Shape memory in hydrogels

SIR — The ability of many polymer gels to modify their shape in response to external factors[1,2] (such as temperature, pH, electric fields and light) may find biomedical application. Of particular interest are polymer hydrogels, in which water molecules fill the interstitial sites of a crosslinked polymer network. Unlike metals, these materials are 'soft' and 'wet', which might improve their compatibility with biological tissue[3]. We have discovered a new phenomenon in polymer hydrogels — a 'shape memory' effect — which could form the basis of a thermally responsive diaphragm, a temperature-activated surgical clamp or a thermal actuator with gentle action.

A material is said to show shape memory if it can be deformed to a new shape (which it retains), only to revert to its original shape when heated above a certain critical temperature. Perhaps the most famous example of such a material is titanium–nickel alloy, produced by a reversible martensitic structural transformation[4]. The mechanism in our polymer gels is very different.

We have shown previously[5] that the mechanical properties of water-swollen gels prepared by copolymerizing acrylic acid and *n*-stearyl acrylate are strongly temperature-dependent. Below 25 °C, the gel behaves as a hard plastic. But if the temperature is raised above 50 °C, the gel becomes very soft and can be stretched to at least 1.5 times its original length. When the swollen gel is heated, its Young's modulus decreases by about three orders of magnitude, from 10^7 dyn cm^{-2} at 25 °C to 10^4 dyn cm^{-2} at 50 °C. These drastic changes in the mechanical properties of the gel were ascribed (on the basis of small-angle X-ray diffraction analyses)[4] to a reversible order–disorder transition associated with the interactions between the alkyl side chains of the stearyl acrylate units. Below 50 °C, the long alkyl chains adopt a crystalline aggregate structure, which renders the material mechanically robust. Above this temperature, the packing of the side chains is amorphous and the material becomes soft and flexible. We suggest that the same mechanism causes the shape memory effect in these gels.

Although we call this the shape memory effect, we emphasize that the shape that the gel 'remembers' is the one in which it was originally formed. If the gel is heated above the transition temperature (50 °C) into its 'soft' state, it can be readily deformed and stretched to a new shape, but if the gel is then cooled while holding it in its deformed state, it becomes rigid and retains its new shape even after the deforming loads have been removed. We suggest that it is the formation of crystalline aggregates among the side chains that locks in the new shape. If the unloaded, deformed gel is then once again heated above the transition, it recovers its original size and shape after a few seconds. This behaviour is illustrated in the figure.

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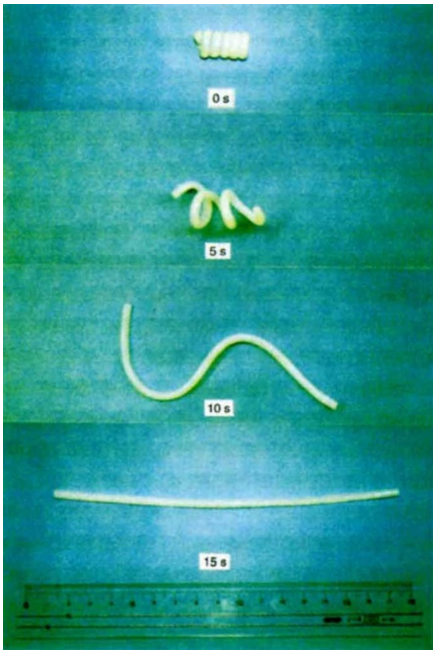

An example of shape memory. The gel was prepared by radical copolymerization at 50°C for 24 h. The total monomer concentration in ethanol was kept at 3.0 mol dm^{-3} in the presence of 3.0×10^{-2} mol dm^{-3} *N,N'*-methylenebis(acrylamide) and 3.0×10^{-2} mol dm^{-3} α,α'-azobis(isobutyronitrile) used as an initiator. The copolymer gel was formed in a straight glass tube of diameter 5 mm and then swollen with water (dry samples do not show the shape memory effect). The gel was then heated to 50 °C, coiled and then cooled to room temperature. The gel is rigid and retains its coiled shape (top panel). On heating again to 50 °C, the gel becomes soft and recovers its original, straight shape.

