JOURNAL OF CELLULAR PHYSIOLOGY 199:359–363 (2004)

Initial Interactions in Electromagnetic Field-Induced Biosynthesis

MARTIN BLANK[1]* AND REBA GOODMAN[2]

[1]Department of Physiology, Columbia University, New York, New York
[2]Department of Pathology, Columbia University, New York, New York

Low frequency electromagnetic (EM) fields induce gene expression, and recent insights into physical interactions of EM fields with model systems suggest a mechanism that could initiate this process. The consistently low thresholds at which EM fields stimulate biological processes indicate that they require little energy. Since it has been shown that such weak fields accelerate electron transfer reactions, they could stimulate transcription by interacting with electrons in DNA to destabilize the H-bonds holding the two DNA strands together. Such a mechanism is consistent with the low electron affinity of the bases in previously identified electromagnetic response elements (EMREs) needed for EM field interaction with DNA. It is also in line with both endogenous and in vitro stimulation of biosynthesis by electric fields. The frequency response of several EM sensitive biological systems suggests that EM fields require repetition and are most effective at frequencies that coincide with natural rhythms of the processes affected. J. Cell. Physiol. 199: 359–363, 2004. © 2004 Wiley-Liss, Inc.

STIMULATION OF BIOSYNTHESIS BY ELECTROMAGNETIC FIELDS

Cells are unusually sensitive to electromagnetic (EM) fields. Transcription is stimulated by both low frequency ($\sim 10-10^2$ Hz) electric fields (Blank et al., 1992; Blank, 1995) and magnetic fields (Goodman and Blank, 1998), as well as by high frequency radio/microwave fields ($\sim 10^{12}$ Hz) (dePomerai et al., 2000; Leszczynski et al., 2002; Weisbrot et al., 2003). The high frequency fields are truly electromagnetic in that the electric and magnetic fields propagate together, whereas at low frequencies the fields can be effectively separated as alternating electric or magnetic fields. The low frequency alternating magnetic fields are usually referred to as EM fields to distinguish them from DC, or fixed, magnetic fields.

Although, many physical stimuli induce transcription, the biosynthetic response to EM fields occurs after exposures of only a few minutes and at 14 orders of magnitude lower energy density than the stimulus of elevated temperature (Blank and Goodman, 2000). Very low thresholds for EM field interaction, given in Table 1, have been found in a variety of biological systems that include changes in rates of enzyme and redox reactions, the biosynthesis of stress proteins, as well as disease-related studies. The consistency of the findings may indicate that these biological EM field effects are due to a similar mechanism.

Since the weak fields that initiate transcription of DNA (Goodman and Blank, 1998) also accelerate electron transfer reactions (Blank and Soo, 2001a,b, 2003), interaction with electrons in DNA could be the basis for initiating transcription. Electrons are most likely to be affected by weak fields because of their low mass, and interaction with electrons could affect the primary biological functions of DNA, information conservation and retrieval. These two processes appear to require contradictory specifications, that DNA be stable to preserve the integrity of the information while retaining the ability to come apart readily for retrieval of the information. In cells, this is accomplished by the large number of H-bonds between the complementary base pairs on the two DNA strands. In H-bonds (indicated as :), electrons from an O or N that is part of a stable bond are shared with a proton in another bond, as in NH:O or NH:N. Since electrons in these bonds are less strongly held than in covalent bonds, control of H-bonds through the electrons would enable DNA to come apart easily for the code to be read, and then 'zipped' up again for storage. Some of this is usually accomplished by enzymes such as topoisomerase and polymerase. We suggest that electric and magnetic fields generate forces on electrons that weaken the H-bonds holding the two DNA strands together. Oscillating fields set up vibrations that eventually destabilize H-bonds, and vibration frequency is an important factor to consider.

Our earlier focus on the specific signaling pathways in the interaction of EM fields with cells to induce stress

Abbreviations: Hz, hertz; mG, milligauss; bp, base pairs.

