Water capture by a desert beetle

This insect has a tailor-made covering for collecting water from early-morning fog.

Some beetles in the Namib Desert collect drinking water from fog-laden wind on their backs[1]. We show here that these large droplets form by virtue of the insect's bumpy surface, which consists of alternating hydrophobic, wax-coated and hydrophilic, non-waxy regions. The design of this fog-collecting structure can be reproduced cheaply on a commercial scale and may find application in water-trapping tent and building coverings, for example, or in water condensers and engines.

The Namib Desert in southern Africa supports a unique sand-dune fauna[2] and experiences high winds, extreme daytime temperatures and dense, early-morning fog[3,4], but rainfall is so low and variable as to be considered negligible here[5]. The tenebrionid beetle *Stenocara* sp. (Fig. 1a) tilts its body forwards into the wind to collect water in a manner that is typical of the family[3]. Droplets form on the top (front) fused 'wings' (elytra) and roll down the beetle's surface to its mouthparts. The mechanism by which water is extracted from the air and formed into large droplets has so far not been explained, despite its biomimetic potential.

A similar rolling of water droplets occurs on lotus leaves, which repel raindrops on their uniformly superhydrophobic surface[6]. But a surface of this nature would not help the beetle — the fog water droplets encountered by *Stenocara* are much finer (1–40 μm diameter[7]) than raindrops and, without a special controlling mechanism, would quickly be lost to the heat and winds of the desert (water droplets in fog are so light that they travel almost horizontally in a breeze)[7–9]. Water collection is therefore not as simple as it may seem.

On a macroscopic scale, the elytra of *Stenocara* are covered in a near-random array of bumps 0.5–1.5 mm apart, each about 0.5 mm in diameter (Fig. 1a). At the microscopic level, the peaks of these bumps are smooth, with no covering (Fig. 1b), whereas the troughs, including their sloping sides, are covered by a microstructure coated in wax (Fig. 1b). The microstructure consists of flattened hemispheres, 10 μm in diameter and arranged in a regular hexagonal array (Fig. 1c), creating a superhydrophobic system reminiscent of the lotus leaf.

The droplet-producing system works by 'growing' droplets on the hydrophilic seeding points of the peaks (as seen in video recordings). The water in the fog settles on the peaks, forming fast-growing droplets that bind to the elytra; water striking the hydrophobic slopes can also be collected as it may bounce or be blown to a hydrophilic region. Each attached droplet eventually reaches a size at which its contact area covers the entire hydrophilic island. Beyond this size, the ratio of its mass to its surface-contact area increases rapidly until the capillary force that attaches it to the surface is overcome (this force is dictated by the area of the hydrophilic island). At this point, the droplet detaches and rolls down the tilted beetle's surface, guided by the slight purchase afforded by other peaks along its path.

By this stage, the droplet is sufficiently massive to roll into the wind, its cross-section (the area of contact with the wind) having increased far more slowly than its volume. Using the control volume form of Euler's first law[10], it is possible to estimate the windspeed, v, below which the droplets will roll downwards:

$$v \approx \sqrt{\left[\left(\frac{\rho_{water}}{\rho_{air}}\right)\left(\frac{4}{3}\right)Rg\sin(\theta)\right]}$$

where R is the droplet radius, g is the gravitational constant (9.8 m s^{-2}), θ is the tilt angle and ρ is the density of a medium ($\rho_{air} = 1$ kg m^{-3}, $\rho_{water} = 1{,}000$ kg m^{-3}). This predicts that the diameter of a spherical droplet must exceed 5 mm if it is to roll down a 45° incline into a headwind of 5 m s^{-1} (as measured in Namibia). This is fairly consistent with video footage of the beetles in their natural environment, in which droplets of roughly 4–5-mm diameter form in a steady, self-replenishing stream.

To determine the biomimetic potential of the structure, we partially embedded 0.6-mm glass spheres into microscope slides coated with warm wax. In one model, spheres were arranged in a square array with a spacing of 0.6 mm; in another, spheres were randomly arranged with an average spacing of 0.5 mm. For comparison, we used a uniformly hydrophobic surface of smooth wax and a uniformly hydrophilic surface of bare glass, which was cleaned by ultrasonic agitation in isopropyl alcohol for 15 min. The four samples were inclined at 45° and sprayed equally with a fine mist of water, which was collected at the base of each slide. We repeated this experiment 10 times using samples at 22 °C.

