Quantitation of the DNA tethering effect in long-range DNA looping in vivo and in vitro using the Lac and \(\lambda\) repressors

David G. Priest\(^a\), Lun Cui\(^c\), Sandip Kumar\(^b\), David D. Dunlap\(^b\), Ian B. Dodd\(^{1,1}\) and Keith E. Shearwin\(^a\)

\(^a\)Discipline of Biochemistry, School of Molecular and Biomedical Science, University of Adelaide, Adelaide, SA 5005, Australia; and \(^b\)Department of Cell Biology, Emory University, Atlanta, GA 30322

Edited by Mark Ptashne, Memorial Sloan Kettering Cancer Center, New York, NY, and approved November 18, 2013 (received for review September 20, 2013)

Efficient and specific interactions between proteins bound to the same DNA molecule can be dependent on the length of the DNA tether that connects them. Measurement of the strength of this DNA tethering effect has been largely confined to short separations between sites, and it is not clear how it contributes to long-range DNA looping interactions, such as occur over separations of tens to hundreds of kilobase pairs in vivo. Here, gene regulation experiments using the Lac and \(\lambda\) Cl repressors, combined with mathematical modeling, were used to quantitate DNA tethering inside \textit{Escherichia coli} cells over the 250- to 10,000-bp range. Although Lac and \(\lambda\) Cl loop DNA in distinct ways, measurements of the tethering effect were very similar for both proteins. Tethering strength decreased with increasing separation, but even at 5- to 10-kb distances, was able to increase contact probability 10- to 20-fold and drive efficient looping. Tethering in vitro with the Lac repressor was measured for the same 600- to 3,200-bp DNAs using tethered particle motion, a single molecule technique, and was 5- to 45-fold weaker than in vivo over this range. Thus, the enhancement of looping seen previously in vivo at separations below 500 bp extends to large separations, underlying the need to understand how in vivo factors aid DNA looping. Our analysis also suggests how efficient and specific looping could be achieved over very long DNA separations, such as what occurs between enhancers and promoters in eukaryotic cells.

\[ j \text{ factor} \mid \text{TPM} \mid \text{promoter-enhancer} \]

Interactions between proteins bound to separate sites on the same DNA molecule are critical in gene regulation and other DNA processes (1–4). The DNA separation between functionally interacting sites ranges from a few base pairs to hundreds of kilobase pairs, as in the case of some eukaryotic enhancers and their promoters. At short separations, it is clear that the DNA acts as a tether that keeps one site in the vicinity of the other so that the proteins at one site can find the other site in 3D space more efficiently than if they were free in solution (Fig. 1). Tethering is also a way to provide specificity because it aids interaction with linked sites but not unlinked sites. However, as the separation between the sites increases, this tethering effect becomes weaker, and it is not understood how the DNA linkage between widely separated sites, for example, between enhancers and promoters, provides the efficiency and specificity required for proper regulation.

The effect of DNA tethering can be quantified by the factor \(j\text{LOOP} (M)\), the effective molar concentration of one site on the DNA relative to the other, or as the free energy of the DNA looping reaction \(\Delta G_{\text{LOOP}}\) (Fig. 1) (5–9). These parameters are interconvertible: \(\Delta G_{\text{LOOP}} = -RT\ln j\text{LOOP}\) (kcal/mol; the reference \(j = 1 \text{ M}\)). The formation of a naked DNA loop is in itself an energetically unfavorable reaction (\(\Delta G_{\text{LOOP}}\) is positive) under physiological conditions due to the enthalpic cost of DNA bending and twisting (particularly important for short DNA segments) and the entropic cost of restricted configurational freedom of the DNA (the major limitation for long DNA loops). Thus, protein-mediated DNA looping reactions are driven by thermodynamic linkage to favorable protein–protein and protein–DNA interactions (Fig. 1). Nevertheless, the DNA tether can help assemble DNA-protein complexes because the effective concentration of the DNA-bound protein at the distant site, \(j\text{LOOP}\), can be greater than the concentration of available free protein (Fig. 1). Despite its critical role in DNA looping interactions, there are few measurements of \(j\text{LOOP}\) in vivo, and these are mostly restricted to short site separations.