*Correspondence to: Martin Blank, Department of Physiology, Columbia University, 630 West 168 Street, New York, NY 10032. E-mail: mb32@columbia.edu

Received 3 August 2003; Accepted 6 November 2003

DOI: 10.1002/jcp.20004

TABLE 1. Estimated biological thresholds

Biological system	EM field (mG)	Reference
Enzyme reaction rates		
Na,K-ATPase	2–3	Blank and Soo (1996)
Cytochrome oxidase	5–6	Blank and Soo (1998)
Ornithine decarboxylase	~20	Mullins et al. (1999)
Oxidation–reduction reaction rate		
Belousov–Zhabotinski	<5	Blank and Soo (2001a)
Biosynthesis of stress proteins		
HL60, Sciara, yeast cells	<8	Goodman et al. (1994)
Breast (HTB124, MCF7) cells	<8	Lin et al. (1998b)
Chick embryo (anoxia protection)	~20	DiCarlo et al. (2000)
Disease related		
Block inhibition of (MCF7) breast		
Carcinoma cells by melatonin	2 < 12	Liburdy (2003)
Leukemia epidemiology	3–4	Ahlbom et al. (2000); Greenland et al. (2000)

protein synthesis showed that they stimulate distinctly different pathways from those implicated in response to elevated temperature (Goodman and Blank, 2002). However, those studies did not provide information about the physical interactions that activated these pathways. At the time, we thought in terms of electron currents in DNA (Ratner, 1999; Porath et al., 2000) that could interact with the EM fields and lead to DNA chain separation. It is now questionable if these currents occur with any frequency, and whether they occur over a large enough number of bases to activate DNA during short exposures (Tran et al., 2000; Boon and Barton, 2002; Zhang et al., 2002).

We have learned, however, that specific DNA sequences (nCTCTn) are involved in the response to EM fields (Lin et al., 1998a, 1999, 2001). Inserting these electromagnetic response elements (EMREs) into a promoter of a reporter gene that is unresponsive to EM fields makes that gene EM field-responsive. Removing or mutating these EMREs eliminates the EM field response. There is also evidence that the EM field response is proportional to the number of EMREs (Lin et al., 1998b). When we assumed that EM fields interacted with electron currents in DNA, our estimate of the relative balance of forces holding DNA together showed that larger forces can be generated at C and T bases (Blank and Goodman, 2002). A simpler, more straightforward rationale for the nCTCTn composition of EMREs can be seen immediately from the electron affinities of the four bases in DNA (A = 0.97, G = 1.51, T = 0.81, C = 0.57). The C and T bases have the lowest electron affinities and are most likely to give up their electrons when external forces are applied. Therefore, the physical properties of EMREs provide a plausible basis for interaction with electrons in DNA as an initiating mechanism.

ELECTRON TRANSFER ACCELERATION BY EM FIELDS

The responses of simpler biological systems to EM fields also support interaction with electrons as an initiating mechanism. The systems studied include two well-characterized enzymes, Na,K-ATPase (Blank and Soo, 1992, 1996) and cytochrome oxidase (Blank and Soo, 1998, 2001b), as well as the Belousov–Zhabotinski (BZ) reaction, the catalyzed oxidation of malonic acid (Blank and Soo, 2001a, 2003). The cytochrome oxidase reaction involves electron transfer between cytochrome C and the enzyme complex; the Na,K-ATPase reaction is the splitting of ATP that precedes the ionic currents of the 'ion pump.' Electron transfer in the cytochrome oxidase reaction is accelerated, as is the ATP-splitting rate of the Na,K-ATPase, where the calculated speed of the charges affected by the field suggests that they are electrons (Blank and Goodman, 2000). An earlier study of the Na,K-ATPase (Britten and Blank, 1973) correlated the non-specific inhibition of cations with their redox potentials, suggesting that electron transfer may be a critical step in enzyme function.

The rapid charge movement in the Na,K-ATPase, calculated to be about 10^3 m/sec, means that it takes about 10^{-11} sec to cross the membrane-spanning distance of about 10 nm. Since a 60 Hz sine wave lasts 1/60 sec, the charge 'sees' a constant DC magnetic field while crossing, and the interactions are effectively with repeated DC fields. Fixed DC fields of this magnitude do not affect the Na,K-ATPase (Blank and Soo, 1997), so the effect on the enzyme must be due to the regular repetitions that occur in 'tune' with the normal molecular motions.

Recent studies on the BZ reaction (Blank and Soo, 2003), a chemical system with no tissue extracts, have confirmed previous observations with the two enzyme reactions. The three reactions show common characteristics:

- EM fields accelerate the reactions;
- the effect of the EM field *varies inversely with the intrinsic rate of the reaction*, that is, the magnetic driving force competes with the chemical driving forces;
- there are frequency optima in the three systems; in the enzyme studies, the frequencies are close to the turnover numbers of the enzyme reactions.

