Reports

Collapse of Gels in an Electric Field

Abstract. *An infinitesimal change in electric potential across a polyelectrolyte gel produces a discrete, reversible volume change. The volume of the collapsed gel can be several hundred times smaller than that of the swollen gel.*

Partially hydrolyzed acrylamide gels in a solvent, such as an acetone-water mixture, undergo discrete and reversible volume transitions upon infinitesimal changes in temperature, solvent composition, *p*H, or concentration of an added salt (*1*, *2*). The degree of volume change varies with the degree of ionization of the gel and may be as large as 500-fold. The volume change is understood as a phase transition of the system consisting of the charged polymer network, counterions, and fluid (*3*). The phase transition is a manifestation of competition among three forces on the gel: the positive osmotic pressure of counterions, the negative pressure due to polymer-polymer affinity, and the rubber elasticity of the polymer network (*2*). The balance of these forces varies with changes in temperature or solvent properties.

We demonstrate here that the phase transition is also induced by the application of an electric field across the gel. The electric forces on the charged sites of the network produce a stress gradient along the electric field lines in the gel. There exists a critical stress below which the gel is swollen and above which the gel collapses. The volume change at the transition is either discrete or continuous, depending on the degree of ionization of the gel and on the solvent composition.

The polyacrylamide gels were prepared by free-radical polymerization (*2*). Acrylamide, the linear constituent; *N*,*N*′-methylenebisacrylamide, the tetrafunctional cross-linking constituent; and ammonium persulfate and *N*,*N*,*N*′,*N*′-tetramethylethylene diamine (TEMED), the initiators, were dissolved in water. Micropipettes with a well-defined diameter (1.4 mm) were immersed in this solution. Within 5 minutes, the solution gelled. After an hour, the gels were removed from the micropipettes and immersed in water to wash away residual monomers. The gels then underwent hydrolysis in a 1.2 percent solution of TEMED (*p*H 12) for more than a month. Approximately 20 percent of the acrylamide groups were converted to acrylic acid groups, some of which were ionized in water,

$$-\mathrm{CONH_2} \rightarrow -\mathrm{COOH} \rightleftarrows -\mathrm{COO^-} + \mathrm{H^+} \qquad (1)$$

(In experiments where the composition of the acetone-water mixture is varied, the volume of these gels can change by a factor of 300 with an infinitesimal change in the solvent composition.) After hydrolysis, the gels were immersed in a 50 percent acetone-water mixture. Once equilibrium was reached, the gels were cut into segments 3 cm long. The diameter of each segment was approximately 4 mm.

The cylindrical gel was placed between two platinum electrodes (Fig. 1a). The voltage applied across the elec-

