measured the occupancy of the qubit's excited state as a function of the interaction time. The observed oscillatory behaviour of this occupancy is a clear quantum effect and indicates reversible qubit–resonator exchange of a single quantum of energy. The typical transfer times for single quanta (the Rabi swap time) was 4 nanoseconds, which is smaller than the energy decay times of 17 ns and 6 ns for the qubit and resonator, respectively. The authors observed a similar oscillatory behaviour in the excited-state occupancy when they transferred a qubit's superposition state, one in which the system is in the ground and excited states at the same time, hence preparing a quantum superposition of the mechanical system. It is also worth noting that, after half the Rabi swap time, the authors' transfer interaction should create an entangled state between the qubit and the mechanical resonator. They point out, however, that their current experimental performance excludes a direct test of entanglement.

Although today it is routine to control the quantum-mechanical motion of individual atoms[9], controlling that of a nano- or micrometre-sized system is not. Quantum mechanics on such scales has been envisaged[10,11] since the 1990s. With their experiment, O'Connell *et al.* have not only set foot firmly in this quantum regime but have also opened the door for quantum control of truly macroscopic mechanical devices. And the prospects are exciting. One in particular is quantum information processing. In this, a key ingredient is the coherent control of many quantum systems, ideally in a scalable architecture. There have been proposals[12,13] to achieve such control by using arrays of mechanical resonators. Although actual implementations will require minimizing the effect of detrimental decoherence mechanisms, the authors[2] have undoubtedly set the stage for such a future.

Another long-term prospect is testing the foundations of quantum physics. For example, superposition states of massive mechanical objects may be used to test possible deviations from quantum mechanics, which have been suggested to eliminate the 'Schrödinger's cat' paradox (in which a cat concealed in a box can be both dead and alive in a superposition of states)[14,15]. Such tests require quantum superpositions of macroscopic spatial separation between two states of an object, literally of an object being both 'here' and 'there'. In O'Connell and colleagues' experiment[2], access to this regime is still hampered by the resonator's high mechanical frequency: the actual displacement between the two motional states of the prepared superposition is on the order of 10^{-16} metres — that is, six orders of magnitude smaller than the size of the unit cells of the resonator's structural lattice.

Although future experiments will need to find a working regime at lower frequencies, O'Connell *et al.* have taken a decisive first step towards an exciting future in mechanical quantum physics. This reminds me of the closing remark of another intriguing talk that was given at the same conference by Pierre Meystre, one of the early pioneers in the field: "Thirty years ago I thought that it was a dead field. Now I think that the surf is up!" ■

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STEM CELLS

Skin regeneration and repair

Cédric Blanpain

Different types of stem cell maintain the skin's epidermis and contribute to its healing after damage. The identity of a stem-cell type that gives rise to different epidermal-cell lineages has just been revealed.

Skin acts as an essential barrier, protecting organisms from their environment. It is composed of two parts: the epidermis, the cells of which form the barrier; and the dermis, which provides support and nutrition to the epidermis. The epidermis also produces appendages, including sweat glands, and hair follicles and their associated sebaceous glands. The different epidermal compartments undergo constant cellular turnover to replace the dead or damaged cells. This homeostatic process is thought to involve several types of stem cell, each located in a specific epidermal region and contributing to the maintenance of a discrete compartment of the skin[1] (Fig. 1a). In a paper published in *Science*, Snippert *et al.*[2] identify the Lgr6 protein as the marker of progenitors that can differentiate into different cell lineages of the skin epidermis.

The first evidence that skin stem cells can differentiate into interfollicular epidermis, sebaceous gland and hair follicle lineages came from transplantation of bulge stem cells[3,4] — a cell population located at the base of hair follicles. Further experiments revealed that, during both embryonic development and normal adult skin homeostasis, bulge stem cells and their progeny contribute to hair-follicle regeneration but not to the maintenance of the interfollicular epidermis[4–6]. In conditions such as wounding, however, bulge stem cells rapidly migrate towards the interfollicular epidermis to help with the rapid regeneration of the wounded skin[5,7,8].