These characteristics are consistent with interaction of EM fields with electrons.

ELECTRONS IN H-BONDS AS TARGETS FOR EM FIELDS

The H-bonds between base pairs that stabilize DNA are much weaker than covalent bonds. They have

energies in the range of 5 kcal/mol, but they vary considerably. The varying bond lengths and bond angles suggest a relatively wide range of bond energies and abilities to withstand perturbations. In some H-bonds, the bonding electrons are shared between more than two nuclei (Suehnel, 2002). Electrons in such non-intra-base-pair H-bonds are more easily displaced. EM fields probably interact with electrons associated with bases having low electron affinity and in non-intra-base-pair H-bonds. In any case, EM fields generate sufficient force to displace them, since the force [in newtons (N)] on an electron,

$$F = q\,v\,B,$$

where $q = 1.6 \times 10^{-19}$ coulombs, v = velocity (in m/sec), and the magnetic flux density, B, is approximately 10 μT (100 mG) in our experiments stimulating stress protein synthesis. The electron velocity, $v = 10^3$ m/sec, estimated from electric and magnetic field thresholds in experiments with the Na,K-ATPase (Blank and Soo, 1992, 1996), is comparable to electron velocities measured in DNA (Wan et al., 1999). This magnitude of electron velocity is also expected if electrons move at the ~nanometer/picosecond flickering rate of protons in H-bonded networks (Fecko et al., 2003). The assumed value for 'v' leads to $F \sim 10^{-21}$ N, and an acceleration of $\sim 10^9$ m/sec^2 for an electron of mass 9.1×10^{-31} kg. With this magnitude of acceleration, an electron can move 1 nm in 1 nsec, a displacement greater than the ~0.3 nm overall length of an average H-bond. Repeated pulses could set up vibrations that destabilize an H-bond.

The displacement of electrons in an H-bonded network may also occur by the unusual charge movements characteristic of the "Grotthus mechanism." In aqueous systems, during the conduction of protons (H^+) in electric fields, an approaching proton 'bonds' with the oxygen of a water molecule and releases the hydrogen on the other end of the molecule as a free proton. The flipping of the bond and its electrons results in a proton moving forward at a much faster rate, even if it is not the same proton. If this type of process occurred in adjacent H-bonds in DNA subjected to an external force, there could be some unusual movements, especially when water molecules are present (Fecko et al., 2003). The more complex H-bonds in DNA with lower energies and more constrained angles would be more vulnerable.

STIMULATION OF TRANSCRIPTION BY ELECTRIC FIELDS

Interaction with electrons should occur with electric fields as with EM fields, and that has been shown. Increases in transcripts of c-*myc* and histone H2B in human cells occur in 60 Hz electric fields of 3 mV/m (Blank et al., 1992), where the force on an electron, $\sim 5 \times 10^{-19}$ N, is almost three orders of magnitude greater than the EM field force that causes the same effect. An even more dramatic example is the pronounced effect of *endogenous* electric stimulation on protein synthesis in mammalian striated muscle (Pette and Vrbova, 1992; Blank, 1995). Different muscle proteins are synthesized at 150 and 20 Hz frequencies, with action potentials delivered by either the nerve or external electrodes. It is even possible to change the protein composition of a 'fast' muscle to that of a 'slow' muscle over a period of a few weeks by changing the frequency of stimulation. The change in protein composition is probably due to activation of different DNA coding regions. In electric stimulation of muscle, the waxing and waning of forces generated by continuously oscillating fields would set up oscillations that could destabilize H-bonds.

The currents of action potentials that penetrate muscle membranes and flow near nuclei can be shown to be large enough to stimulate DNA. The current magnitudes can be estimated from muscle action potentials, which rise from resting level to a peak of ~100 mV in about 1 msec, and propagate at ~10 m/sec. In the 1 msec that it takes the potential to peak, the front of an action potential advances 10 mm, so peak and resting potentials are separated by 10 mm, for a gradient of 10 V/m. This electric field gradient is three orders of magnitude larger than the 3 mV/m that stimulates transcription in human cells, and suggests a large margin of safety in muscle. The gradient is even larger than the 0.5 mV/m electric field threshold to change Na,K-ATPase activity (Blank and Soo, 1992).