Many in vivo techniques used to detect DNA looping interactions can quantitate relative contact efficiencies but do not permit measurement of \(j\text{LOOP}\). Chromosome conformation capture (3C) and related methods have revealed a complex network of in vivo interactions, many over megabase pair DNA distances, between DNA sites in the genomes of organisms ranging from bacteria to humans (4, 10, 11). Assays using DNA recombinases have shown, as expected from DNA polymer theory, that specific contact efficiencies decrease with increasing DNA separation between the sites over the 1- to 100-kb range (12, 13). None of these methods reveal the fraction of the time that the sites are in contact.

\(j\text{LOOP}\) for naked DNA in vitro is quite low at long separations. DNA cyclization measurements show that \(j\text{LOOP}\) decreases with increasing tether length beyond \(\sim 500 \text{ bp}\), falling to \(\sim 10 \text{ nM}\) at \(4,000 \text{ bp}\) (5, 14). Measurements of \(j\text{LOOP}\) for protein-induced looping give a similar picture. Most studies have focused on linear tethers \(\sim 500 \text{ bp}\), finding variable \(j\text{LOOP}\) values generally below \(100 \text{ nM}\) (9). Lower \(j\text{LOOP}\) values are seen at longer separations: \(\sim 18 \text{ nM}\) for Cre DNA recombination at 3,000 bp (15), whereas LacI DNA binding cooperativity was undetectable at

Significance

Proteins bound to DNA often interact with proteins bound elsewhere on the same DNA to regulate gene expression. The intervening DNA tethers the proteins near each other, making their interaction efficient and specific, but the importance of this tethering effect is poorly understood at large DNA separations. We quantitated tethering inside bacterial cells, using two different proteins at separations up to 10,000 bp, to show that tethering is strong enough to drive efficient interactions over these distances. The same interactions were \(\sim 10\)-fold weaker outside cells, implying that cellular factors enhance tethering. However, tethering was lost at a DNA separation of 500,000 bp inside bacteria, indicating special mechanisms inside eukaryotic cells to provide efficient and specific interactions over such distances.


The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

\(^1\)To whom correspondence should be addressed. E-mail: ian.dodd@adelaide.edu.au.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1317817111/-/DCSupplemental.

www.pnas.org/cgi/doi/10.1073/pnas.1317817111

PNAS | January 7, 2014 | vol. 111 | no. 1 | 349–354
Most existing estimates of \( j_{\text{LOOP}} \) in vivo have been obtained by analysis of DNA loop-dependent repression of transcription by the Lac and λ CI repressors (6–8, 18–20). In such noncatalytic systems, the degree of repression reflects the fraction of the time that the repressor is bound at the promoter, allowing the thermodynamic stability of the looping interaction to be estimated. Analyses of data for LacI looping at short DNA separations (21, 22) have given \( j_{\text{LOOP}} \) values of the order of 1 μM (6, 8, 19), which is much higher than would be expected based on in vitro estimates and modeling. However, at longer separations, in vivo looping by Lac repressor seems to be weak, with little effect seen at a spacing of 1,500 bp (21) and no effect at 4,300 bp (22), leading these authors to conclude that long-range looping by LacI is inefficient. In contrast, we estimated \( j_{\text{LOOP}} \) of ~850 nM for λ CI DNA loops of 3.8 and 2.3 kb (7, 23), and single-molecule imaging in live Escherichia coli cells of CI-mediated interactions over a 2.3-kb separation gave results indicating a \( j_{\text{LOOP}} \) of ~240 nM (20).

