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Surface phenomena

Contact time of a bouncing drop

When a liquid drop lands on a solid surface without wetting it, it bounces with remarkable elasticity[1–3]. Here we measure how long the drop remains in contact with the solid during the shock, a problem that was considered by Hertz[4] for a bouncing ball. Our findings could help to quantify the efficiency of water-repellent surfaces (super-hydrophobic solids[5]) and to improve water-cooling of hot solids, which is limited by the rebounding of drops[6] as well as by temperature effects.

The way in which a water drop of radius R deforms during its impact with a highly hydrophobic solid depends mainly on its impinging velocity, V. The Weber number, $W=\rho V^2R/\gamma$, compares the kinetic and surface energies of the drop, where ρ and γ are the liquid density and surface tension, respectively. The greater the value of W, the larger are the deformations that occur during the impact (Fig. 1).

High-speed photography (Fig. 1) enabled us to measure the drop's contact time, τ. The frame rate could be greater than 10^4 Hz, allowing precise measurements of τ, which we found to be in the range 1–10 ms. As the impact is mainly inertial (with a restitution coefficient[2] as great as 0.91), τ is expected to be a function of only R, V, ρ and γ, and thus to vary as $R/V.f(W)$. For a Hertz shock, for example, the maximum vertical deformation, δ, scales as $R(\rho^2V^4/E^2)^{1/5}$, where E is the Young's modulus of the ball[7]. Taking a drop's Laplace pressure, $E\approx\gamma/R$, as an equivalent modulus and noting that $\tau\approx\delta/V$, we find for a Hertz drop that $f(W)\sim W^{2/5}$ and that the contact time varies as $V^{-1/5}$ and $R^{7/5}$.

Figure 2a shows that the contact time does not depend on the impact velocity over a wide range of velocities (20–230 cm s^{-1}), although both the deformation amplitude and the details of the intermediate stages largely depend on it. This is similar to the case of a harmonic spring, although oscillations in the drop are far from being linear. Moreover, this finding confirms that viscosity is not important here.

Figure 2b shows that τ is mainly fixed by the drop radius, because it is well fitted by $R^{3/2}$ over a wide range of radii (0.1–4.0 mm). Both this result and the finding shown in Fig. 2a can be understood simply by balancing inertia (of the order $\rho R/\tau^2$) with capillarity (γ/R^2), which yields $\tau\approx(\rho R^3/\gamma)^{1/2}$, of the form already stated with $f(W)\sim W^{1/2}$. This time is slightly different from the Hertz time because the kinetic energy for a solid is stored during the impact in a localized region, whereas in our case it forces an overall deformation of the drop (Fig. 1).

The scaling for τ is the same as for the period of vibration of a drop derived by Rayleigh[8], and is consistent with a previous postulation[9], although the motion here is asymmetric in time, forced against a solid, and of very large amplitude. Absolute values are indeed found to be different: the prefactor deduced from Fig. 2b is 2.6 ± 0.1, which is significantly greater than $\pi/\sqrt{2}\approx2.2$ for an oscillating drop[8]. Another difference between the two systems is the behaviour in the linear regime ($W\ll1$): for speeds less than those shown in Fig. 2, we found that τ depends on V, and typically doubles when V is reduced from 20 to 5 cm s^{-1}, which could be due to the drop's weight[10].

The brevity of the contact means that a drop that contains surfactants, which will spread when gently deposited onto the solid, can bounce when thrown onto it; this is because the contact time is too short to allow the adsorption of the surfactants onto the fresh interface generated by the shock. Conversely, the contact time should provide a measurement of the dynamic surface tension of the drop.

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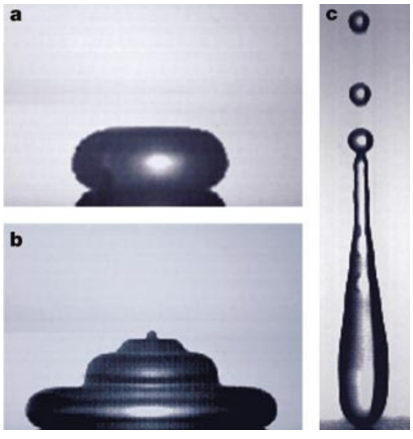

Figure 1 Millimetre-sized water drops with different Weber numbers (W) hitting a super-hydrophobic solid. W compares the kinetic and surface energies of the drop ($W=\rho V^2R/\gamma$, where R is the drop radius, V is the impact velocity, and ρ and γ are the density and surface tension, respectively, of the liquid). **a,** When W is close to unity, the maximum deformation during contact becomes significant. **b,** When $W\approx4$, waves develop along the surface and structure the drop. **c,** When $W\approx18$, the drop becomes highly elongated before detaching and gives rise to droplets; however, the contact time is independent of the details of the impact (see Fig. 2a).