Recent use of nanosecond electric pulses in electroporation has resulted in stimulation of the cell interior (Joshi et al., 2002). Normally, electroporation is used to permeabilize cell membranes with high voltage (~kV/m) microsecond pulses that do not readily penetrate cell membranes. The high frequency electric fields that penetrate activate apoptosis through caspase release and cause DNA fragmentation (Beebe et al., 2003). It appears that stimulation of cell interiors is possible with high frequency (nanosecond pulses) electric fields, as well as with low frequency EM fields, but the lower energy EM fields do not damage cellular structures and are to be preferred.

FIELD FREQUENCY AND REACTION SPECIFICITY

Studies of the frequency dependence of biochemical reaction rates in electric or magnetic fields indicate optimal frequencies (Table 2). The increased Na,K-ATPase activity at 60 Hz is very close to the natural rate of the enzyme (Blank and Soo, 2001a). In cytochrome oxidase (Blank and Soo, 1998), the optimal frequency of about 800 Hz is close to the range of its function in mitochondria. These data suggest that the field is most effective when it coordinates with the natural rhythm of a reaction. Since the effects on both enzymes vary inversely with intrinsic enzyme rates, it is clear that the fields compete with biochemical driving forces.

Studies of *E. coli* F_0F_1-ATPase activity in electric fields (Martirosov and Blank, 1995) also show that inhibition is a function of frequency, and that the optimal frequency is close to F_0F_1-ATPase turnover numbers (10–80 Hz). Frequency dependence requires the native enzyme structure, since mutant strains show lower frequency dependence, and there is a loss of frequency dependence in precursor F_0F_1 when activity decreases in cold storage. The F_0F_1-ATPase optimal frequency increases with field strength, with minima around 1,000 Hz at 2.3 V/cm, and about 30 Hz at 3.6 V/cm. The existence of two characteristic frequencies for an active center could occur if higher fields cause

TABLE 2. Optimal stimulation frequency

Biological system	Frequency (Hz)	Reference
Enzyme reaction rates		
Na,K-ATPase (EM field)	60	Blank and Soo (2001a)
Cytochrome oxidase (EM field)	800	Blank and Soo (2001a)
F_0F_1 ATPase (low E field)	1,000	Martirosov and Blank (1995)
(High E field)	30	Martirosov and Blank (1995)
Oxidation–reduction reaction rate		
Belousov–Zhabotinski (EM field)	250	Blank and Soo (2001b)
In vitro biosynthesis		
Human HL60 cells (EM field)	45	Wei et al. (1990)
In vivo biosynthesis (mammalian)		
'Fast' muscle (E field)	150	Pette and Vrbova (1992)
'Slow' muscle (E field)	20	Pette and Vrbova (1992)

significant structural changes or changes in the rate limiting steps of the reaction. It is possible that this energy-converting enzyme, optimized for its function through evolution, might work at a slower rate when there is a greater driving force.

The stimulation of biosynthesis in EM fields also shows a dependence on frequency. Increases in transcripts of c-*myc* and histone H2B in HL60 cells, reported in 60 Hz electric fields (Blank et al., 1992), are optimal at 45 Hz (Wei et al., 1990). The optimal frequency is in the range of RNA synthesis rates (bases/sec), and may be related to an effect on charge transfer in the RNA polymerase reaction.

Endogenous electric field stimulation of biosynthesis by the currents of action potentials also shows a relation between rate of stimulation and the proteins synthesized. Neither the speed nor the magnitude of an action potential is affected by frequency, but electrons at a particular site on the DNA are subjected to more perturbations at higher frequency, and summation is possible. Both effects would lead to threshold events more easily at the higher frequency, and could be related to different effects of high or low frequency action potentials in muscle. The repeated electric stimuli of cardiac action potentials or central nervous system rhythms probably have similar effects on the nuclei of adjacent cells, and may be involved in regulation of natural biosynthetic mechanisms, as well as the onset and pace of development. Endogenous electric fields may also interact with non-coding DNA to accomplish some of the critical timing during development.

CONCLUSION

We have proposed that interaction of EM and electric fields with electrons in DNA is a plausible basis for activation of DNA. Because of the low energy required, interaction with electrons in H-bonds may be the initial perturbation that leads double stranded DNA to come apart and begin the complex process of transcription to messenger RNA. The response to EM fields takes advantage of the natural mechanism that responds to internal electric forces.