In theory, \( j_{\text{LOOP}} \) for DNA loops formed by LacI or λ CI should be the same at large separations, where protein conformation effects are minimal. To resolve this apparent discrepancy and to extend the estimates of \( j_{\text{LOOP}} \) for long DNA separations in vivo, we performed systematic repression-based \( j_{\text{LOOP}} \) assays over the 300-bp to 10-kb range using the LacI and λ CI repressors in E. coli. To test whether the in vivo enhancement of looping seen at short separations holds at long separations, we measured \( j_{\text{LOOP}} \) in vitro with TPM using the Lac repressor for 600- to 3,200-bp separations with the same DNA constructs. The results for the two different repressors were similar and show that long-range DNA looping in vivo is considerably more efficient than for naked DNA in vitro, indicating long distance suppressing factors inside cells. Strategies for maximizing looping efficiency are discussed.

Results

System to Estimate \( j_{\text{LOOP}} \) Using Lac Repression in Vivo. We made chromosomally integrated lacZ reporters driven by the catabolite activator protein (CAP)-independent PlacUV5 promoter controlled by a proximal lac operator (\( O_P \)) at the normal OI position (centered at +11) and an upstream distal lac operator (\( O_D \); Fig. 2D). To characterize the system, we used three natural operators (\( O_1, O_2, \) and \( O_3 \)) at \( O_P \), and three operators (\( Oid \), a high affinity operator; \( OI \); and a mutant operator, \( O' \)) at \( O_D \), with a 300-bp spacing (center to center) between \( O_D \) and \( O_P \). Expression of lacZ was measured in the absence of Lac repressor (\( L0 \)) or at two different LacI concentrations (\( L1 \) and \( L2 \)), expressed from PlacI-lacI or PlacP-lacI constructs integrated at a separate chromosomal site (Fig. 2C). The results showed, as expected, that the presence of \( OI \) or Oid at \( O_D \) increased repression substantially, depending on the operator combination and the LacI concentration (Fig. 2B).

By fitting the data to a statistical-mechanical model of LacI repression (Fig. 2C), we were able to estimate a number of in vivo parameters (Fig. 2D). The model is similar to Han et al. (9), with the addition of RNA polymerase (RNAP) binding to PlacUV5 in competition with LacI (24). The cellular concentration of LacI tetramers supplied from the WT lacI promoter has been estimated at 18 nM (25) (11 tetramers in a 1-fL volume) and was used for \( L1 \). The model does not permit determination of absolute binding constants, and \( K_I \) was arbitrarily fixed to 1 nM. The relative dissociation constants obtained for the four operators are similar to those found by Garcia and Phillips (25) (0.22, 1, 4.5, and 333 for \( \text{Kid} \), \( K1 \), \( K2 \), and \( K3 \), respectively). Western blotting and Plac\( _* \) and Plac\( ^P \) activities (Fig. S4) supported the estimate of the ratio of the high and low LacI repressor concentrations of \( L2/L1 \approx 10.9 \). Other reporter measurements (SI Materials and Methods) supported the estimate of 18.1 background LacZ units from the PlacUV5-lacZ reporter (Fig. 2D).

The fitting gives an estimate of \( j_{\text{LOOP}}/L1 \) that is independent of the fixed values chosen for \( K_I \) or \( L1 \). Assuming \( L1 = 18 \) nM gives \( j_{\text{LOOP}} = 1,400 \) nM (for this 300-bp spacing), similar to estimates of ~1 μM for short lac operator spacings (6, 8, 19).

Effect of DNA Spacing on LacI Looping in Vivo. To measure \( j_{\text{LOOP}} \) over longer distances, we used Oid-02 reporters with operator spacings ranging from 242 to 5,600 bp. The sequence of spacer DNA had no effect on the efficiency of short LacI DNA loops (Fig. 2E), so we made two series of spacers: series 1 (300–5,600 bp) and series 2 (242–3,200 bp). We also inserted Oid (or \( O' \)) in the chromosome 500 kb away from O2 (SI Materials and Methods).