Costs of conception in baboons

SIR — Packer *et al.*[1] reported that miscarriage occurred more frequently in high-versus low-ranking female baboons at Gombe National Park. We obtained a comparable result at Mikumi; confirmed abortions among females of high- to low-dominance rank quartiles comprised 15, 13, 8 and 3 per cent of all pregnancies, respectively (number of pregnancies = 47, 48, 37, 38; $P < 0.05$, logistic regression). Here I provide data to suggest that the higher miscarriage rate results from a less socially and physiologically constrained conception rate among high-ranking females. Their conception appears to be less socially constrained because survival of offspring born to dominant females is much less affected by their time of birth in relation to others[2,3]. Dominant females accordingly conceive more readily[1,3] at lower progesterone concentrations than do low-ranking females. These hormone concentrations are sufficient for high-ranking females to establish implantation, but may not always be sufficient to maintain it.

I collected fresh faecal samples between 1990 and 1992 from 30 individually recognizable adult female baboons of proven fertility in two separate troops at Mikumi National Park, Tanzania. I analysed samples for progestins and oestrogens (progesterone and oestradiol metabolites, respectively)[4–7], because early luteal-phase progestin and oestrogen concentrations are positively correlated with successful implantation in baboons[8,9] and humans[10,11].

Mean luteal-phase concentrations of progestins and oestrogens were significantly higher in conceptive versus non-conceptive cycles (see figure). Mean luteal-phase progestin concentrations during conceptive cycles were significantly lower in females of high- versus low-dominance rank, but did not differ by rank

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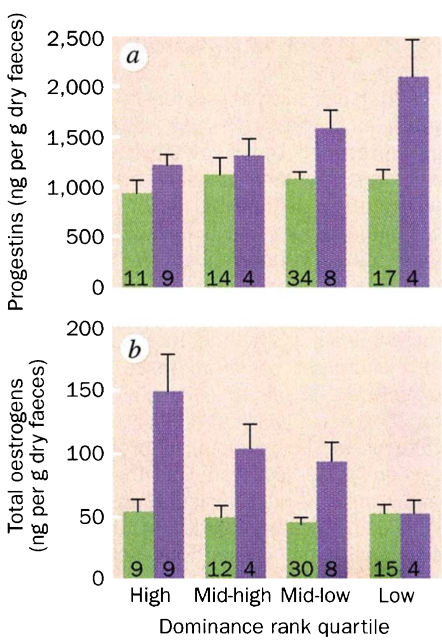

Mean luteal-phase (post-ovulation days 4–11) progestin (*a*) and total oestrogen (*b*) concentrations in faeces of conceptive (purple) and nonconceptive (green) cycles as a function of female dominance rank. Post-ovulation day 4 corresponds to the day in which progestin and oestrogen concentrations in conceptive cycles became significantly different from those in nonconceptive cycles. Post-ovulation day 11 corresponds to the time of implantation[15], given the 36-h time lag between steroid secretion in blood and excretion in faeces[5]. Mean luteal-phase progestin and oestrogen concentrations were significantly higher in conceptive than nonconceptive cycles ($P < 0.0001$ in both cases), as well as significantly associated with dominance rank ($P < 0.04$ and < 0.02, respectively). The interaction between pregnancy and dominance rank was also significant for oestrogens ($P < 0.03$; ANOVA). Rank was quantified based on the outcome of bouts of aggression systematically recorded[16]. Sample sizes are shown in bars. Subjects were fully habituated to human observers, having been studied almost daily since 1974. Faecal samples were obtained from each female approximately 1–3 times per week, depending on reproductive condition. Samples were stored, extracted and assayed for progestins and oestradiol using the methods in refs 4–7. Total oestrogens were measured using the RSL ^{125}I total oestrogen kit (ICN Biomedicals, Costa Mesa, CA). Every attempt was made to include only ovulatory cycles in this study, based on a transient rise in luteal-phase progestin concentrations. Ovulation was presumed to have occurred 2 days before onset of sex-skin detumescence[15]. All conceptive cycles in this study ended with a birth. Some cycles classified as nonconceptive undoubtedly represented early abortions. The 17 miscarriages described in the text occurred before the hormone study.

during nonconceptive cycles (*a* in the figure). The dominance-related faecal oestrogen pattern was opposite to that of faecal progestins (*b* in the figure). Oestrogen concentrations during conceptive cycles were greatest in females of high- versus low-dominance rank, while showing no rank effect during nonconceptive cycles.