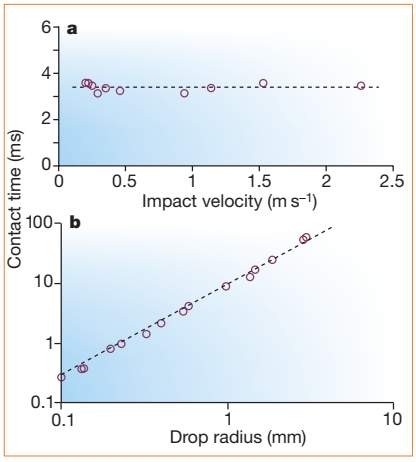

Figure 2 Contact time of a bouncing drop as a function of impact velocity and drop radius. **a, b,** In the explored interval (Weber number, W, between 0.3 and 37), the contact time is **a**, independent of the impact velocity, V, but **b**, depends on the drop radius, R. Dotted lines indicate slopes of 0 (**a**) and 3/2 (**b**).

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Evolutionary biology

Hedgehog crosses the snail's midline

According to the dorsoventral axis-inversion theory[1], protostomes (such as insects, snails and worms) are organized upside-down by comparison with deuterostomes (vertebrates)[2–5], in which case their respective ventrally (belly-side) and dorsally (back-side) located nervous systems, as well as their midline regions, should all be derived from a common ancestor[5]. Here we provide experimental evidence for such homology by showing that an orthologue of *hedgehog*, an important gene in midline patterning in vertebrates, is expressed along the belly of the larva of the limpet *Patella vulgata*. This