The upstream operator aided repression most strongly at the shortest spacing (242 bp). Although its effect weakened with increasing spacer length, there remained a significant effect of the upstream operator at 5,600 bp at the \( L1 \) concentration (Fig. 3A). The operator placed 500 kb away had no effect on repression.

The reporter data were fitted using the model and the parameters from Fig. 2D but allowing \( j_{\text{LOOP}}/L1 \) to vary for each operator spacing (SI Materials and Methods). These \( j_{\text{LOOP}}/L1 \) values (Fig. 3B and Fig. S5) show that the effective concentration of the operators relative to each other ranges from 180-fold the \( L1 \) concentration of LacI in solution at 242 bp to 1.8-fold \( L1 \) at 5,600 bp. Thus, even at a 5,600-bp separation, a Lac repressor at the distal lac operator is seen by the promoter almost two times more frequently than all of the other Lac repressors in the cell combined. In contrast, the data for the 500-kb spacing was fitted with a \( j_{\text{LOOP}}/L1 \) value of 0.09 (Fig. 3C); a Lac repressor bound 500 kb away contacts the proximal operator no more frequently than any of the other ~11 Lac repressors in the cell.

The \( j_{\text{LOOP}}/L1 \) values allow calculation of the fraction of looping for Oid and O2 at each separation and [lacI] (Fig. 3C). LacI looping is sensitive to concentration; at low concentrations, looping is obstructed by the formation of doubly bound species (species 6; Fig. 2C). Maximal looping decreases with increasing spacing, but even at separations of 5,600 bp, Oid-O2 are looped at least 30% of the time over a 100-fold range of [lacI] (0.2–20 nM; Fig. 3C).

Effect of Separation on Long-Range Looping by λ CI Repressor in Vivo. We used λ CI to obtain an independent measurement of the relationship between \( j_{\text{LOOP}} \) and DNA separation in vivo. DNA looping by λ CI can be detected by repression of the λ PRM.
promoter (7, 23, 27). At low concentrations, CI dimers form tetramers on OR1.OL2 or OR1.OL2R2, activating PRM, and these tetramers can interact to form an octamer-bridged DNA loop (Fig. 4A; free energy ΔGloop). The loop allows a dimer bound at OR2 to help a dimer bind to the weak OR3, forming a trans- tetramer and repressing PRM (Fig. 4A; dimer-dimer interaction free energy ΔGdimer). Thus, repression at moderate CI concentrations requires the distal OR site. With a statistical-mechanical model for CI regulation (7, 23), the free energy for the DNA looping reaction in vivo, ΔGloop, can be extracted from a comparison of PRM activity ± OL at high CI concentrations.

The looping reaction comprises the unfavorable DNA looping energy ΔGloop and a favorable protein–protein interaction ΔGPTN between DNA-bound CI tetramers: ΔGloop = ΔGPTN + ΔGPTN. Estimating ΔGPTN from a measure of the free energy of CI octamerization in vitro (−9.1 kcal/mol) (28, 29), it is possible to derive ΔGloop from ΔGoct (7) (SI Materials and Methods).

We made a series of OR.PRM.lacZ reporters with OL (or an OR sequence) at distances from 150 to 10,000 bp upstream of OR (Fig. 4A, Figs. S1 and S2, and SI Materials and Methods). A chromosomally integrated ci gene (or vector only) provided repression (lactZ activity). Data errors are 95% confidence limits; n ≥ 8. (C) Statistical mechanical model of regulation by LacI tetramers. L is the concentration of LacI tetramers, Ks are dissociation constants, and R is a dimensionless constant describing RNAP occupation of the promoter. (D) Parameters obtained from data fitting. Kid, K1, K2, and K3 are dissociation constants for Oid, O1, O2, and O3, respectively. Zmax is the lacZ activity obtained if the promoter were to be fully occupied by RNAP (average shown; SI Materials and Methods). bkg is the LacZ units obtained if the promoter is completely repressed. Errors are SDs from 100 data fittings (SI Materials and Methods).