Later findings also showed that sebaceous-gland cells are maintained by progenitors located above the bulge, which express the Blimp1 protein during morphogenesis[9]. Maintenance of the interfollicular epidermis, meanwhile, involves many small units of proliferation scattered throughout this skin layer, called epidermal proliferative units[10,11]. The infundibulum — the upper part of the hair follicle, which interfaces with the interfollicular epidermis — is thought to be maintained by progenitors located in a hair-follicle region known as the isthmus; these cells, which express the marker proteins MTS24 and Lrig1 (refs 12–14), can differentiate into all epidermal cell lineages after transplantation[13,14].

Snippert *et al.*[2] set out to identify the 'mother' of these epidermal stem cells. They find that, during skin formation in mice, the transmembrane receptor Lgr6 is expressed in both the hair follicle and the interfollicular epidermis. In adult animals, however, Lgr6 expression becomes restricted to the isthmus, where about one-third of Lgr6-marked cells also express MTS24 and a few co-express Blimp1.

To more precisely define the differentiation potential of Lgr6-expressing cells, the authors used genetic wizardry to permanently label Lgr6-expressing cells and their progeny. As expected from the first set of results[2], as well as previous data[6,8], Lgr6-expressing cells gave rise to cells of both the hair follicle and the sebaceous gland during embryonic development. Moreover, some cells of the interfollicular epidermis were derived from Lgr6-expressing cells (Fig. 1b).

The authors' lineage tracing of adult skin shows that Lgr6 labelling was initially restricted mainly to the cells of the isthmus region, with some labelling of cells in the interfollicular epidermis and other parts of the hair follicles, albeit at lower frequency. Two months later, Lgr6 progeny were found mainly in the isthmus and sebaceous gland, with some in the interfollicular epidermis, and more rarely elsewhere in the hair follicle. These findings suggest that Lgr6-expressing cells contribute mostly to the homeostasis of the isthmus region and the

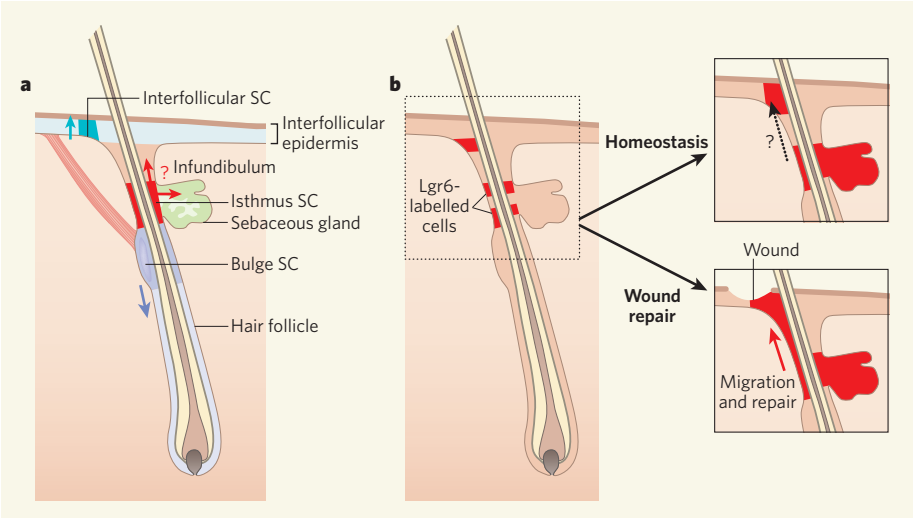

Figure 1 | Various stem cells ensure skin homeostasis. a, The anatomy of the skin epidermis. Arrows indicate the flux of the different stem cell (SC) progeny. **b**, Snippert *et al.*[2] show that, as part of the skin's homeostasis, Lgr6-expressing progenitor cells originally residing in the isthmus region of the hair follicle give rise to new isthmus and sebaceous-gland cells. Moreover, these cells might even migrate to, and replenish cells in, the interfollicular epidermis, as they do during wound repair.

sebaceous gland, whereas a few may have the potential to differentiate into other epidermal lineages. It remains unclear whether a single subpopulation within the Lgr6-marked cells regenerates both the isthmus and sebaceous gland or whether Lgr6 is expressed in both the previously identified[12–14] isthmus progenitors expressing Lrig1 and MTS24, and the Blimp1-expressing sebaceous-gland progenitors[9].