The square array of beads collected the most water (1 unit), with large, almost spherical droplets quickly forming to roll downwards when they reached a diameter of 3.8–4.0 mm. The random array collected an average of 0.95 units and the bare wax sample an average of 0.5 units, as droplets of about 1 mm diameter; many droplets were lost when blown off the edges of the slide. Bare glass gave the most variable results: a single large (over 7 mm) flat droplet formed on the surface and ran down the slide by a specific route that varied within each experiment. If the route led to the collecting vial, as in four of the experiments, 1 unit of water was collected. If it did not, as in six experiments, no water was collected.

The results were virtually identical at substrate temperatures of 66 °C to those at 22 °C, except in the case of bare glass, where the flat droplets evaporated because of their large surface area. We conclude that the

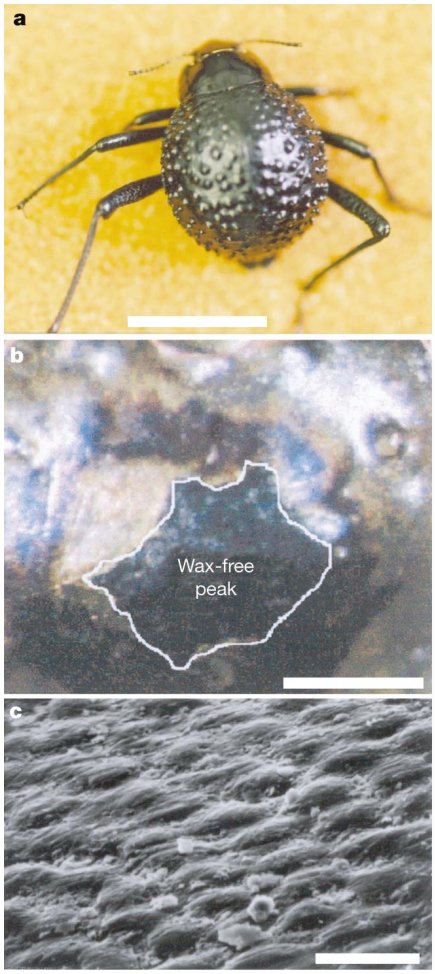

Figure 1 The water-capturing surface of the fused overwings (elytra) of the desert beetle *Stenocara* sp. **a,** Adult female, dorsal view; peaks and troughs are evident on the surface of the elytra. **b,** A 'bump' on the elytra, stained with Red O for 15 min and then with 60% isopropanol for 10 min, a procedure that tests for waxes. Depressed areas of the otherwise black elytra are stained positively (waxy, coloured), whereas the peaks of the bumps remain unstained (wax-free; black). **c,** Scanning electron micrograph of the textured surface of the depressed areas. Scale bars, **a,** 10 mm; **b,** 0.2 mm; **c,** 10 μm.

combination of hydrophilic and hydrophobic points was best for collecting water from mist at both 22 °C and 66 °C.

The *Stenocara* structure[11] can easily be reproduced in sheet form by injection-moulding or printing techniques, allowing a variety of uncooled devices to be produced for controlled collection of vapour, including water for drinking or farming in inhospitable regions[7,9] (see supplementary information).

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Supplementary information accompanies the paper on *Nature*'s website (www.nature.com).

Metabolism

Partial leptin deficiency and human adiposity

The adipocyte-derived hormone leptin is crucial for energy homeostasis in mammals; mice[1] and humans[2,3] without it suffer from a voracious appetite and extreme obesity. The effect on energy balance of variations in plasma leptin above a minimal threshold is uncertain, however, particularly in humans. Here we examine a group of individuals who are genetically partially deficient in leptin, and show that differences in circulating leptin levels within the range found in normal human populations can directly influence the laying down of fat tissue (adiposity).

In three unrelated families of Pakistani origin, we identified 13 subjects who were heterozygous for a frameshift mutation (deletion of a glycine at residue 133; ΔG133) in the *ob* gene, which encodes leptin. We also identified three of their relatives as homozygous for the wild-type *ob* sequence. Serum leptin levels and anthropometric measurements in these subjects were compared with those in 96 ethnically matched controls with a similar sex distribution (38% and 44% male, respectively) and age (41 ± 12 yr and 48 ± 15 yr, respectively).

Serum leptin concentrations in ΔG133 heterozygotes were markedly lower than in controls (Fig. 1a). As expected, these were positively correlated with body-mass index (BMI) in control subjects ($r = 0.54$) and in the wild-type relatives of the heterozygotes (Fig. 1b). In contrast, there was no significant correlation between BMI and serum leptin in the ΔG133 heterozygotes.