Fig. 2. Using regulation by LacI looping to measure jloop in vivo. (A) Chromosomal PlacUV5.lacZ reporters with a lac operator at the promoter (O3) and 300 bp upstream (O2), with Lac supplied from a chromosomal lac gene with plac (low [LacI] = L1) or plac (high [LacI] = L2). (B) Data and model fits for the four O2–O3 combinations tested, assuming L1 = 18 nM. The numbers on the plots are data (model) in the absence of LacI. Data errors are 95% confidence limits; n ≥ 8. (C) Statistical mechanical model of regulation by LacI tetramers. L is the concentration of LacI tetramers, Ks are dissociation constants, and R is a dimensionless constant describing RNAP occupation of the promoter. (D) Parameters obtained from data fitting. Kid, K1, K2, and K3 are dissociation constants for Oid, O1, O2, and O3, respectively. Zmax is the lacZ activity obtained if the promoter were to be fully occupied by RNAP (average shown; SI Materials and Methods). bkg is the LacZ units obtained if the promoter is completely repressed. Errors are SDs from 100 data fittings (SI Materials and Methods).

Long-Range Looping by lac Repressor in Vitro. Previous studies indicate that LacI looping with short DNA tethers (<500 bp) is less efficient in vitro than in vivo. To test whether this difference holds for longer DNA tethers, we examined LacI looping in single molecules by TPM (9, 30–32), where looping of a DNA molecule attaching a bead to a surface can be detected as a restriction in the Brownian motion of the bead (Fig. 5A). The fragments were the same as the 600-, 900-, 1,200-, and 3,200-bp spacing in vivo constructs, but with O1 at OP (Fig. S4, Fig. S5, and SI Materials and Methods).

Looped and unlooped states were followed over time over a range of LacI concentrations. Excursion values from the motion records of all selected beads in one experimental condition were assembled in a histogram from which average looping probabilities were determined (Fig. 5B). As expected, the probability of looping goes through a maximum with respect to [LacI] (Fig. 5C). At LacI concentrations at which Oid is fully occupied, the decrease in looping with increasing [LacI] allows estimation of jloop independently of the affinity of O1 (Fig. 5D), because looping or unlooping is a simple binding competition between bound or free LacI (9).

The 600-bp jloop value obtained by TPM is 5.7-fold lower than the LacI and CI in vivo estimates (Fig. 5E), consistent with previous studies. Interestingly, this difference increases at longer separations: 11-fold at 1,200 bp and 45-fold at 3,200 bp (Fig. 4D). The TPM measurement of ΔGact = 1.7 kcal/mol for CI looping at 2,300 bp (17) gives a jloop value that is also approximately sevenfold lower than the in vivo CI and LacI estimates (Fig. 4D).

Discussion
DNA Can Foster Long-Range Interactions Even at Large Site Separations. We used two well-characterized bacterial systems where transcription is regulated by DNA looping to obtain measurements of jloop in vivo for DNA tether lengths beyond 5 kb. The results for LacI
and λ CI were in remarkable agreement, especially considering the differences in looping mechanism, with formation of a LacI loop primarily a DNA-protein interaction (Figs. 1A and 2C) and formation of the CI loop dominated by a protein-protein interaction (Figs. 1B and 4D). The different modeling approaches and the distinct additional parameters needed to extract $J_{\text{LOOP}}$ (L1 for LacI and $\Delta G_{\text{PTN}}$ for CI) make the estimates quite independent of each other. In addition, as discussed, our estimates for shorter spacings agree well with previous in vivo measurements (6, 19, 20).