Snippert *et al.* also find that, like isthmus stem cells[13,14], Lgr6-expressing cells transplanted into immunodeficient mice give rise to all epidermal cell lineages. Moreover, like bulge stem cells, Lgr6-expressing stem cells are activated by wounding and migrate towards the epidermis to aid wound repair (Fig. 1b). These intriguing observations suggest that at least two different hair-follicle stem-cell populations can actively contribute to the repair of the damaged epidermis.

The presence of Lgr6-derived cells in the interfollicular epidermis during tissue homeostasis is more puzzling. According to previous cell-lineage tracing of embryonic skin[6,8], all cells of the mature hair follicle, including those of the isthmus region, are derived from cells expressing two other progenitor markers, Shh and Sox9. By contrast, the interfollicular epidermis is not labelled with these markers unless wounded, suggesting little or no contribution of hair-follicle cells to the maintenance of the interfollicular epidermis[6,8].

Three scenarios could explain Snippert and colleagues' observation that Lgr6-derived cells are present in the interfollicular epidermis. First, some rare Lgr6-expressing isthmus cells might originate from a pool of hair-follicle progenitors different from those expressing Shh and Sox9, and these would then migrate to the interfollicular epidermis to contribute to its maintenance. Second, Lgr6 might be more broadly expressed than Shh or Sox9, thus marking a population of progenitors that resides in the interfollicular epidermis, and contributing locally to the development and homeostasis of cells there. Finally, micro-wounding or stress to the epidermis might cause migration of cells from the follicle into the interfollicular epidermis.

This study[2] adds yet another piece to the complex puzzle of skin homeostasis, clearly demonstrating that Lgr6-expressing progenitors actively cycle to ensure the renewal of the isthmus region and the sebaceous gland under physiological conditions. During wounding, both bulge stem cells[5,7,8] and Lgr6-expressing stem cells[2] are actively recruited to repair the interfollicular epidermis. For most skin stem cells, the natural turnover of cells serves several purposes: to replace the dead cells that are shed from the skin surface (interfollicular epidermal stem cells), to fuel hair growth (bulge stem cells) or to make oil cells (sebaceous-gland stem cells). But Lgr6-expressing cells are constantly cycling and are not known to die frequently. So where are their progeny going?

One possibility is that the proliferation of Lgr6-marked isthmus cells essentially serves to fuel the high turnover of sebaceous-gland cells. It would be interesting to determine the intrinsic and extrinsic signals that dictate the fate of different skin epidermal progenitors during development, and to define factors that control their regionalization during both development and homeostasis. Moreover, deciphering the mechanisms that allow the migration of isthmus and bulge stem cells across these boundaries during wound healing will be essential. ■

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EARLY EARTH

Faint young Sun redux

James F. Kasting

Given that the Sun was dimmer in its youth, our planet should have been frozen over for much of its early history. That it evidently wasn't is a puzzle that continues to engage the attention of Earth scientists.

The 'faint young Sun' problem refuses to go away. It was first pointed out by Sagan and Mullen[1] almost 40 years ago, and many potential solutions have been offered since. The latest proposal comes from Rosing *et al.*[2] on page 744 of this issue.

Early in the history of the Solar System, the Sun's brightness may have been as little as 70% of what it is today, a difference caused by the higher ratio of hydrogen to helium in its core at that time. All other things being equal, Earth should have been frozen over for the first half of its existence, a time known as the Archaean. But it wasn't — evidence for liquid water, and life, abounds in the geological record of that time. Sagan and Mullen themselves suggested that enhanced concentrations of reduced greenhouse gases, specifically ammonia (NH_3) and methane (CH_4), kept the early Earth warm. This was based on the premise, now widely accepted[3], that levels of atmospheric oxygen were low before 2.4 billion years ago.