Stimulation and modulation of DNA function by magnetic and electric fields have shown that physical forces can lead to specific effects as with biochemical reactions. In addition to the frequency, stimulus duration and different patterns of pulsing of magnetic and electric fields can further alter responses and specificity. The correlation between magnetic field frequency and the rate of charge transfer reactions offers promise for clinical applications.

Finally, when considering environmental influences, EM field activation of DNA reinforces concerns about human exposure to the exogenous fields due to power lines, communication devices, etc. The Liburdy study, listed in Table 1 (Liburdy, 2003) and replicated in four other laboratories, shows that low level EM fields affect the growth of human estrogen receptor positive breast cancer cells. The melatonin-induced growth inhibition, overcome by 12 mG fields but not by 2 mG fields, places the threshold between these two values, which are on either side of the epidemiology threshold for childhood leukemia (Ahlbom et al., 2000; Greenland et al., 2000). Health concerns are often expressed in terms of the need to prevent oxidative damage. Acceleration of electron transfer in EM fields is acceleration of oxidation.

LITERATURE CITED

Ahlbom H, Day N, Feychting M, Roman E, Skinner J, Dockerty J, Linet M, McBride M, Michaelis J, Olsen JH, Tynes T, Verkasalo PK. 2000. A pooled analysis of magnetic fields and childhood leukemia. Br J Cancer 83:692–698.

Beebe SJ, Fox P, White PF, Blackmore PF, Rec LJ, Joshi RP, Schoenbach KH. 2003. Nanosecond Pulsed Electric Fields Modulate Cell Function through Intracellular Signal Transduction Mechanisms. Abstracts of the XVII International Symposium on Bioelectrochemistry and Bioenergetics, Florence, Italy, June 2003, p 101.

Blank M. 1995. Electric stimulation of protein synthesis in muscle. Adv Chem 250:143–153.

Blank M, Goodman R. 2000. Stimulation of the stress response by low-frequency EM fields: Possibility of direct interaction with DNA. IEEE Trans Plasma Sci 28:168–172.

Blank M, Goodman R. 2002. Electromagnetic initiation of transcription at specific DNA sites. J Cell Biochem 81:689–692.

Blank M, Soo L. 1992. The threshold for alternating current inhibition of the Na,K-ATPase. Bioelectromagnetics 13:329–333.

Blank M, Soo L. 1996. The threshold for Na,K-ATPase stimulation by electromagnetic fields. Bioelectrochem Bioenerg 40:63–65.

Blank M, Soo L. 1997. Frequency dependence of Na,K-ATPase function in magnetic fields. Bioelectrochem Bioenerg 42:231–234.

Blank M, Soo L. 1998. Enhancement of cytochrome oxidase activity in 60 Hz magnetic fields. Bioelectrochem Bioenerg 45:253–259.

Blank M, Soo L. 2001a. Optimal frequencies for magnetic acceleration of cytochrome oxidase and Na,K-ATPase reactions. Bioelectrochem 53:171–174.

Blank M, Soo L. 2001b. Electromagnetic acceleration of electron transfer reactions. J Cell Biochem 81:278–283.

Blank M, Soo L. 2003. Electromagnetic acceleration of the Belousov-Zhabotinski reaction. Bioelectrochem 61:93–97.

Blank M, Soo L, Lin H, Henderson AS, Goodman R. 1992. Changes in transcription in HL-60 cells following exposure to AC electric fields. Bioelectrochem Bioenerg 28:301–309.

Boon EM, Barton JK. 2002. Charge transport in DNA. Curr Opinion Struct Biol 12:320–329.

Britten JS, Blank M. 1973. Effects of cations on biologically active surfaces—Specific binding sites in the Na,K-ATPase. J Coll Interf Sci 43:564–570.

dePomerai D, Daniells C, David H, Allan J, Duce I, Mutwakil M, Thomas D, Sewell P, Tattersall J, Jones D, Candido P. 2000. Non-thermal heat-shock response to microwaves. Nature 405:417–418.

DiCarlo AL, Mullins JM, Litovitz TA. 2000. Thresholds for EM field-induced hypoxia protection: Evidence for a primary electric field effect. Bioelectrochem Bioenerg 52:9–16.