At separations <300 bp, $J_{\text{LOOP}}$ was >1 μM and decayed with separation roughly as a power law with exponent −1.2 (Fig. S10). In the 5- to 10-kb separation range, $J_{\text{LOOP}}$ was still ~20−40 nM, substantially higher than the 1.7 nM concentration of a single molecule within a cell volume of 1 fL (1 μm³). Thus, as long as the concentration of a protein in the cell is reasonably low, even a distant operator can strongly increase its effective local concentration. As a result, even at these distances, the fraction of time that the DNA sites spend looped can be considerable. For Oid-O2 at 5,600-bp separation, the fraction looped could be almost 40% (Fig. 3C). For λ OL-OR at 10-kb separation, the fraction looped can be at least 50% at CI concentrations >3 WLU (Fig. 4D).

This reasonably strong tethering effect at 5−10 kb disappears at a separation of 500 kb, where the distal operator has no detectable effect on regulation by LacI or CI. Thus, even at large separations, distance matters: a DNA site 10 kb away is much closer than a site 500 kb away. A question remains whether there is a gradual decline in $J_{\text{LOOP}}$ over the 10- to 500-kb range or whether tethering is lost at separations well short of 500 kb. Simple extrapolation of the in vivo data in Fig. 5E (Fig. S10) suggests that substantial tethering could exist at separations ~100 kb. Previous measurements of relative contact efficiencies using sites for recombinases in bacteria have revealed a steady drop in relative contact efficiency over the 10- to 90-kb range (13). It may be possible to use our λ CI reporter system to quantitate $J_{\text{LOOP}}$ at 100-kb separations, because $J_{\text{LOOP}}$ values as low as 3 nM ($\Delta G_{\text{act}}$ of ~3 kcal/mol) should be measurable (Fig. 4C).

**In Vivo Factors Increase $J_{\text{LOOP}}$ at Long Separations.** The in vitro $J_{\text{LOOP}}$ values obtained for LacI looping by TPM were ~5- to 45-fold lower and appeared to decay faster with separation than the in vivo values (Fig. 5E), fitting a power law with an exponent of ~1.5 (Fig. S10). Our TPM estimates are roughly comparable with published in vitro values. Our $J_{\text{LOOP}}$ = 75 nM for the 600-bp LacI loop is higher than the ~10- and ~30-nM values obtained for LacI by TPM for ~100- and ~300-bp loops, respectively, by Han et al. (9), but this is consistent with the expected increase in $J_{\text{LOOP}}$ over these separations due to relief of enthalpy costs (5). The TPM results of Johnson et al. (26) indicate even poorer looping with short spacers, with $J_{\text{LOOP}}$ values of 0.3−4 nM for different ~100-bp LacI loops. Our 900-bp estimate of $J_{\text{LOOP}}$ = 54 nM is similar to the $J_{\text{LOOP}}$ = 37 nM obtained for an 870-bp loop formed by Cre recombinase (15). At the 3,200-bp spacing, our in vitro $J_{\text{LOOP}}$ fell to ~5 nM, which is comparable to 18 nM at 3,044 bp (36) and ~10 nM for DNA cyclization at 4,000 bp (14). TPM analysis of CI looping at 2,300 bp gave $J_{\text{LOOP}}$ = 24 nM (17), somewhat higher than our TPM values (Fig. 5E); however, this may be an overestimate because a low value of $\Delta G_{\text{act}}$ was used.

Thus, we are confident that the in vivo—in vitro difference is real and applies over two orders of magnitude of the separation between sites (100−10,000 bp).

In vivo factors that increase flexibility or compaction of DNA such as DNA supercoiling and nonspecific DNA-binding proteins that bend or bridge DNA, such as the nucleoid protein HU, are thought to enhance short-range DNA looping (8, 33−36). It is not clear whether these factors also act at distances over which DNA bending and twisting are not limiting. However, increased DNA flexibility due to random binding of bend-inducing proteins such as nucleoid proteins or histones (35) should make the DNA more likely to wind back on itself, keeping it more compact and making it less likely that sites far apart on the DNA will be far apart in space. Unconstrained DNA supercoiling is implicated in aiding long-range looping in vivo (13). We note that our in vivo data can be reasonably well fitted by assuming that the DNA is a flexible polymer with an apparent persistence length of 23 nm (66 bp; Fig. S10). Relative FLP recombination rates over separations of ~70−15,000 bp in human cells indicated a similar apparent persistence length of 27 nm (12).