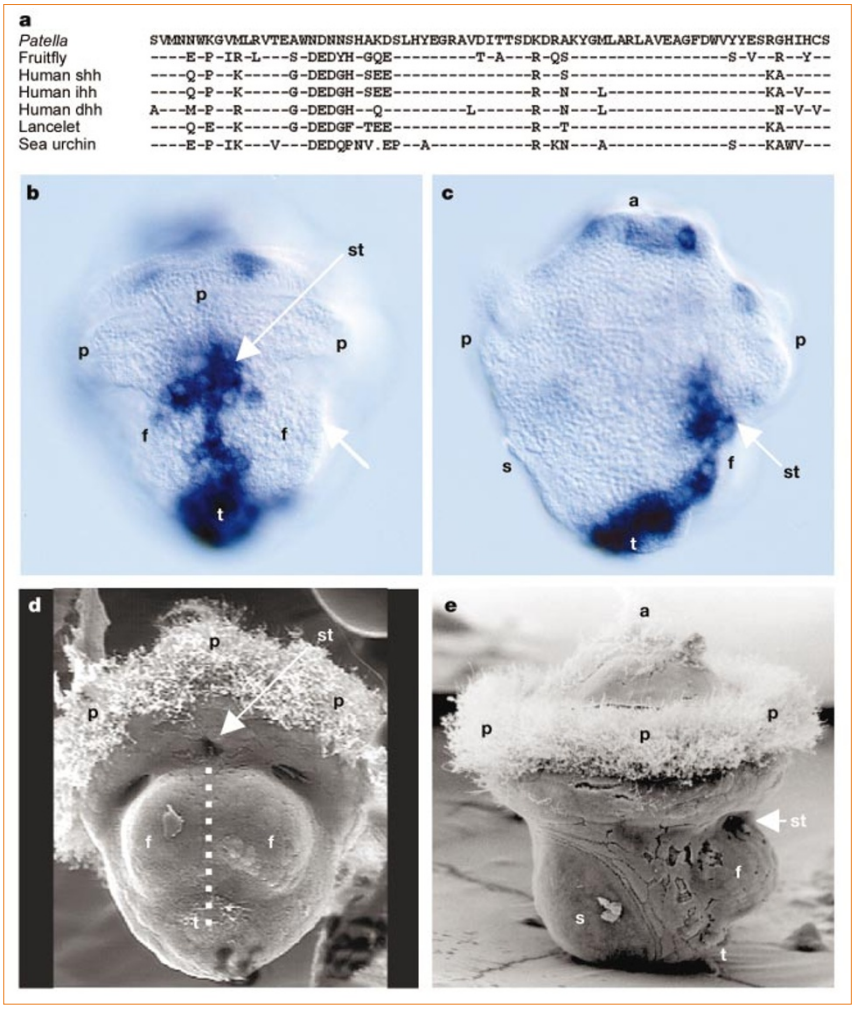

Figure 1 The *hedgehog* gene in the limpet *Patella vulgata* is expressed in the ventral midline of the trochophore larva. **a,** Alignment of part of the deduced *hedgehog* amino-acid sequence from *P. vulgata* with *hedgehog* proteins from fruitfly (*Drosophila*), human (*Homo; sonic, indian* and *desert* variants), lancelet (*Branchiostoma*) and sea urchin (*Lytechinus*). Dashes denote residues identical to those at the same position in the *hedgehog* protein of *Patella*. (The *hedgehog* gene sequence of *Patella* has been deposited at GenBank under accession no. AF435840). **b, c,** Expression of the *hedgehog* gene of *Patella*, as revealed by *in situ* hybridization (specific stain for *hedgehog* messenger RNA; dark blue), in whole-mount embryos (24-h-old pretorsional trochophore larvae) shown from the ventral side (**b**) and the right side (**c**). **d, e,** Scanning electron micrographs of larvae of the same age, shown from the ventral side (**d**) and the right side (**e**). Dashed line in **d** shows the ventral midline running from the future mouth (stomodaeum), over the foot and down towards the ciliated telotroch. Anterior is at the top. a, apical tuft; s, developing shell; st, stomodaeum; p, prototroch; f, foot; t, telotroch.

finding supports the existence of a similar mechanism for the development of the midline of the nervous system in protostomes and deuterostomes.

In protostomes as well as deuterostomes, the midline is an embryonic region that functions in patterning of the adjacent nervous tissue[6,7]. The ventral midline in insects is the region from which cells detach to form the ventrally located nerve cords; in vertebrates, the midline is originally located dorsally. During development, it folds inwards and becomes the ventral part of the dorsally located neural tube and is then called the ventral midline, or floor plate.

The dorsoventral axis-inversion theory predicts that similar genes should participate in embryonic patterning of the midline region in both protostomes and deuterostomes, but so far this has not been demonstrated[5]. *Sonic hedgehog* is expressed in the midline of the early vertebrate embryo, most prominently in the floor plate of the developing nervous system, where it functions in the differentiation of ventral neural-tube structures and the dorsoventral patterning of adjacent tissues[6]. However, in the protostome insect *Drosophila* it is not expressed in the ventral midline — instead, it sets up the border between segments[8], a finding that argues against homology of the deuterostome and protostome midlines.

We isolated a *hedgehog* homologue (the predicted partial amino-acid sequence of which is shown in Fig. 1a) from the snail *Patella vulgata* and used it as a probe for *in situ* hybridization of whole larvae to determine the site of its expression. We obtained a positive hybridization signal in the ectodermal cells of the ventral midline of a 24-hour-old snail larva (Fig. 1b, c) — the ventral midline is evident as the region running from what will become the mouth, over the foot, and down to a ciliated structure below the foot known as the telotroch (Fig. 1d, e).

To our knowledge, this expression of *hedgehog* in *Patella* is the first example of an orthologue (gene homologue) of a deuterostome midline gene being expressed in the ventral midline of a protostome larva. Although the *Patella* trochophore larva does not contain a ciliated band at the ventral midline, other larvae of this type do[9–11]. There is good evidence that the nervous systems of deuterostomes and protostomes are both derived from ciliated bands (see refs 12, 13, for example), so the *hedgehog* gene of *Patella* could be involved in nervous-system development, supporting the idea of a homologous mechanism for midline development in protostomes and deuterostomes.

Further similarities in nervous-system development between protostomes and deuterostomes may come to light by looking at other understudied organisms besides *P. vulgata*. The striking correspondence in midline signalling between vertebrates and this snail points to an evolutionarily ancient role of the *hedgehog* gene in early patterning of the nervous system.

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