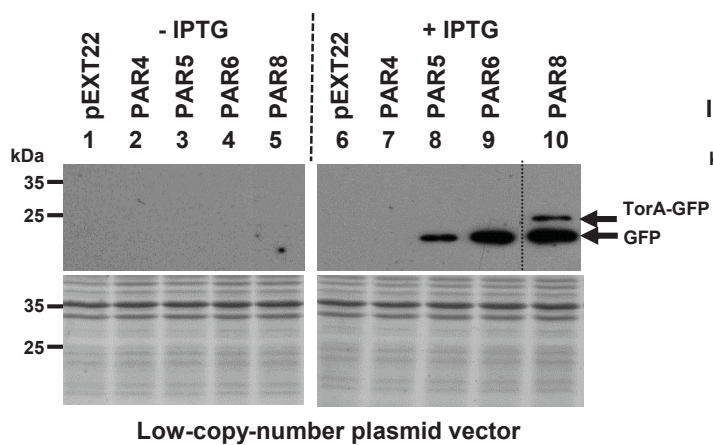


Figure 4

A



B



C