Our data do not identify which factors are responsible for improved long-range looping in vivo. However, our work provides a quantitative target for the in vivo/in vitro difference—an ~10-fold effect—and provides an experimental system to measure the effects of candidate factors by addition of factors in vitro or removal of factors in vivo.

**Creating Efficient Long-Range Looping.** Given a fixed $J_{\text{LOOP}}$ between any two DNA sites, how can DNA looping be maximized? The LacI and λ CI proteins represent extremes of a biochemical continuum (Fig. 1). In the case of LacI, the protein—protein interaction...
interactions that connect the two DNA-binding ends of the complex are strong, and the DNA-looping multimer, the tetramer, forms at exceedingly low concentrations (37). For CI, the assembly of dimers into tetramers, and tetramers into the loop-forming octamer is relatively weak so that the DNA looping complex does not form readily in solution (29).

Efficient LacI looping requires the protein concentration to be substantially below $J_{\text{LOOP}}$ and to lie close to the $K_D$ of both DNA sites (9, 26). At very long separations, where $J_{\text{LOOP}}$ is small, efficient looping by LacI is thus likely to be limited by difficulties in achieving reliable low protein concentrations inside cells due to gene expression noise.

Fig. 4. Effect of DNA separation on $\lambda$ CI looping in vivo. (A) Approach for measuring $J_{\text{LOOP}}$ with $\lambda$ CI. Structure of the OL-spacer-OR:PRM: LacZ reporters. CI activates PRM at low concentrations and represses it at high concentrations. Repression is dependent on the presence of OL and the free energy of loop formation between OL and OR, $\Delta G_{\text{loop}}$. (B) Decreased repression of PRM with increasing OL-OR separation. OR:PRM: LacZ reporters ± OL placed various distances upstream were assayed at 3.3 WT lysogenic units (WLU) of CI and in the absence of CI (SI Materials and Methods and Fig. S7). Also shown are previous $J_{\text{LOOP}}$ estimates for in vivo CI looping (square, ref. 7; triangle, ref. 23; red diamond, ref. 20); as well as the $J_{\text{LOOP}}$ values for LacI (Fig. 3C), assuming $L_1 = 18$ nM (blue circles). (D) Predicted fraction of looping for OL and OR at different separations up to 3.3 WLU, using $J_{\text{LOOP}}$ estimates from C.

Fig. 5. Measurement of $J_{\text{LOOP}}$ by TPM. (A) The TPM setup. (B) Examples of excursion vs. time traces for single beads, showing transitions between looped and unlooped states (left) and mean excursion probability distributions (right) for tethers with lac operators separated by 600–3,200 bp at 10 nM LacI. Different Lac loop conformations (two peaks) were distinguishable for the 900-bp loop. (C) The probability of looping vs. LacI concentration for the 900-bp separation. (D) $J_{\text{LOOP}}$ for each DNA was determined from the average fraction of time the DNA is looped ($p_{\text{looped}}$) at each [LacI], using the [LacI] dependence of loop blockage at [LacI] 0.5–20 nM (Oid was filled at 0.1 nM), according to the equation $p_{\text{unlooped}}/p_{\text{looped}} = 2K_1/J_{\text{LOOP}} + 2[LacI]J_{\text{LOOP}}$ (K1 was fixed at 1 nM). The slope of each $p_{\text{unlooped}}/p_{\text{looped}}$ vs. [LacI] plot equals $2J_{\text{LOOP}}$–1. (E) Comparison of the TPM $J_{\text{LOOP}}$ values with the in vivo values (LacI, blue; CI, brown). The red square shows a previous TPM estimate for $\lambda$ CI (17).
For CI, efficient looping requires the free energy of the protein–protein interaction, ΔGPTN, to compensate for the unfavorable ΔGLOOP. The interaction of two CI tetramers is estimated to provide −9.1 kcal/mol to drive the looping reaction (28, 29). However, this octamerization reaction alone would fail to give more than 50% looping for DNA separations above ~1,000 bp, where ΔGLOOP > +9.1 kcal/mol (ΔGLOOP < 384 nM). One way to improve CI looping would be to strengthen ΔGPTN by increasing the strength of the interactions between protein subunits. However, such changes would tend to increase the formation of larger complexes in solution, which would block looping.