The rank-related progestin patterns in conceptive cycles appear to be tied to oestrogen-mediated changes in progesterone receptor densities. Oestrogen increases progesterone receptor densities in the epithelial layer of the endometrium (where implantation occurs), but has little effect in the deeper layers (stroma and myometrium) that maintain pregnancy in Old World primates[12–15]. Progesterone has the opposite effect, decreasing progesterone receptor densities in the epithelial layer.

These findings suggest that the higher oestrogen concentrations observed in the early luteal phase of dominant females (*b* in the figure) may be dampening the progesterone-induced decline in progesterone-receptor densities over the early luteal phase. The resultant higher receptor density should make implantation easier to achieve in dominant females with less progesterone present. However, the lack of similar receptor-density changes in the stroma and myometrium seems to compromise the ability of this lower progesterone in dominant females to sustain the pregnancy. Subordinate females would experience the opposite: based on oestrogen concentrations (*b* in the figure), their progesterone receptor densities would be lower, requiring more progesterone for implantation, which also should improve their ability to sustain pregnancy (*a* in the figure).

In conclusion, high-ranking females can afford to conceive more readily because their offspring are more buffered from the social conditions in which they are born. However, the physiological mechanisms that facilitate these conceptions seem to bear a cost of increased susceptibility to miscarriage.

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Hot PUMPing plants ?

SIR — In their Scientific Correspondence, Vercesi and colleagues[1] suggest that the presence of PUMP, an uncoupler-like protein in potato tuber mitochondria, may correspond with the absence of the alternative oxidase in this tissue. But is the alternative oxidase thermogenic; does the location of PUMP correspond with the absence of the alternative oxidase; and does PUMP fulfil an analogous role?

The alternative oxidase is responsible for heat production in thermogenic lilies[2], but in this system heat production is linked to a massive increase in enzyme activity concurrent with a complete decrease in cytochrome oxidase activity[2,3]. There are no reports linking alternative oxidase activity to thermogenesis in other plants. Why should a plant need this heat production mechanism? At the levels of activity reported for the alternative oxidase (about 100 nmol O_2 per mg mitochondrial protein per min) in plant tissues, the heat change would be very small compared with the rate that can be achieved in thermogenic lilies (2 μmol O_2 per mg mitochondrial protein per min)[4]. The alternative oxidase is implicated in various processes, such as wounding, pathogen attack, elevated carbohydrate status and addition of salicylic acid[5], but none of these requires thermogenesis.

Is the presence of PUMP correlated with the absence of the alternative oxidase? Although potato tuber mitochondria do not naturally exhibit alternative oxidase activity, it can be easily induced in these tissues[6], showing that they can express this enzyme.

Do PUMP and the alternative oxidase function in an analogous role? The alternative oxidase has been implicated in various processes. Although its exact role is unclear, it does function to oxidize reduced compounds without the production of ATP. Rather than this function being related to the generation of heat, it is more easily envisaged as being related to the diversion of metabolites in the Krebs cycle to other biosynthetic functions[5]. The uncoupled oxidation of reduced compounds allows the cycling of cofactors necessary for glycolysis and the Krebs cycle and so keeps catabolism at a high rate[7]. Under such conditions plants will be synthesizing a number of compounds for growth and development. The control of alternative oxidase activity by two separate biochemical parameters[8] ensures that this activity is highly regulated in reference to the metabolism of the cell/plant. In my view, there is no evidence to suggest that the PUMP protein has this role.

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