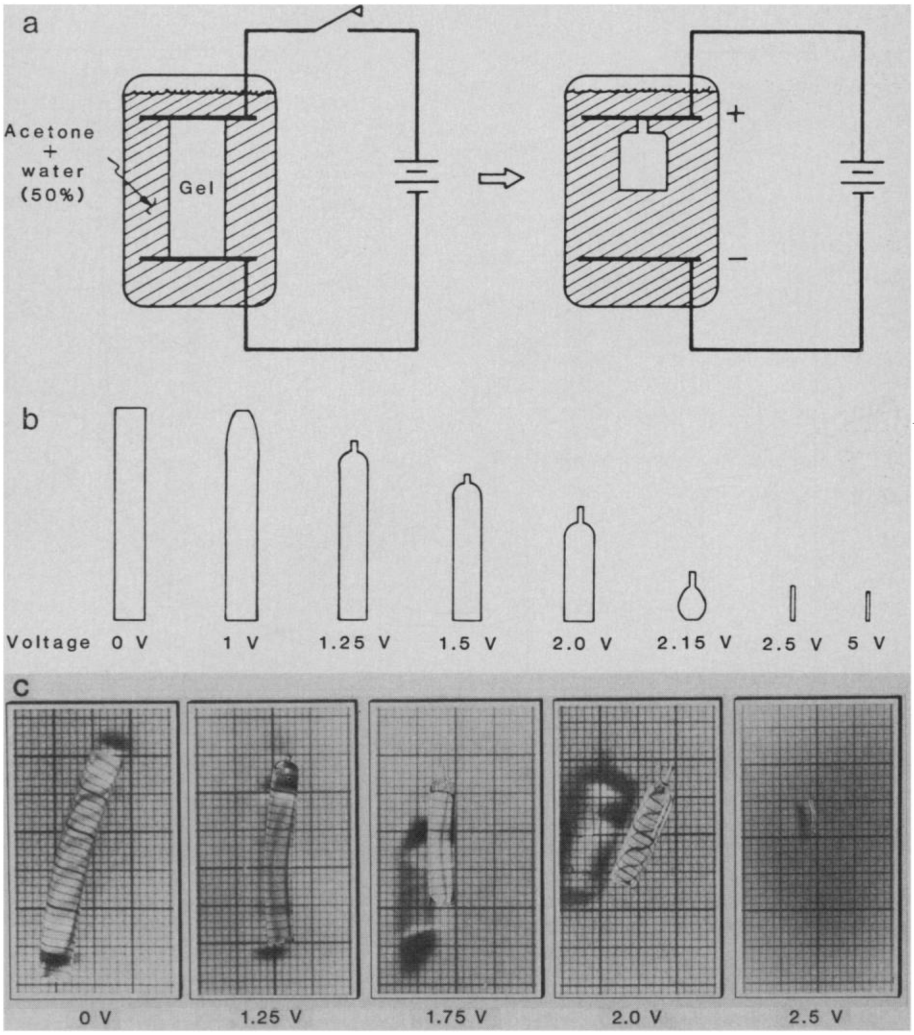

Fig. 1. (a) A cylindrical gel segment 3 cm long is placed between platinum electrodes and immersed in a 50 percent acetone-water mixture. When an electric field is applied to the gel, a stress gradient appears along the electric field. A portion of the gel having stress larger than a critical value collapses while the rest of the gel remains swollen. (b) The proportion of collapsed to swollen regions in the gel varies with the electric potential. (c) Photographic sequence showing how the volume of a 3-cm gel segment diminishes under an increasing electric field. The straight gel (first photograph) is a control under no electric field.

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trodes ranged from 0 to 5 V (Fig. 1, b and c). The electric field produces not only a force on the H$^+$, causing a stationary current in the gel, but also a force on the negatively charged acrylic acid groups in the polymer network, pulling the gel toward the positive electrode. This latter action creates a uniaxial stress along the gel axis, maximum at the positive electrode and minimum at the negative electrode. The stress gradient deforms the gel. The new shape is in equilibrium within a day. For potentials less than 1 V, there is no drastic change in the gel shape. At 1.25 V, 20 percent of the gel adjacent to the positive electrode collapses 200-fold in volume. The other 80 percent of the gel remains swollen. With an increase in voltage, more of the gel collapses. Above 2.15 V, the entire gel collapses. This phenomenon is reversible—when the electric field is removed, the gel assumes the original swollen shape. If the 50 percent acetone-water mixture is replaced by pure water, the gel diameter changes continuously along the gel axis when the electric field is applied.

The phenomenon can be explained in terms of a mean field theory, initially formulated for gels by Flory and Huggins (*4, 5*). Consider a network consisting of ν polymers with their ends cross-linked. Each polymer consists of N_0 freely jointed segments, of which f segments are ionized. When formed, the network is cylindrical with length L_0, diameter D_0, and concentration ϕ_0 and is in the special condition of no interaction between polymer segments. This special condition is taken as a reference state from which expansion or contraction is measured. A uniform electric field E is applied along the gel axis. One end of the gel is fixed to an electrode to avoid the translational motion of the entire gel along the electric field. Depending on the direction of the electric field, the gel is either compressed or stretched along its axis as a result of the presence of a charged site on the network. Consider a thin disk in the gel of thickness ΔZ_0 before application of the electric field and located at a distance Z from the free end of the gel (Fig. 2). Under the effect of E, the thickness changes to $\beta\Delta Z_0$ and the diameter to αD_0. The aim of this analysis is to find the combinations (α,β) that minimize the free energy F of the disk. The free energy includes a term associated with the deformation of the gel F_g and a term for the work done against the electric field F_e,

$$F = F_g + F_e \qquad (2)$$

For F_g we use the Flory-Huggins formula (*5*),

$$F_g = \nu kT \left\{ N_0 \frac{1-\phi}{\phi} \left[\ln(1-\phi) + \frac{\Delta F}{kT}\phi \right] + \frac{1}{2}\left[2\alpha^2 + \beta^2 - 3 - (2f+1)\ln(\alpha^2\beta)\right] \right\} \frac{\Delta Z_0}{L_0} \qquad (3)$$

where T is the absolute temperature, k is the Boltzmann constant, ϕ is the volume fraction of the polymer network, and ΔF is the free energy decrease associated with a contact between two polymer segments (ΔF varies with the solvent composition). The free energy needed to expand the network against the electric-potential is given by

$$F_e = \nu f e E(Z/L_0)(\beta - 1)\Delta Z_0 \equiv B\nu kT(\Delta Z_0/L_0)(\beta - 1) \qquad (4)$$

where e is the electron charge and $B \equiv feEz/kT$ is the reduced electric potential.