The efficiency of looping by λ CI is increased by increasing the number of interacting proteins at each site. The additional bridge formed by the interaction of a CI dimer at each site, to form a transfetramer, effectively means that ΔGPTN (octamerization) and ΔGtet (tetramerization) combine to counterbalance ΔGLOOP. As suggested by Dröge and Müller-Hill (38), this approach of using a DNA scaffold to assemble at each site a large complex of proteins that individually interact weakly but in combination provide a strong protein–protein interaction seems optimal for creating strong looping at very long separations, such as in eukaryotic genomes. A similar method could also be used to make LacI-style looping more efficient. Additional looping at each site could permit a DNA loop to be bridged by two Lac tetramers.

However, strategies that use multiple interacting sites for the same protein to strengthen looping will eventually be limited by the formation of short DNA loops within each set of binding sites. A way around this limitation could be to combine different looping proteins. This kind of approach for making looping efficient has the advantage that specificity of looping could be provided by using a relatively small number of different looping proteins in different combinatorial patterns. Such a strategy may be necessary to provide both efficiency and specificity for the very long-range DNA interactions in eukaryogenic genomes.

Materials and Methods

Reporter and Expression Constructs. The lacZ reporters and LacI and CI expression constructs were chromosomally integrated using the OSP system and its precursors (23, 39) into MG1655 rph ΔlacI274 (SI Materials and Methods). Cells were grown at 37 °C in minimal medium (LacI looping strains) or in rich medium (CI looping strains) and assayed by a modified LacZ microtiter plate method (7) (SI Materials and Methods).

Mathematical Modeling. Data fitting to extract ΔGptn values from the λ CI reporter data was as previously described (23) with some modifications. Details of this and the LacZ modeling are given in SI Materials and Methods.

TPTM. TPTM experiments were conducted as previously described (30–32) with some modifications (SI Materials and Methods). Drift correction was improved by subtracting the motion of one to five stuck beads in the same field of view. Stringent selection of motion records based on symmetry and unlooped excursion amplitude was used. The mean square excursion of the bead was used to determine tether length by reference to a calibration curve with tethers of known length.

ACKNOWLEDGMENTS. We thank Laura Finzi, Iain Murchland, Julian Pietsch, and other members of the Shearwin, Dunlap, and Finzi laboratories, as well as including data for discussion purposes, to acknowledge Suleyman Ozturkucu and Weng Lee Lim in the Emory Physics Department for enhancements to bead tracking software and Kathleen Matthews for the Lac repressor. Support was from Human Frontiers Scientific Program Grant RGP0051, a University of Adelaide PhD scholarship to D.G.P., the China Scholarship Council (L.C.), Australian Research Council Grants DP1100828 and DP11010470, the WH Elliott Fellowship in Biochemistry and National and Medical Research Council (Australia) Grant APP1025549 (to I.B.D.), National Institutes of Health Grant R01GM087070 (to D.D.D.), and the Center for Pediatric Nanomedicine in the Department of Biomedical Engineering, Georgia Institute of Technology and Children's Healthcare of Atlanta (D.D.D.).