In all human populations studied so far, serum leptin is positively correlated with indices of adiposity[4]. However, lower leptin levels in ΔG133 heterozygotes were accompanied by an increased prevalence of obesity, with 76% of heterozygotes having a BMI greater than 30 kg m^{-2}, compared with 26% of controls ($P < 0.01$). As BMI is only a surrogate measure of body fat, we measured body fat directly by dual-energy X-ray absorptiometry in 12 of the ΔG133 heterozygotes and in 6 Pakistani subjects who were wild-type at the leptin locus. We compared these direct measures of body fat to body-fat predictions on the basis of age, sex, height and weight[5].

In wild-type subjects, the mean measured percentage of body fat was similar to the predicted value (Fig. 1c). In ΔG133 heterozygotes, however, it significantly exceeded the predicted proportion of body fat (41.4% and 34.4%, respectively; $P < 0.001$), with all 12 heterozygous individuals showing a deviation in the same direction.

Humans who inherit only one functional copy of the leptin gene therefore have markedly lower serum leptin levels than control subjects, particularly in view of their increased mass of adipose tissue. These observations are supported by studies of leptin deficiency in rodents — heterozygous $Lep^{ob/+}$ mice have about 32% more fat and adjusted serum leptin concentrations that are about 27% lower than their wild-type littermates[6], which is strikingly similar to our findings in humans.

If leptin evolved principally to signal the transition between states of starvation and nutritional adequacy[7], then sensitivity to changes in its circulating concentration should be enhanced at very low values. This could account for inconsistent effects on appetite or weight when leptin in normal or obese humans is supplemented by injection of recombinant human leptin[8]. If the human energy-balance system is insensitive to positive perturbations of leptin, is it also insensitive to negative ones? Our results would suggest that this is not the case.

Our findings show that a relatively small drop in leptin production may be sensed by the homeostatic feedback system that controls energy balance, with fat mass being increased in an attempt to restore leptin levels to some 'set point'. As a substantial minority of subjects with common forms of obesity, not associated with leptin mutations, have relatively low levels of circulating leptin[9], our results indicate that augmenting serum leptin in this subgroup may be therapeutically worthwhile.

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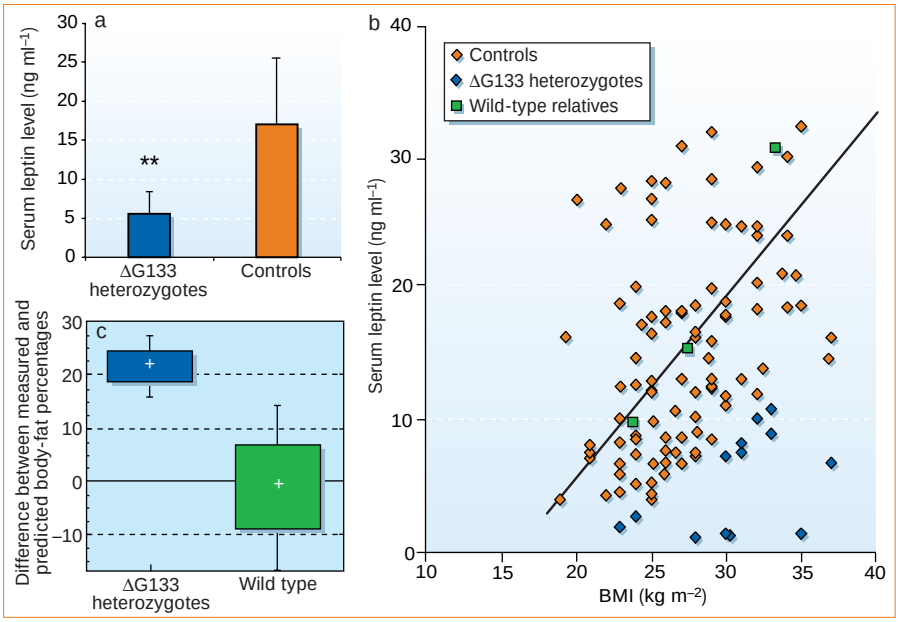

Figure 1 Human heterozygotes for the ΔG133 mutation in the leptin gene have low serum leptin levels and increased body-fat percentage relative to controls. **a,** Serum leptin concentrations (mean ± s.d.) in 13 Pakistani subjects who are heterozygous for the ΔG133 leptin mutation and in 96 control subjects from the same ethnic group; ** denotes $P < 0.001$. **b,** Serum leptin concentrations plotted against body-mass index (BMI), showing the regression line for controls; correlation coefficient, 0.54. **c,** Body-fat percentage, measured by dual-energy X-ray absorptiometry in 12 ΔG133 heterozygotes and 6 wild-type subjects, compared to that predicted by the Deurenberg formula[5] for both groups. Values are means ± 2 s.e.m.