Minimization of the total free energy yields two equations,

$$\alpha^2 = \beta^2 + B\beta \qquad (5)$$

and

$$\frac{N_0}{\phi_0}\left[\ln(1-\phi) + \phi + (1-\tau)\phi^2/2\right] - (f + 1/2)(\alpha^2\beta) + 1/\beta = 0 \qquad (6)$$

where $\tau \equiv 1 - 2\Delta F/kT$ is the reduced temperature. Equation 5 shows that the anisotropy of deformation of the disk is uniquely determined by B. If B is positive, the disk is compressed more in the axial direction than radially ($\alpha > \beta$). The reverse is true if B is negative. For certain values of τ and B, Eqs. 5 and 6 have two solutions corresponding to two minima of free energy. In this case, the smaller free energy minimum represents the stable state. A discrete volume transition occurs from one minimum to the other when the values of two minima coincide. These results are summarized in Fig. 2, where the stable states (α,β) are plotted at various combinations of τ and B. Figure 2 shows that the discrete transition can occur when τ is changed for a fixed B or when B is varied for a fixed τ. The magnitude of the discrete transition is greater for lower τ and B. At

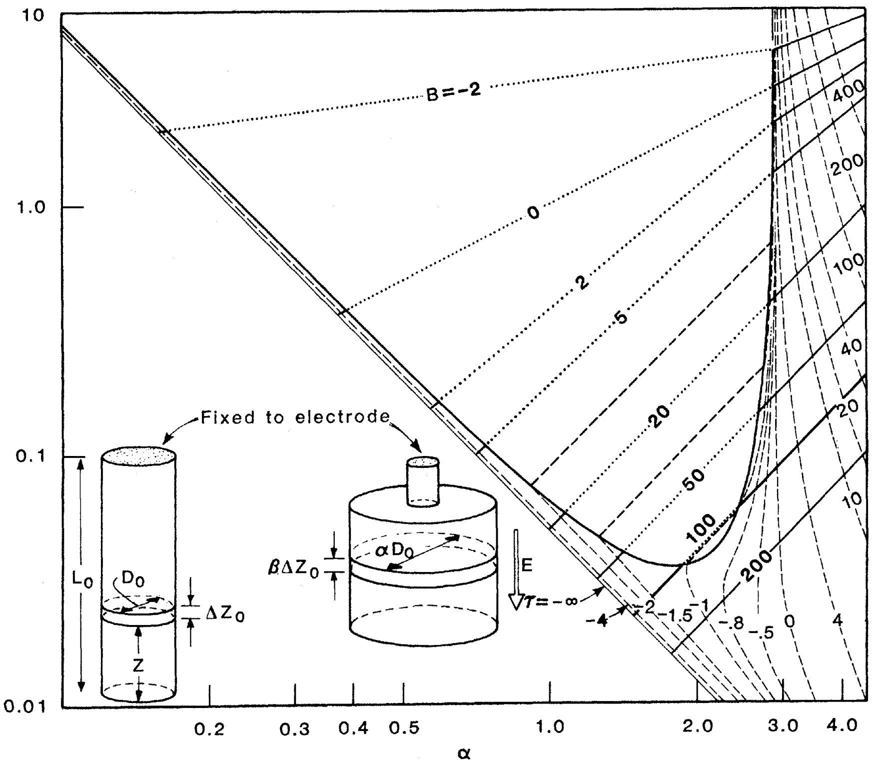

Fig. 2. Phase diagram of a gel disk under an electric field. Each point in the diagram represents values of the radial expansion α and the axial expansion β which minimize the free energy of the disk for a given combination of the reduced temperature τ and reduced electric potential B calculated from Eqs. 5 and 6. The solid lines represent constant B for various values of τ, while the broken lines represent constant τ for various values of B (B was varied in the experiment). The domain surrounded by the parabola-like boundary represents unstable states. The dotted and dashed lines inside the unstable region connect two stable states with the same free energy. The gel state can change between these two states with an infinitesimal change in B (the dashed line) or τ (the dotted line).

larger values of these parameters, the transition becomes continuous. This analysis accounts for both the discrete transition observed in a 50 percent acetone-water mixture and the continuous transition in pure water. The former corresponds to a low τ value, whereas the latter corresponds to a high τ value. Although only the electric force was considered in describing the phase transition, other factors may play a role. The effects of inhomogeneous distributions of ions, currents, and solvent composition within the gel and electrochemical reactions occurring at the electrodes need to be considered for a complete understanding of the phenomena.