Fecko CJ, Eaves JD, Loparo JJ, Tokmakoff A, Geissler PL. 2003. Ultrafast hydrogen-bond dynamics in infrared spectroscopy of water. Science 301:1698–1701.

Goodman R, Blank M, Lin H, Khorkova O, Soo L, Weisbrot D, Henderson AS. 1994. Increased levels of hsp70 transcripts are induced when cells are exposed to low frequency electromagnetic fields. Bioelectrochemistry and Bioenergetics 33:115–120.

Goodman R, Blank M. 1998. Magnetic field stress induces expression of hsp70. Cell Stress Chaperones 3:79–88.

Goodman R, Blank M. 2002. Insights into electromagnetic interaction mechanisms. J Cell Physiol 192:16–22.

Greenland S, Sheppard AR, Kaune WT, Poole C, Kelsh MA. 2000. A pooled analysis of magnetic fields. Epidemiology 11:624–634.

Joshi RP, Hu Q, Schoenbach KH, Beebe SJ. 2002. Simulations of electroporation dynamics and shape deformations in biological cells subjected to high voltage pulses. IEEE Trans Plasma Sci 30:1536–1546.

Leszczynski D, Joenvaara S, Reivinen J, Kuokka R. 2002. Non-thermal activation of the hsp27/p38MAPK stress pathway by mobile phone radiation in human endothelial cells: Molecular mechanism for cancer-and blood-brain barrier-related effects. Differentiation 70:120–129.

Liburdy RP. 2003. Electromagnetic fields and control of cell growth, drugs, hormones, and human tumor cells: A summary of replication studies at five laboratories. In: McLean MJ, Engstrom S, Holcomb RR, editors. Magnetotherapy: Potential therapeutic benefits and adverse effects. New York: TFG Press. pp 57–88.

Lin H, Han L, Blank M, Head M, Goodman R. 1998a. Magnetic field activation of protein-DNA binding. J Cell Biochem 70:297–303.

Lin H, Head M, Blank M, Jin M, Goodman R. 1998b. Myc-mediated transactivation of HSP70 expression following exposure to magnetic fields. J Cell Biochem 69:181–188.

Lin H, Blank M, Goodman R. 1999. A magnetic field responsive domain in the human HSP70 promoter. J Cell Biochem 75:170–176.

Lin H, Blank M, Rossol-Haseroth K, Goodman R. 2001. Regulating genes with electromagnetic response elements. J Cell Biochem 81: 143–148.

Martirosov S, Blank M. 1995. Inhibition of F_0F_1-ATPase activity in AC-fields. Bioelectrochem Bioenerg 37:153–156.

Mullins JM, Penafiel LM, Juutilainen J, Litovitz TA. 1999. Dose-response of electromagnetic field-enhanced ornithine decarboxylase activity. Bioelectrochem Bioenerg 48:193–199.

Pette D, Vrbova G. 1992. Adaptation of mammalian skeletal muscle fibers to chronic electrical stimulation. Rev Physiolog Biochem Pharmacol 120:115–202.

Porath D, Bezryadin A, deVries S, Dekker C. 2000. Direct measurement of electrical transport through DNA molecules. Nature 403: 635–637.

Ratner M. 1999. Electronic motion in DNA. Nature 397:480–481.

Suehnel J. 2002. Beyond nucleic acid base pairs: From triads to heptads. Biopolymers 61:32–51.

Tran P, Alavi H, Gruner G. 2000. Charge transport along the λ-DNA double helix. Phys Rev Lett 85:1564–1567.

Wan C, Fiebig T, Kelley SO, Treadway CR, Barton JK. 1999. Femtosecond dynamics of DNA-mediated electron transfer. Proc Nat Acad Sci USA 96:6014–6019.

Wei LX, Goodman R, Henderson A. 1990. Changes in the levels of c-*myc* and histone H2B following exposure of cells to low-frequency sinusoidal electromagnetic fields: Evidence for a window effect. Bioelectromagnetics 11:269–272.

Weisbrot D, Lin H, Ye L, Blank M, Goodman R. 2003. Effects of mobile phone radiation on growth and development in *Drosophila melanogaster*. J Cell Biochem 89:48–55.

Zhang Y, Austin RH, Kraeft J, Cox EC, Ong NP. 2002. Insulating behavior of λ-DNA on the micron scale. Phys Rev Lett 89:198102-1–198102-4.