The discrete volume transition of the gel induced by an electric field can be used to make switches, memories, and mechanochemical transducers. For example, ionic gels controlled by coordinated signals from a microcomputer may be used for an artificial muscle. It may also be possible to store two- or three-dimensional images by using the local collapse and swelling of the gel.

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Gestational Zinc Deprivation in Mice: Persistence of Immunodeficiency for Three Generations

Abstract. *Pregnant Swiss Webster mice were fed a diet moderately deficient in zinc from day 7 of gestation until parturition. Offspring of these mice showed depressed immune function through 6 months of age. In addition, the second and third filial generations, all of which were fed only the normal control diet, continued to manifest reduced immunocompetence, although not to the same degree as in the first generation.*

A number of nutritional factors modulate immunological function (*1*). Although initial interest in this subject was generated by the immunodeficiency observed in protein-malnourished children, it is now recognized that such individuals suffer from a wide range of nutritional deficiencies (*2*). Attention has thus become focused on the role of specific nutrients in immune responsiveness. In particular, much has been learned about the influence of dietary zinc on the maintenance of immunological function in adult animals (*3*). Zinc deficiency has been associated with impaired immune responses, particularly those mediated by T lymphocytes (*4*), and has been shown to influence the course of infectious (*5*), neoplastic (*6*), and autoimmune disease (*7*). Similar observations have been made in humans (*8*). However, relatively little is known about the role of zinc in the ontogeny of immunity. We previously showed that when mice are deprived of zinc during the suckling period, their ability to generate an effective immune response is markedly compromised (*9*). Indeed, mice only marginally deficient in zinc show decreased responses to mitogens and sheep red blood cells (SRBC's) and highly altered serum immunoglobulin profiles (*10*). We now report that moderate deprivation of zinc during prenatal life alone is also associated with a depressed plaque-forming cell (PFC) response to SRBC inoculation and with impaired development of serum immunoglobulins. In addition, these defects in immunological function persist into the second and third generations.

Pregnant young adult Swiss Webster mice were fed a zinc-deficient diet or a control diet ad libitum from day 7 of gestation (the beginning of pregnancy was designated day 0) to term. The biotin-fortified, egg white–based diet (*7*) contained 5 ppm zinc and the control diet 100 ppm zinc. The choice of these dietary levels of zinc was based on our previous studies in BALB/c and N:NIH(S) mice (*7, 9*). Moderate deficiency was defined as a reduction in serum zinc to levels 60 to 70 percent of those in control mice (*9*). Because zinc deficiency is known to cause inanition (*10*), which also may alter immune function (*11*), pair-fed controls were also studied. During the period of zinc deprivation all the mice were maintained under conditions designed to reduce extraneous zinc contamination (*7, 10*). At parturition, litters were culled to five pups and all dams and offspring were returned to the control diet, which they consumed until the end of the experiment. The PFC response to SRBC's and the concentration of immunoglobulin M (IgM) in serum were assessed in some offspring at 6 weeks, 10 weeks, and 6 months of age; the remainder of the offspring were mated (brothers to sisters) at 10 weeks of age to produce an F_2 generation. Because a consequence of zinc deprivation during pregnancy is impaired development of the mammary gland and reduced lactational ability (*12*), pups from zinc-deprived dams were cross-fostered to control dams and pups from control dams were cross-fostered to zinc-deficient dams. The F_2 and F_3 offspring were culled to five pups and studied at the same ages as the F_1 offspring or bred at 10 weeks of age. All F_1, F_2, and F_3 mice were thus fed the control diet throughout their lives. The only period of zinc deprivation was during gestation of the F_1 offspring.

Overt signs of zinc deficiency, such as alopecia and exfoliative dermatitis, were not observed in the zinc-deprived dams; nonetheless, other features were observed, such as decreased food intake, fewer and smaller offspring, and slightly higher neonatal mortality rates (*13*). Analysis of maternal plasma on day 17 of gestation indicated that a significant degree of zinc deficiency had been achieved, with the controls fed ad libitum and the pair-fed controls having zinc concentrations of 106.4 and 109.7 μg per 100 ml of plasma, respectively, compared to 58.0 μg per 100 ml in dams fed the 5 ppm zinc diet. These zinc concentrations were not as low as those generally seen in animals fed a diet nearly devoid of zinc (*14*), indicating that a moderate deficiency was achieved. No further differences were observed between plasma zinc levels in any groups at any age. Thus, the postnatal effects of zinc depletion during gestation were due to a defect in development rather than to a persistence of low plasma zinc.

The F_1 offspring of zinc-deficient dams had no detectable IgM at 6 and 10 weeks of age (Fig. 1A). By 6 months of age, significant amounts of IgM had appeared, but the concentrations were still below those of both control groups.

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